Guide for Curing of Portland Cement Concrete Pavements, Volume I

PUBLICATION NO. FHWA-RD-02-099

JANUARY 2005

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

Foreword

Curing has long been recognized as an important process in constructing durable concrete pavements. Proper curing allows the concrete to develop its potential strength and durability. Inadequate curing can result in surface damage in the form of plastic shrinkage cracking, spalling, and erosion of paste. Since many variables influence the choice of curing materials and when and how to apply curing, the guidance contained in this document should be very helpful to those responsible for concrete curing operations. It was developed through a review of the literature and of other available guidance supplemented by laboratory testing as necessary where information was lacking. It places particular emphasis on attention to details with respect to moisture retention and concrete temperature control.

This is Volume I of two volumes. Sufficient copies of this report are being distributed to provide eight copies to each FHWA Resource Center, four copies to each FHWA Division, and a minimum of six copies to each State highway agency. Direct distribution is being made to the division offices for their forwarding to the State highway agencies. Additional copies for the public are available from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Virginia 22161. Fifty copies of *Curing of Portland Cement Concrete Pavements, Volume II Final Report* (FHWA-HRT-05-038) will be distributed, and Volume I and Volume II will be available online at www.tfhrc.gov.

T. Paul Teng, P.E.
Director, Office of Infrastructure
Research and Development

Technical Report Documentation Page

1. Report No. FHWA-RD-02-099	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle GUIDE FOR CURING OF PORTLAND CEMENT CONCRETE PAVEMENTS		5. Report Date January 2005 6. Performing Organization Code: CEERD-GM-C
7. Author(s) Toy S. Poole		8. Performing Organization Report No.
9. Performing Organization Name and Address Structures Laboratory USAE Research and Development Center (ERDC) 3909 Halls Ferry Road Vicksburg, MS 39180-6199		10. Work Unit No. 11. Contract or Grant No. DTFH61-98-Y-50030
12. Sponsoring Agency Name and Address Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296		13. Type of Report and Period Covered 14. Sponsoring Agency Code
15. Supplementary Notes Contracting Officer's Technical Representatives (COTR): Stephen Forster and Peter Kopac, HRDI-11		

16. Abstract

This document provides guidance on details of concrete curing practice as they pertain to construction of portland cement concrete pavements. The guide is organized around the major events in curing pavements: curing immediately after placement (initial curing), curing during the period after final finishing (final curing), and termination of curing and evaluation of effectiveness of curing. Information is presented on selection of curing materials and procedures, analysis of concrete properties and jobsite conditions, and on ways to adjust curing practice to account for specific project conditions.

17. Key Words Portland cement concrete pavements, curing		18. Distribution Statement	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this Page) Unclassified	21. No of Pages 49	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

Curing is the process of deliberate control of moisture and temperature conditions within prescribed limits. The process allows concrete properties to develop and prevents damage as a result of drying and/or thermal gradients during the early history of the structure.

Sometimes concrete may need no additional curing procedures. For example, when environmental conditions and concrete properties are such that no significant drying or thermal stresses develop on the concrete structure, curing is not needed. However, because of their surface-to-volume ratio and exposure, pavements rarely are in this class of concrete.

Significant damage to a concrete pavement can result when conditions exceed these critical limits and when curing practices are improperly applied. Damage typically takes one of several forms: cracking, weak near-surface concrete, and mechanical damage to the concrete surface.

A number of curing-related conditions can lead to cracking. The most common problem seems to be plastic shrinkage cracking (PSC). PSC occurs when concrete is still plastic (i.e. before time of initial setting), and when excessive loss of mixing water causes shrinkage sufficient to crack the plastic concrete. PSC may take the form of relatively large, parallel, well-spaced cracks that begin shallow but may penetrate deeply into the concrete. In other cases, PSC may take the form of a fine pattern of map cracks that penetrate only 15–30 millimeters into the concrete. These are difficult to see on textured or tined pavements. These types of cracks do not seem to cause problems in some situations, but in other cases they provide an entry for deicing salts and may contribute to freezing and thawing damage.

Another cause of cracking is thermal stress. While thermal stress is often thought to be a mass concrete problem, conditions can develop in pavement concrete when steep thermal gradients develop from the surface into the depth of the pavement at early ages.

A third cause of cracking is drying shrinkage of hardened concrete. Hardened concrete is always expected to shrink on drying (unless some kind of shrinkage-compensating component is present in the concrete) regardless of the degree of curing. Ultimately, the amount of drying shrinkage is more dependent on the amount of hydrated cement paste in the concrete rather than on curing practices. This shrinkage is expected and compensated for by planned joint cutting. However, if significant drying of the hardened concrete occurs within the first few days after placement, drying shrinkage can develop that exceeds this expected shrinkage, resulting in cracking at closer intervals than expected and planned for by the contraction joints. Stresses due to drying and temperature loss may be additive, leading to increased potential for uncontrolled cracking. Insufficient curing before opening a pavement to traffic may result in concrete with poor abrasion resistance. Loss of surface mortar can then occur in areas that get heavy traffic. Poorly cured near-surface concrete is also more permeable to liquids and may contribute to more rapid deterioration from scaling following use of deicing salts. Load-bearing capacity is not normally affected by too much drying because the weakened zone is usually confined to the top 50 mm of concrete. Load bearing could be a problem during cold weather, particularly if ice has formed in partially hardened concrete. It could also be a problem if concrete is cured for an insufficient amount of time or if full-depth cracking occurred.

Inadequate curing can result in surface damage to concrete in the form of erosion of paste and spalling of the surface.

Even though poor curing practices may not result in damage, curing is rarely omitted as a construction requirement because critical conditions are difficult to predict with certainty and the damage that can occur is usually irreversible.

Because curing is almost always required in job specifications, this guide does not attempt to give guidance on when or when not to cure. Instead, this guide includes recommendations on the details of curing practice under various conditions.

The major steps in curing portland cement concrete (PCC) pavements are the same as for all concrete, and can be generally summarized as follows:

1. Protect freshly placed concrete from excessive drying and mechanical damage until sufficient physical properties are developed that final curing procedures can be implemented. American Concrete Institute (ACI) publication 308 R calls this the initial curing period, and this step normally takes several hours.[(1)]

2. Select and apply final curing procedures appropriate to the conditions of the work at the correct time.

3. Maintain final curing procedures (temperature and moisture balance) until sufficient physical properties have developed that deliberate curing is no longer needed. ACI 308 R calls this the final curing period. This step takes 3–14 days.

Differences between curing concrete pavements and curing other types of concrete are discussed in this general guidance. The information in this document is intended to focus on critical details associated with curing pavements. Many of the critical details can be either determined prior to placing concrete, or at least anticipated as likely events so that corrective action can be taken during the paving and curing operation.

The information in this guide is organized around four major topics:

- Chapter 2. General testing, analysis, and planning before construction.
- Chapter 3. The initial curing period.
- Chapter 4. The final curing period.
- Chapter 5. Termination of curing and verification of curing effectiveness.

Each topic is outlined in an annotated block diagram at the beginning of the chapter.

CHAPTER 2. GENERAL TESTING, ANALYSIS, AND PLANNING BEFORE CONSTRUCTION

Many of the problems associated with curing portland cement concrete pavements (PCCP) can be anticipated from knowledge of concrete materials, mixture proportions, and early age properties along with knowledge of probable climatic conditions during placing and in the several days after placing. Figure 1 summarizes major action items.

Materials and mixture proportions	To avoid problems, be aware of major factors affecting curing requirements	-Water-cementitious materials ratio -Fineness and type of cementitious materials -Cement content -Large amounts of pozzolans -Effects of admixtures
Measure bleeding	-Bleeding patterns determine the amount of water that can be lost to evaporation without damage. -Bleeding also affects quality of curing membrane formation	-Basic test method: AASHTO T 158[2] -Can be modified into a field test -Should be measured at 30-minute intervals to show time dependency
Measure time of setting	Time of initial setting determines the end of the bleeding period and optimal time to apply final curing	-AASHTO T 197[3] -Can be approximated in the field -Adjust for in-place temperature
Anticipate probable drying and thermal conditions	-Drying conditions affect probability of plastic shrinkage cracks. -Early concrete temperature affects evaporation rates strongly -Maximum concrete temperature affects thermal stresses - cracking	-Estimate range of probable drying conditions using ACI 308, figure 1[4] -Calculate probable concrete temperature using ACI 305[5] -Anticipate thermal stress problems using HIPERPAV™
Analysis	Net balance between evaporative water loss and bleed water formation determines whether and when damage due to plastic shrinkage cracking is likely	-Plot bleeding v. time -Plot probable maximum evaporation v. time -Critical points are probably soon after placing and/or immediately before time of setting
Plan corrective action	Must be prepared to take action if critical conditions develop	-Evaporation reducers -Reduce concrete placing temp -Wind barriers -Misting -Adjust time of day for placing

Figure 1. Chart. Major points for preconstruction planning.

CONCRETE MATERIALS AND MIXTURE PROPORTIONS—EFFECT ON CURING

General Comment

Properties of cementitious materials (cement and pozzolan) and chemical admixtures are important to consider in anticipating problems with curing. Variation in aggregate properties is probably less important (except possibly for lightweight aggregate, which is not commonly used in paving), although there may be subtle effects. None of the properties described in this section necessarily requires specific action when values deviate from the acceptable limits, but being aware of effects may help anticipate a problem.

Cement Types

The cement properties that are most important in determining curing requirements are strength gain, time of setting, and fineness. Most paving is made with types I, II, or I/II portland cement; guidance is found in publications from the American Association of State Highway and Transportation Officials (AASHTO M 85) [(6)] and the American Society for Testing and Materials (ASTM C 150).[(7)] Type V is used where soils are high in sulfate. The strength gain rates among types I, II, and I/II tend to all converge within a given geographic area, so the user really has very little choice in this property. Blended cements specified by AASHTO 240[(8)] and ASTM C 595[(9)] have strength-gain behaviors that are essentially equivalent to the M 85/C 150 types. ASTM C 1157, which has no AASHTO equivalent, is a general specification for hydraulic cement (portland and blended cements).[(10)] Requirements are based on performance properties, with little or no prescriptive specifications. Strength development of the various grades is essentially equivalent to C 150 types (e.g., type O is approximately equivalent to C 150 type I in performance).

Strength Gain of Cement

The length of required curing of a concrete structure is sometimes directly tied to the strength-gain rate of the cementitious materials. In most guidance, the length of curing is either a prescribed amount of time or the time required to achieve a given strength of the concrete. The strength-gain rate of cementitious materials can affect the strength gain of concrete, but other variables are also involved, most notably the water-cement ratio. The strength-gain rate of cement also affects the amount of cement necessary in a concrete mixture to obtain a given strength in a required time interval. High cement content can result in large amounts of long-term drying shrinkage, particularly if the cement is well hydrated. Hydrated cement paste contributes strongly to drying shrinkage.

Mortar strengths of about 24 MPa at 3 days and 31 MPa at 7 days are most common for types I, II, and I/II cements. Strengths for type V cements are typically about 21 MPa at 3 days and 28 MPa at 7 days. Strengths of available cements can range from about 3.5

MPa less than these values to about 7 MPa higher, but these are less common. Within a geographical area, cement strengths among producers tend to converge on similar values.

Some specifications that are based on fixed-time curing requirements cite the need for extra curing time of concrete made with type II cement. Before 1980, type II cement was usually made with a composition that gained strength at a significantly slower rate than type I cement. Typical 3-day mortar strengths were about 14 MPa. This is now rarely true except in custom-made cements, usually produced for mass concrete applications. Except when the optional heat of hydration requirement is cited, the only practical distinction between type I and type II cement has to do with sulfate resistance.

Fineness

The principal direct effect of fineness on curing has to do with its effect on bleeding and, in concretes with a very low water-cement (w/c) ratio, on development of internal desiccation due to early consumption of mixing water. Modest bleeding tends to buffer the effects of early-age drying and help prevent PSC. Since finer cements tend to hydrate faster, they also generate more heat and potentially cause temperature gradients in the concrete depending on ambient conditions and curing procedures employed (see discussion of HIPERPAV™ in chapter 4.

Blaine fineness values for portland cements tend to range between 325 and 375 square meters per kilogram (m^2/kg). Values higher than 400 m^2/kg may indicate a problem with development of too little bleed water when drying conditions are high, and/or internal desiccation if water-cement ratios are less than about 0.40. Pozzolans are sometimes very fine and can contribute significantly to this problem. Silica fume is particularly noted for this property, but is rarely used in slip-form paving because of workability and cost issues. Slag can also be fine enough, particularly in grade 120, to have a detectable effect on water demand. Fly ashes are typically not so fine as to be problematic, although ultrafine products that may have some noticeable effect are being introduced into the market.

Pozzolans

Class F pozzolan (AASHTO M 295,[(11)] ASTM C 618[(12)]) was the major type of pozzolan used in paving until recent years. The major effect of this class of pozzolan is that setting times are usually delayed by 1 to several hours, and strength gain can be retarded relative to concrete made without pozzolan. The major effect of delayed setting time is that the optimal time for applying final curing is also delayed, hence more time for occurrence of PSC. Slow strength gain can result in prolonged curing-time requirements, unless concrete temperatures are warm. These properties have typically limited the amount used in paving to about 20, by mass of total cementitious materials.

In the last 10 years, class C fly ash has become an abundant product in concrete construction. This class of fly ash is often popular in paving concrete because strength gain is higher than with class F pozzolan; however, setting times may be delayed by times similar to class F. Some of these materials contain chemical phases that hydrate very rapidly upon contact with water, and may tend to tie up the water in the concrete within a few minutes of mixing. This property normally causes some early stiffening.

Class N pozzolan is not commonly available, but some of the products available in the past have been very finely divided, giving good early strengths but seriously affecting water demand.

Chemical Admixtures

Water-reducing admixtures (WRAs) can have two effects on curing. One effect is that they facilitate reducing the w/c rating which impacts curing requirements as discussed below. The other effect involves the occasional case of cement-admixture interaction. Occasionally certain cements and certain WRAs interact badly, resulting in very rapid early hydration of the cement. This may result in rapid consumption of a significant amount of the free mixing water and substantially reduce or eliminate bleeding. Under certain drying conditions (described below), this will make the concrete more susceptible to plastic shrinkage cracking.

WRAs are sometimes advertised as being helpful in reducing drying shrinkage cracking. This effects stems from the fact that if the water-cementitious materials (w/cm) ratios are low enough, most of the mixing water is either chemically bound or tightly bound as surface water in gel pores, and not available to evaporate and cause shrinkage. Unfortunately, when taken to extremes, this overconsumption of mixing water creates internal desiccation, which is similar in effects to atmospheric drying.

Mixture Proportions

The w/cm ratio, total cementitious materials content, and percentage of cement replaced by pozzolan are the three most important mixture-design variables affecting curing requirements, as discussed in the following paragraphs.

Water-Cementitious Materials Ratio

The amount of bleeding is highly dependent on the w/cm ratio. Small to moderate bleeding is effective in buffering excessive drying when concrete is in the plastic state and susceptible to PSC. Excessive bleeding can be detrimental because it tends to result in deposition of a layer of weak material on the surface of the concrete. The w/cm ratio of paving concrete mixtures is rarely high enough to result in this problem.

The relationship between bleed rate and w/c ratio is approximately linear. The empirically developed equation shown in figure 2 approximately relates the average rate of bleeding, in kilograms per square meter per hour ($kg/m^2/h$), to the w/cm ratio.[13] *T* is pavement thickness in centimeters.

$$Bleed\ Rate = [0.051 * w/cm - 0.015] * T$$

Figure 2. Equation. Bleeding rate from water-cement ratio.

Paving concretes tend to have w/cm ratio between 0.38 and 0.48. For 30-cm thick pavement, bleeding would then range from about 0.13 to 0.28 kg/m^2/h. These are lower average bleeding rates than found in more general-use concretes, which range from about 0.5 to 1.5 kg/m^2/h. The result is that paving concretes are more susceptible to losing excessive or unsafe amounts of bleed water to evaporation. ACI 308(4) states that drying conditions of less than 0.5 kg/m^2/h represent a mild threat to most concrete. A safer upper limit for paving would be about 0.3 kg/m^2/h. Recommendations on how to evaluate danger of excessive drying are described below.

Cementitious Materials Content

The cementitious materials content of paving concrete typically ranges from 325 to 385 kg/m^3. It is relatively common practice to compensate for slow strength gain, particularly when using flexural strength as the design property, by adding more cement.

High cementitious materials contents, particularly if cementitious materials are very finely divided, tend to contribute to a reduced amount of bleeding.

A major effect of high cementitious materials contents is long-term drying shrinkage, even if the concrete is well cured. Since hydration ties up free water and results in a volume decrease, hydrated cement paste is the major component of concrete causing drying shrinkage. Long-term drying shrinkage is almost totally dependent on the fraction of hydrated cement in the concrete.

High cement contents can also contribute significant heat of hydration, particularly if the concrete is placed several hours before the hottest part of the day. Portland cement typically reaches its most intense hydration period (and hence heating) 2-4 hours after time of initial setting. Given that time of setting is typically 2-4 hours after mixing, the period of peak heat evolution is approximately 4-8 hours after placing. Temperature-related problems begin after the concrete reaches peak temperature. As the concrete begins to cool, temperature stresses go from compressive to tensile (a situation where concrete is relatively weak).

In general, cement contents as low as compatible with adequate strength gain and durability are beneficial in reducing effects of drying shrinkage and thermal heating effects.

Pozzolan Contents

Retardation of early strength gain is strongly related to the amount of pozzolan replacement of portland cement, particularly if Class F pozzolan is used. Class C pozzolan tends to make a strength contribution at an earlier age than Class F pozzolan. The *AASHTO Guide Specifications for Highway Construction* recommends 3 days' extra curing if substantial (greater than 10) replacement amounts of pozzolan are used.(14) However, preconstruction mixture verification studies should be used to verify this effect. Calculations based on maturity concepts can help anticipate required curing time. The strength gain rate of pozzolan concretes reported to be more temperature sensitive than pure PPCs.(15) If the temperature is expected to be in the 5-15 ^{o}C range, then some preliminary exploration of strength gain using maturity calculations may help quantify potential delays in strength gain. See chapter 5 for a discussion of the maturity method.

DETERMINATION OF BLEEDING FOR JOB CONCRETE

It is important to determine the bleeding behavior of concrete intended for use in paving because this indicates the amount of water that can be safely lost to evaporation. Plotting bleeding over time allows one to identify potentially critical intervals during the bleeding period, which occurs between placing and initial time of setting. Concrete ceases to bleed after the time of initial setting.

Bleeding of job concrete is easily measured during mixture verification testing. The basic method is described in AASHTO T 158(2) and ASTM C 232,(16) but several modifications make the data more useful for the present purposes. The standard test method stipulates using a unit-weight bucket as a test apparatus.

The procedure calls for fabricating a test specimen from job concrete using the same procedures as used in making strength cylinders (AASHTO T 23,(17) ASTM C 31(18)). Make the specimen about the same height as the thickness of the pavement. If the pavement is to be placed on a porous base, then a layer of sand in the bottom of the mold can be used to simulate this drainage potential. Control evaporative losses by keeping the container covered except when taking measurements. About every 30 minutes between fabrication and time of initial setting, tilt the cylinder slightly to one side and let the bleed water collect for about 5 minutes. Draw off the bleed water with a syringe or medicine dropper and measure, either by volume using a small graduated cylinder (5–10 milliliters (mL)) or by weighing. Making a slight depression on the downhill side of the specimen surface will facilitate collecting and drawing off the bleed water.

Calculate the average bleed rate over each time interval using the equation shown in figure 3.

$$Av\ Bleed\ Rate = \frac{V}{A \cdot t}$$

Figure 3. Equation. Time-averaged bleed rate.

where:

V = the amount of bleed water (in kg)
A = the surface area of the specimen (m^2)
t = time (h)
Units of bleeding are kg/m^2/h for that specific thickness of pavement

Plotting the amount of bleed during each time interval gives a time profile of bleeding. Periods when bleeding is less than 0.3 kg/m^2/h may be potentially critical periods. However, the level of criticality depends on drying conditions. Figure 4, using data found in volume II,[13] shows such a plot for a paving mixture.

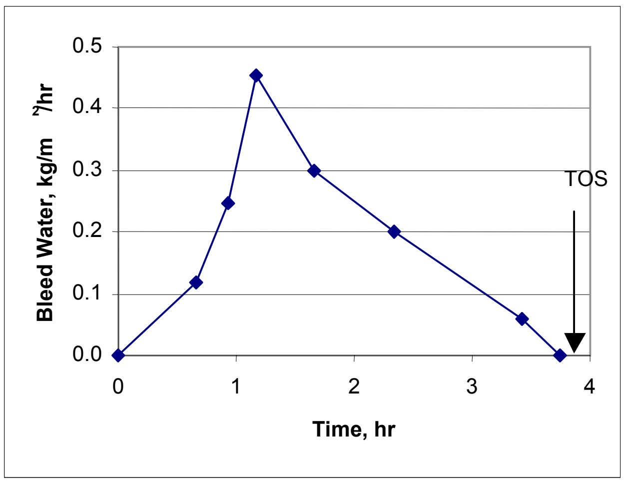

Figure 4. Graph. Plot of bleed water formation v. time for a typical paving mixture.

For this concrete, bleeding rates are low during the first hour and again immediately before time of setting, which occurred at 5 hours. Even at the peak, the bleeding rate was less than the 0.5 kg/m^2/h cited in ACI 308[4] as a limit below which caution should be exercised. Additional information on interpreting such data and accounting for drying conditions is found later in this chapter.

IMPORTANCE OF TIME OF INITIAL SETTING

Time of initial setting is an important property in paving practice because it indicates bleeding is complete and final curing procedures can be initiated. This detail is not usually part of standard guidance on the start of final curing. Application of final curing is usually directed to start when final finishing is complete and the surface sheen is gone. In conventional concreting, final finishing is typically not executed until about the time of initial setting. In slip-form paving, final finishing is usually completed within a few minutes of placing the concrete, well before the time of initial setting and the end of the bleeding period. If bleeding rates are low relative to evaporation rates, then loss of surface sheen will appear rather soon after placing, suggesting that final curing should be initiated even though bleeding is continuing.

Starting final curing before the time of initial setting can lead to several problems. With water and sheet curing, the surface can be damaged due to lack of strength. Water tends to wash out fines, and sheet materials can mar the surface. With curing compounds, continued bleeding under an applied membrane can lead either to poor membrane formation (and loss of critical mixing water) or to spalling of surface mortar. See chapter 4 for a discussion of this phenomenon.

Time of setting is measured as described in AASHTO T 197[3] and ASTM C 403,[19] and is conveniently done during mixture verification work prior to the start of construction. The time of setting is strongly affected by the concrete temperature, and therefore the field time of setting will differ from the laboratory-determined time if the two temperatures differ. This is important in field application, since in-place concrete temperatures can differ significantly from laboratory concrete temperatures, and the effect can be substantial. Laboratory values can be adjusted for actual concrete temperature using the following equation.[13]

$$TOS = TOS_{std} \cdot e^{R\left(\frac{1}{CT} - \frac{1}{StdTemp}\right)}$$

Figure 5. Equation. Time of setting—adjustment for concrete temperature.

where:

TOS = time of setting at temperature of in-place concrete, same units as in standard test
$TOS_{StdTemp}$ = time of setting under standard conditions, any units
CT = temperature of in-place concrete, K
$StdTemp$ = temperature of concrete during laboratory test, K
R = constant

The constant, R, can be determined empirically, but a value of 5,000 Kelvins (K) works well. This equation can be programmed into a spreadsheet to simplify the calculation for use in exploratory work.

ANTICIPATE PROBABLE DRYING AND THERMAL STRESS CONDITIONS ON THE JOB

It is important to be able to anticipate likely drying conditions immediately after placing to determine whether water in excess of bleed water is likely to be lost, making the concrete vulnerable to PSC.

A nomograph ACI has been found to be reasonably accurate in estimating drying conditions for inputs of wind velocity (0.5 m above the concrete surface), concrete temperature, air temperature, and relative humidity of the air above the concrete.

The range of probable drying conditions can be forecast for a given locale based on typical range of weather conditions and projected concrete temperatures. Drying rates of greater than 0.3 kg/m^2/h may present a problem for paving concrete, depending on bleeding rates during the same time (see below).

The information in the nomograph can be represented by the equation shown in figure 6. This equation can be programmed into a spreadsheet to simplify the calculation. The nomograph from ACI 308 is shown in figure 7.[(4)]

$$ER = 4.88\left[0.1113 + 0.04224\frac{WS}{0.447}\right](0.0443)(e^{0.0302(CT\cdot 1.8)+32}) - \left[(RH/_{100})(e^{0.0302(AT\cdot 1.8)+32})\right]$$

Figure 6. Equation. Evaporation rate of bleed water—effect of environmental conditions.

where:

ER = evaporation rate (kg/m^2/h)
WS = the wind speed (m/s)
CT = concrete temperature ($^{\circ}$C)
AT = air temperature ($^{\circ}$C)
RH = relative humidity (%)

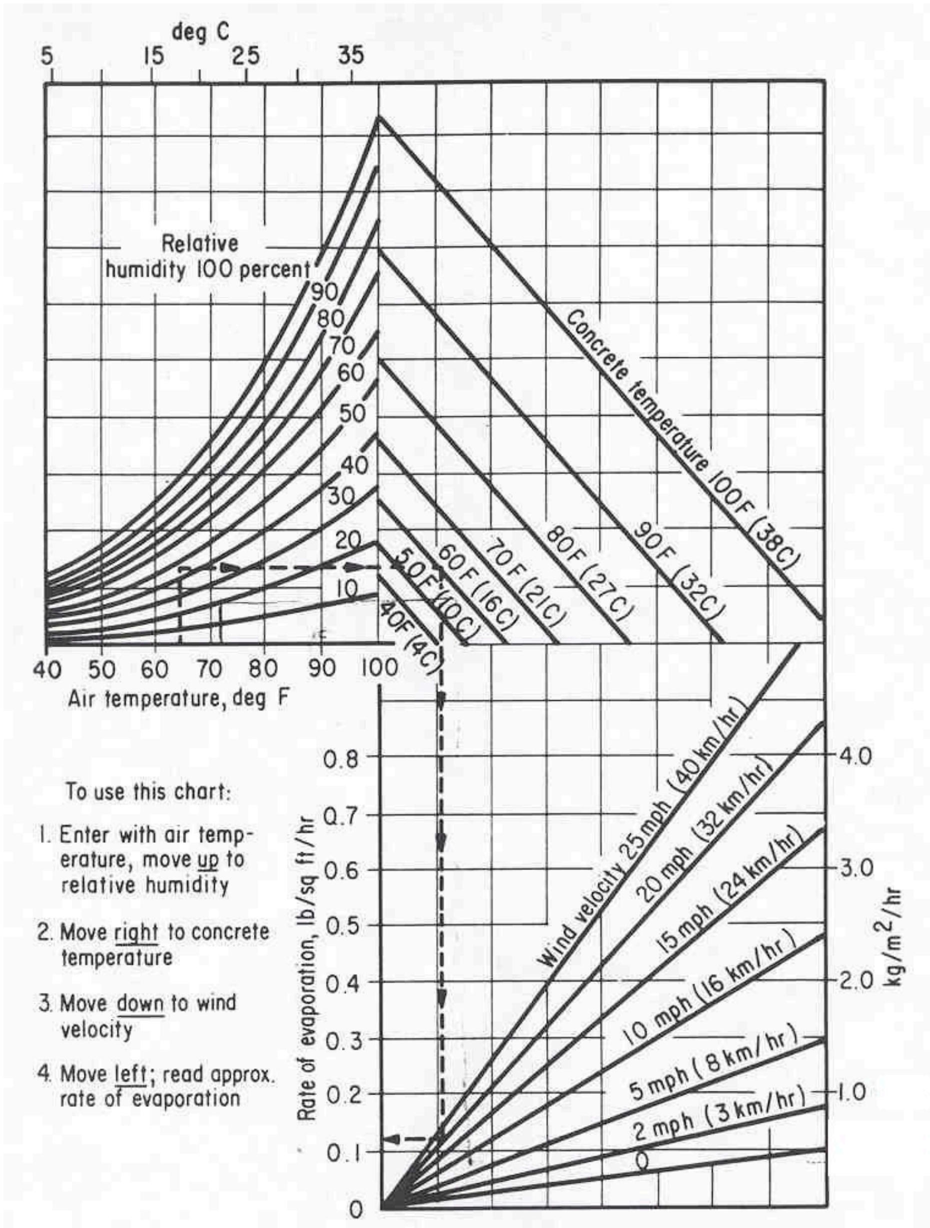

Figure 7. Chart. Evaporation rate nomograph from ACI 308.[4]

It is very instructive to explore the effects of ranges of environmental conditions expected in a given construction location on the evaporation of the bleed water. This information, along with bleeding data and time of setting, allow the engineer to anticipate critical conditions. Wind and concrete temperature are usually found to be the most critical variables. The temperature of freshly placed concrete is a property over which a producer has some control by adjusting the temperature of concrete-making materials. ACI 305 R contains equations that relate the temperature of materials to temperature of concrete.(5)

Anticipating thermal stress conditions on the job can be complicated because of the many variables involved. The Federal Highway Administration (FHWA) has developed a software program called HIPERPAV™ that allows the user to enter plausible data on concrete and site conditions and get thermal-stress output back, in the form of warnings on critical times after placing when cracks may develop (see chapter 4). This program also includes an evaporation-rate calculator similar to the results obtained from the equation shown in figure 6.

ANALYSIS OF MULTIPLE FACTORS AFFECTING EARLY MOISTURE-LOSS MANAGEMENT

Comparing bleeding behavior with probable drying conditions will identify potential critical points during construction. The time of initial setting indicates the end of this critical period. Figure 8 shows the cumulative bleed rate calculated from the data shown in figure 4 plotted along with the cumulative evaporation rate, assuming a constant evaporation rate of 0.30 $kg/m^2/h$.

In this example, evaporation rates exceed bleeding rates for the first hour after placing and again after about 3.5 hours. The time of setting is about 5.2 hours. These two periods represent critical periods from a PSC perspective. Sometimes concrete will endure the first critical period because the mixture is plastic enough to adjust to evaporative losses by simply shrinking into a thinner placement. However, the period after about 3.5 hours may result in cracking because the concrete may have developed some stiffness at this point, and cannot adjust to the loss of water by simply reducing volume.

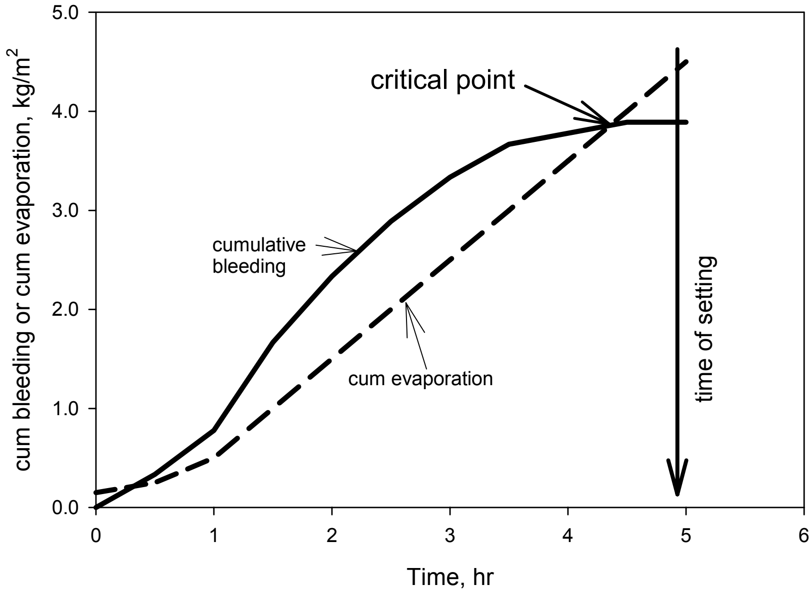

Figure 8. Graph. Plot of cumulative bleed and cumulative evaporation v. time.

PLANNING FOR POTENTIAL CORRECTIVE ACTION

Standard guidance recommends that when evaporation exceeds bleeding, something must be done to reduce evaporation rates. Standard remedies include use of fogging and wind breaks. Neither of these methods is particularly useful for large paving projects.

Three practices are potentially useful in paving large areas. One is to shift paving operations to a time of day when the drying conditions are less severe. Nighttime placement is often attractive because relative humidity is usually higher than during the day.

Another effective option is to reduce the temperature of the concrete at placing. This is a very strong variable affecting evaporation rates. ACI 305 R gives guidance on calculating placing temperature (also discussed in chapter 3). This calculation can be used to explore the amount of benefit expected from cooling concrete ingredients. For example, figure 9 shows the effect of reducing the concrete temperature by 5 ^{o}C (using data from the nomograph in figure 3) on evaporation rates. Evaporation rates become less critical as a result of this adjustment.

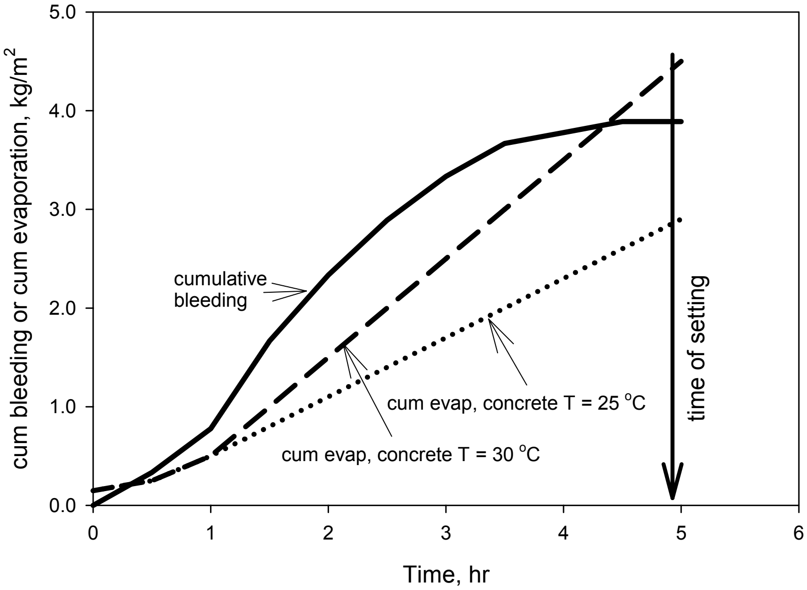

Figure 9. Graph. Effect of reducing concrete placing temperature from 30 °C to 25 °C.

Still another approach is to use evaporation reducers. Evaporation reducers can reduce evaporation rates by as much as 65 percent. (13) Figure 10 shows the effect of a 50 percent reduction in evaporation, using the data shown in figure 4. The cumulative effect is similar to the reducing concrete placing temperature by 5 °C. Currently, there are no test methods or specifications for evaporation reducers, and the user must rely on the manufacturer's guidance.

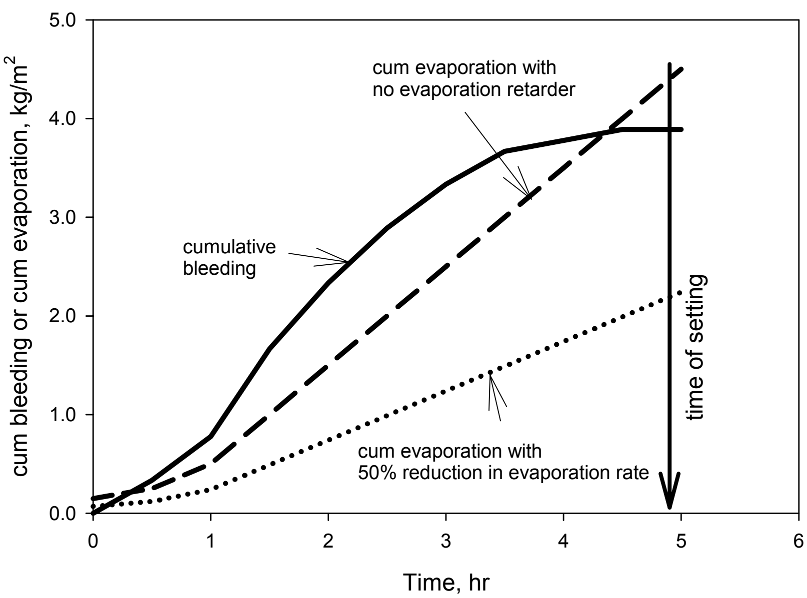

Figure 10. Graph. Effect of reducing evaporation by 50 percent by using an evaporation reducer.

A limited laboratory investigation demonstrated that evaporation reducers can reduce evaporation rates by an amount ranging from 0 to 65 percent. Evaporation reducers must be reapplied if the time of setting is extended and drying rates are high. The approximate application interval is discussed in chapter 3.

In conclusion, reducing concrete placing temperature and use of evaporation reducers can have a relatively strong influence on potential for plastic shrinkage cracking.

CHAPTER 3. THE INITIAL CURING PERIOD

The initial curing period is defined in ACI 308 R as the period between placing the concrete and application of final curing.(1) As discussed above, the proper time for application of final curing is approximately at the time of initial setting. Approximate conditions during the initial curing period should be forecast prior to construction, as described in chapter 2. Activities during construction focus on verifying actual conditions and making onsite adjustments. Figure 11 summarizes major action items.

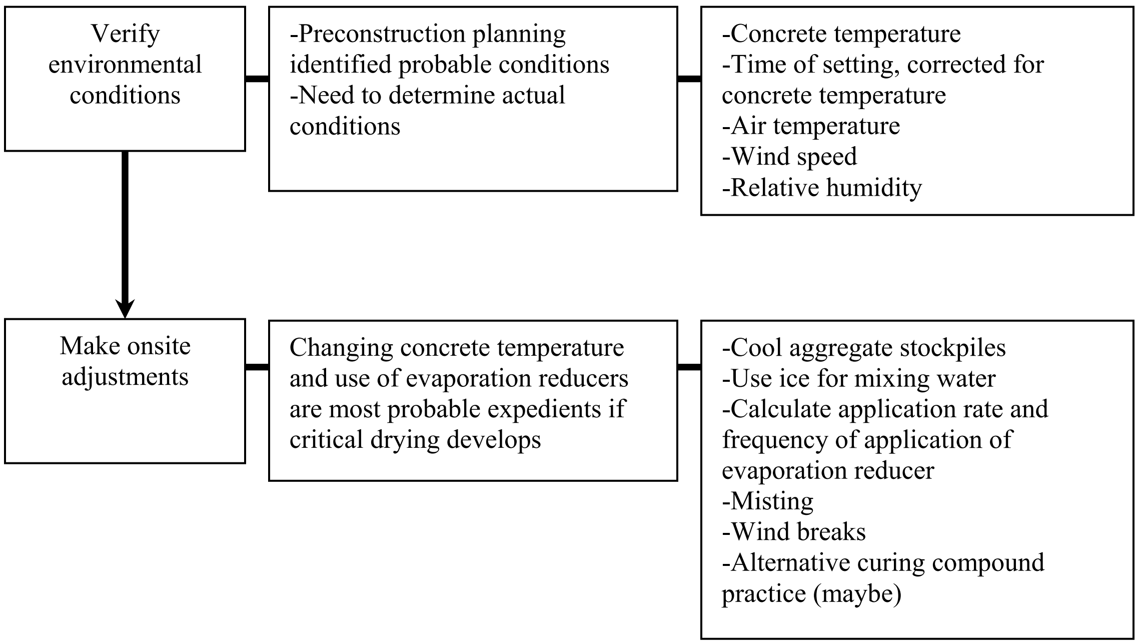

Figure 11. Chart. Major items requiring attention during construction—initial curing period.

VERIFY ONSITE DRYING CONDITIONS

Evaporation Conditions

During placement operations, verify concrete temperatures, wind velocity, air temperature, and relative humidity. Inexpensive instrumentation is readily available for measuring these properties. From these data, evaporation rates can be calculated to determine whether critical drying rates exist, using the equation 4 shown in figure 6 or the nomograph from ACI 308 shown in figure 7.(4)

As discussed in chapter 2, generally speaking, evaporation rates greater than 0.3 $kg/m^2/h$ will present a problem for slip-form pavements. However, exact levels depend on the particular bleeding conditions of the job concrete.

Calculate Time of Initial Setting

Using the concrete placing temperature, the time of initial setting can be estimated, as described in the equation shown in figure 5. The time of initial setting is the optimal time for application of final curing.

EFFECTIVE ONSITE ADJUSTMENTS TO CORRECT FOR EXCESSIVE DRYING

Two onsite adjustments can be useful in reducing evaporation rates of bleed water: reducing concrete placing temperatures and use of evaporation reducers.

Concrete Placing Temperatures

Of the variables affecting evaporation rate of bleed water from freshly placed concrete, concrete temperature is one of the most important and probably the only one that can be practically applied at the jobsite for large paving operations. Cooling aggregate stockpiles, cooling mixing water, or using ice for mixing water are very effective ways of reducing concrete temperatures.

The amount of cooling that can be expected from these measures, and its probable effect on evaporation rates, can be estimated from the calculations in ACI 305 R(5) and the evaporation-rate nomograph in ACI 308,(4) both of which can be programmed into a spreadsheet to simplify the calculation. The equation shown in figure 6, above, reproduces the information in the ACI 308 nomograph.(4) The ACI 305 R calculation of concrete placing temperature from ingredient temperatures is reproduced below in figure 12.(5)

$$T = \frac{0.22(TcaWca + TfaWfa + TpWp + TcWc) + TwWw + TcaWcam + TfaWfam - Wi(79.6 - 0.5Ti)}{0.22(Wca + Wfa + Wc + Wp) + Ww + Wi + Wcam + Wfam}$$

Figure 12. Equation. Temperature of fresh concrete from ingredients.

where:

T = concrete placing temperature
Tca = temperature of coarse aggregate
Tfa = temperature of fine aggregate
Tc = temperature of cement
Tp = temperature of pozzolan
Tw = temperature of mixing water, excluding ice
Ti = temperature of ice
Wca = dry mass of coarse aggregate
Wfa = dry mass of fine aggregate
Wc = mass of cement
Wp = mass of pozzolan
Wi = mass of ice

Ww = mass of mixing water
$Wcam$ = mass of free and absorbed moisture in coarse aggregate
$Wfam$ = mass of free and absorbed moisture in fine aggregate

Evaporation Reducers

Evaporation reducers are a relatively new product developed to specifically address the condition of excessive evaporation rates. The approach is to apply evaporation reducers in sufficient quantity and frequency that the concrete does not ever lose critical amounts of water to evaporation. Application is made using the same (or similar) equipment as that used to apply curing compounds.

Evaporation reducers are water emulsions of film-forming compounds. The film-forming compound is the active ingredient that slows down evaporation of water. There is also a benefit from the water fraction of the evaporation reducers, in that it compensates to a small degree for losses of mixing water to evaporation.

Evaporation reducers may need to be applied several times, depending on the conditions. The equation in figure 13, below, yields a conservative estimate of the frequency of application for a given condition.

$$F = \frac{AR}{ER(1-0.4)-BR}$$

Figure 13. Equation. Frequency of application of evaporation reducer.

where:

F = frequency of application, h
AR = application rate, kg/m^2
ER = evaporation rate of bleed water, $kg/m^2/h$
BR = bleed rate of concrete, $kg/m^2/h$

The constant, 0.4, is taken to be the reduction in evaporation rate affected by an evaporation reducer. The exact value is difficult to know in the absence of test methods and specifications, but most manufacturers claim at least a 50 percent reduction in evaporation. Therefore, this equation is probably conservative. An application of 0.2 kilograms per square meter (kg/m^2) also expressed as 5 square meters per liter (m^2/L), is a commonly recommended rate. This is also often near the maximum that can be applied practically without runoff.

Alternative Curing Compound Practice

The relatively common practice of applying some or all of the curing compound very soon after placing will serve as an effective evaporation reducer. However, there may be problems associated with this practice, as described in chapter 4. If used, this practice should be verified as part of the laboratory verification of curing compound properties, as also described in chapter 4.

CHAPTER 4. THE FINAL CURING PERIOD

The final curing period is defined as the time interval between application of curing procedures and the end of deliberate curing. Final curing methods can be classified into three types: curing-compound methods, water-added methods, and water-retentive methods. For most paving applications, selection among these methods is largely a matter of economics of materials and labor. Technical issues enter into the decision process for some special-purpose concretes. Figure 14 summarizes major considerations.

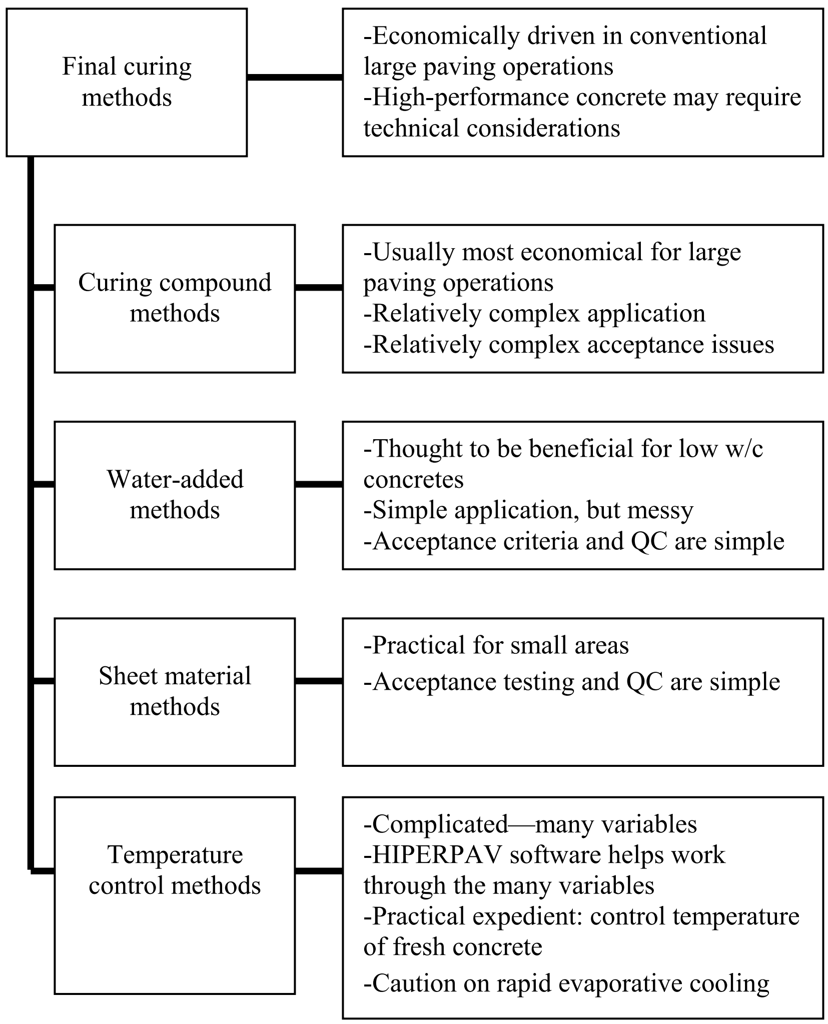

Figure 14. Chart. Major items requiring attention during construction—final curing period.

CURING COMPOUND METHODS

Curing compounds are normally the most economical method for curing large areas of paving because of the relatively low labor costs. Once the application is satisfactorily completed, little or no additional attention is required. The negative side to using curing compound methods is the relatively complicated selection and specification-compliance issues that are frequently encountered, and the skill required to apply the material correctly. Figure 15 summarizes the major issues associated with use of curing compounds.

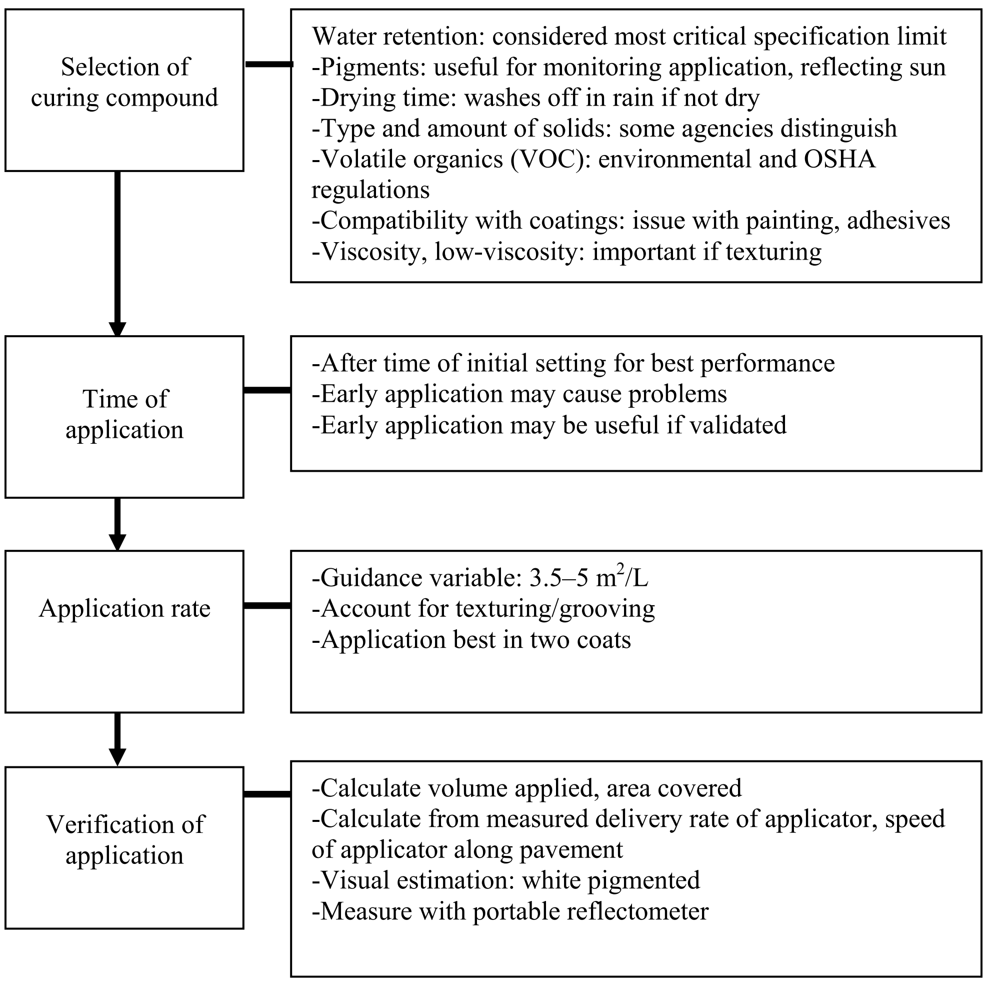

Figure 15. Chart. Major features in curing compound practice.

Selection

Specifications for curing compounds are covered by AASHTO M 148,[20] which is equivalent to ASTM C 309,[21] and by ASTM C 1315.[22] The guidance in ASTM C 1315[22] contains more stringent requirements on water retention than ASTM C 309[21] and a minimum requirement on solids content. Both of these documents are pertinent to paving applications, but the specification also contains several requirements that usually do not pertain to paving applications. These include compatibility with adhesives (flooring) and surface sealing properties.

Selection criteria for curing compounds for paving applications include:

- Water retention.
- Pigments.
- Drying time.
- Type and amount of solids.
- Volatile organic compounds (VOC).
- Compatibility with coatings.

Tendency to run (viscosity) is another important criteria for tined (textured) pavements, but not part of most standard criteria. Each of these criteria is discussed below.

Water Retention

Water retention is the major performance property of curing compounds. It is tested according to AASHTO T 155[23] or ASTM C 156[24] (or some variant of this test), which measures water loss after a fixed period (usually 72 hours) of exposure to a standard drying condition. Most of the moisture loss occurs in the first 24 hours, and at least one State Department of Transportation (DOT)—Caltrans—uses that test age with a modified specification limit. The environmental conditions used in ASTM C 156 represent an evaporation rate, as determined by direct measurement, of between 0.65 and 1.1 $kg/m^2/h$.[24] The between-laboratory precision of this method is poor, and causes considerable contention between buyer and seller.

The standard water-retention limit (AASHTO M 148,[20] ASTM C 309[21]) is a moisture loss of 0.55 kg/m^2 (max). Some State DOTs require lower values, down as low as about 0.25 kg/m^2. ACI 305 R (on hot weather) recommends reducing the limit to 0.39 kg/m^2 for hot weather concreting.[5] Hot weather concreting is vaguely defined in this document, but can reasonably be interpreted to mean conditions in which evaporation rates exceed 0.50 $kg/m^2/h$, as determined by the evaporation rate nomograph in ACI 308 and 305 R.[4,5]

The research behind the 0.55 kg/m^2 limit dates to the 1930s and 1940s. It was determined that this level of moisture loss led to strength development in concrete (of stripped and coated cylinders) at least as high as with moist curing. Recent research is limited, but suggests this limit to be adequate for most applications.

Volatile Organic Compounds

For a material to conform to standards for volatile organic compounds (VOCs), it can contain no more than 350 grams per liter (g/L) of volatile solvents. Many products list the VOC content on the package or on the materials safety data sheet. New federal regulations require use of low VOC materials in certain applications, particularly in enclosed areas. This regulation is also commonly applied to pavement construction even though the enclosed-area concept does not usually apply. Most manufacturers market a wide variety of low VOC products. The major problem with low VOC materials is that they contain a relatively large amount of water, which can make the product very slow to dry under conditions of low evaporation rates (see below).

Drying Time

Drying time is an important property because a curing compound is susceptible to washing off if it is rained on before it has dried. Wet curing compound also limits walking on the pavement. The standard drying time in AASHTO M 148[20] and ASTM C 150[7] is 4 hours under prescribed laboratory drying conditions. The laboratory conditions represent an evaporation rate of approximately 0.43 kg/m^2/hr. While this rate is not exactly specified, it is the value from the conditions described in the test method. The test method is rather approximate and could be the cause of some compliance disputes; some State DOTs require shorter drying times. As mentioned in the previous paragraph, low VOC curing compounds may be slow to dry. The following empirical equation has been found to be useful in anticipating the amount of drying time needed under poor drying conditions, such as evaporation rates of less than 0.10 kg/m^2/h. The equation given in figure 16, below, does not really apply well to estimating drying times less than about 4 hours.

$$Drying\ Time = ER^{-0.67}$$

Figure 16. Equation. Drying time for curing compound—temperature correction.

In figure 16, ER is the evaporation rate (units of kg/m^2/h) as estimated using the ACI 308 nomograph.[4] According to this equation, evaporation rates less than about 0.1 kg/m^2/h may result in prolonged drying times.

Pigments

White-pigmented curing compound is most often used in paving. The white pigment reflects sunlight and helps with temperature control in hot weather. In addition to these functional properties, the pigment is a very strong indicator of the amount and uniformity of the application. Other pigments, typically pink or yellow-green, are used as fugitive pigments (they bleach out within a few days) and are designed principally for architectural applications where the more persistent white pigments is objectionable. These colored pigments are not as good for estimating application properties as white pigment. Methods exist for estimating application rates from reflectance of white pigment.

Type and Amount of Solids

The solid fraction of the curing compound contains ingredients that form the curing membrane. The white pigment is also part of the solids, but is not active in membrane formation. It is termed "vehicle solids." Active solids are classified as either wax or resin. Both are competent materials. Waxes are sometimes not favored for paving for practical reasons; waxes are less resistant to marring than resins, and some are believed to clog nozzles easily. Resins come in a wide variety of chemical types, and often are not specifically identified by the manufacturer.

Total solids content is an approximate indicator of water retention properties, within a given type of chemistry. Total solids of approximately 12-15 percent are usually required to meet the 0.55 $kg/m^2/h$ limit stated in AASHTO M 148(20) and ASTM C 309.(21) Total solids content of about 25 percent may be required to meet the more demanding requirement of ASTM C 1315.(22)

Compatibility with Coatings

Some curing compounds act as bond breakers. If paint or adhesives are intended to be applied to the finished surface, then either the curing compound must be removed or a compound compatible with coatings selected. The manufacturer's literature clearly indicates this special property of a curing compounds. Absence of information on compatibility with coatings is an indication that this property does not exist with a particular product.

Viscosity (Tendency to Run)

On grooved or textured pavements, some curing compounds are of such low viscosity that they tend to run down into the bottom of the grooves, leaving a deficiency on the vertical surfaces. A limited laboratory study found wide variation among products in the maximum application rate that could be tolerated without running. Some products tended to run at applications as light as 10 m^2/L, while others could be applied at 5.0 m^2/L without running, which is the application rate typically recommended by most manufacturers. At least one State DOT has a test and specification requirement for this property.(25) Application of curing compound in two light coats will help avoid this problem, if it exists. There are curing compounds manufactured specifically for application to vertical surfaces, but the viscosity is so high that they may not work with the type of application equipment normally used in highway paving.

Time of Application

Curing compounds perform best if applied after time of initial setting. Typical guidance on paving is to apply the curing compound when the surface sheen has disappeared. Taken literally, this practice can lead to poor performance. Paving concretes tend to be made with a relatively low w/c ratio, so under even relatively mild drying conditions, the surface sheen may disappear soon after placing even though bleeding is continuing. Application of the curing compound then slows or stops the evaporation of bleed water, which then either accumulates under the membrane or dilutes the curing compound. In either case, the membrane is likely to be damaged and suffer reduced performance during the final curing period. This damage is sometimes visible as cracks or tears in the membrane. In other cases the damage can only be seen with moderate magnification. If drying conditions are mild (e.g., <0.5 kg/m^2/h), this result may have no detrimental effect.

There have been occasions in which curing compound applied under these conditions will apparently bond to the surface layer of mortar, which will then delaminate as the bleed water works its way to the surface.[4] The damage develops as thin spalls (a few millimeters thick) of surface mortar early in the pavement history, but not necessarily immediately. This is apparently not a common phenomenon.

It is relatively common practice to apply curing compound very soon after placing. When this happens, the curing compound may act as a relatively good evaporation reducer. The potential difficulty with this practice is that the curing compound will not retain water during the final curing period to the level of performance expected from the job specification on the material for the reasons cited above. However, it may be reasonable practice to apply part of the curing compound early, for purposes of controlling evaporative losses during the initial curing period, then applying the remainder after time of initial setting to restore the integrity of the membrane from any damage suffered from the early application. If this practice is anticipated, it should be verified with laboratory testing. This verification can reasonably be done at the same time curing compound compliance testing is being done. Rather than waiting for the sheen to disappear from the test specimen, curing compound can be applied within a few minutes after forming, the water loss measured, and the physical integrity of the membrane and mortar surface verified.

Application Rate

AASHTO guidance recommends a coverage rate of no more than 5 m^2/L. This rate is also common in the manufacturers' guidance. As discussed above, many curing compounds cannot be applied at this rate in a single pass without serious running into low areas. Grooving patterns increase the effective surface area. This effect must be accounted for to maintain the target application rate. The equation given in figure 17, below, can be used to calculate the application rate necessary to compensate for the increased area.

$$AR = (AR_{ungrooved}) \cdot \frac{(S + W)}{S + 2D + W}$$

Figure 17. Equation. Application rate for curing compound—correction for texturing.

where:

AR = the adjusted application rate (m^2/L)
$AR_{ungrooved}$ = the specified application rate for an ungrooved pavement
S = the space between grooves

W = the width of the grooves
D = the depth of the grooves

Curing compound is best applied to textured pavements in two perpendicularly applied coats.

Verification of Application

After-the-fact verification of application rates is sometimes accomplished by documenting the volume of curing compound used and the area of pavement covered. Another way is to directly verify the flow rate through nozzles by measuring the volume delivered over a known time interval; by monitoring the movement rate of the application equipment, an application rate can be determined. Both of these methods are competent to determine average application rates, but neither is useful for verifying uniformity of application.

No method exists for verifying uniformity of nonpigmented compounds, but two approaches are potentially useful for white-pigmented compounds. The visual check is the easiest to use. The inspector looks for areas of less-than-white appearance. White-pigmented curing compound meeting AASHTO M 148[20] and ASTM C 309,[21] and applied at a rate of 5 m^2/L, has a very white appearance. Any hint of gray is an indication of serious under-application. Variations on the order of 2 m^2/L are detectable by this method. This method is most effective soon after the curing compound has been applied. Concrete tends to lighten in shade considerably as it dries, so an underapplication may be difficult to perceive after about 24 hours.

Portable reflectometers are manufactured for assessing coverage of paint. These devices are effective in measuring reflectance of field applications of white-pigmented curing compounds.[26] This instrument is more sensitive than the human eye to variations in whiteness (hence application rate). A limited evaluation indicates that this equipment can detect variations on the order of 1 m^2/L if a calibration is prepared using job concrete with a range of known application rates to form a standard curve.

WATER-ADDED METHODS

Water-added methods include ponding, fogging, and wet burlap or other wetted absorbent materials. Major criteria are summarized in figure 18.

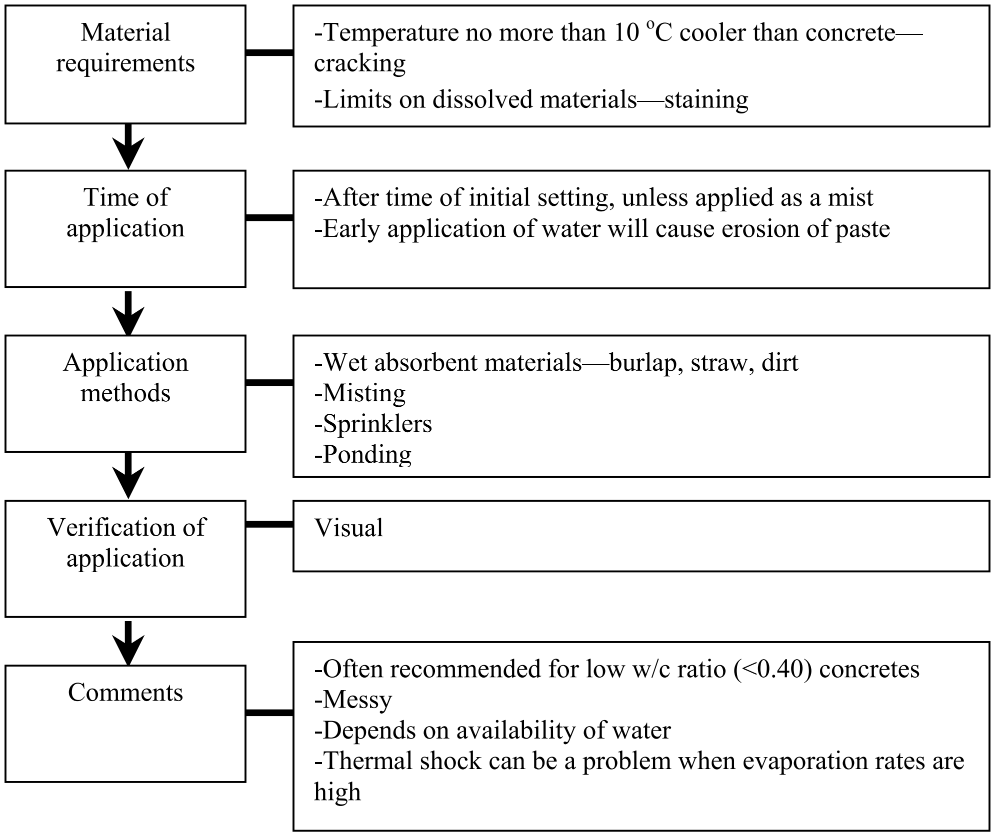

Figure 18. Chart. Major features of curing with added water.

Water-added methods are not practical for curing pavements, but may be practical for patching and slab replacements. Water-added methods are commonly believed to be the only effective curing method for avoiding cracking due to internal desiccation in very low w/c ratio concrete (which becomes critical at w/c ratio levels starting at about 0.40 and less). Consequently this method is often used for bridge decks. However, it is not clear whether water effectively penetrates very deeply into low w/c ratio concretes. Concrete made with type K expansive cement, which has been uncommonly available in recent years, performs better with water-added curing.

Material Requirements

Requirements on curing water are relatively simple. ASTM C 94 contains requirements on mixing and curing water.(27) Major limits are on chlorides and sulfates. Where staining is a concern, there are often limits on iron. Requirements on burlap are more complicated. Burlap is covered by AASHTO M 182.(28) Burlap is made in a variety of weights and thread counts, which are typically the basis for job specifications. Some job specifications also limit use of previously used burlap. The basis for this is unclear.

Time of Application

Fogging can be applied at any time after placing as long as it is not so heavy that runoff develops. Flowing water cannot be tolerated before time of initial setting because of the danger of washing out cement fines. Absorbent materials/ should usually not be applied before time of initial setting because of the danger of physically damaging the surface.

Application Methods

Sprinklers and soaker hoses are effective methods for keeping a horizontal surface wet. Water-absorbent materials can be covered with plastic to eliminate evaporation and reduce the amount of water needed for effective curing. Burlap can be purchased with an impervious layer on one side.

Extreme drying conditions may cause a problem when using some water-added curing methods. High rates of evaporation of the curing water create a strong cooling effect and can result in a sufficiently strong temperature gradient that cracking occurs. The U.S. Army Corps of Engineers limits the temperature gradient in the outer 50 mm of a concrete structure to no more than 13 ^{o}C. Laboratory work has shown that a wet concrete exposed top evaporation rates greater than 1.4 kg/m^2/h can develop a cooling gradient over a 50 mm depth larger than 13 ^{o}C. Covering wet absorbent materials with a layer of plastic sheeting will prevent significant evaporative cooling. The HIPERPAV software program contains features that can help with an analysis of this condition.

Verification

Verification of curing is a matter of visual inspections. Typical guidance is that all concrete be inspected at least once per day or more often if conditions warrant, and if dry concrete is found, the situation is corrected and an additional day added to the curing requirement.

CURING WITH SHEET MATERIALS

Methods involving impervious sheeting are simple and relatively free of specification compliance issues. Major criteria are summarized in figure 19. This method is probably impractical for large areas of paving and/or windy conditions, but may be very practical when used for smaller areas. Some agencies (e.g., U.S. Army Corps of Engineers) do not allow use of plastic sheeting directly against the surface of the concrete because of the mottled pattern that sometimes develops.

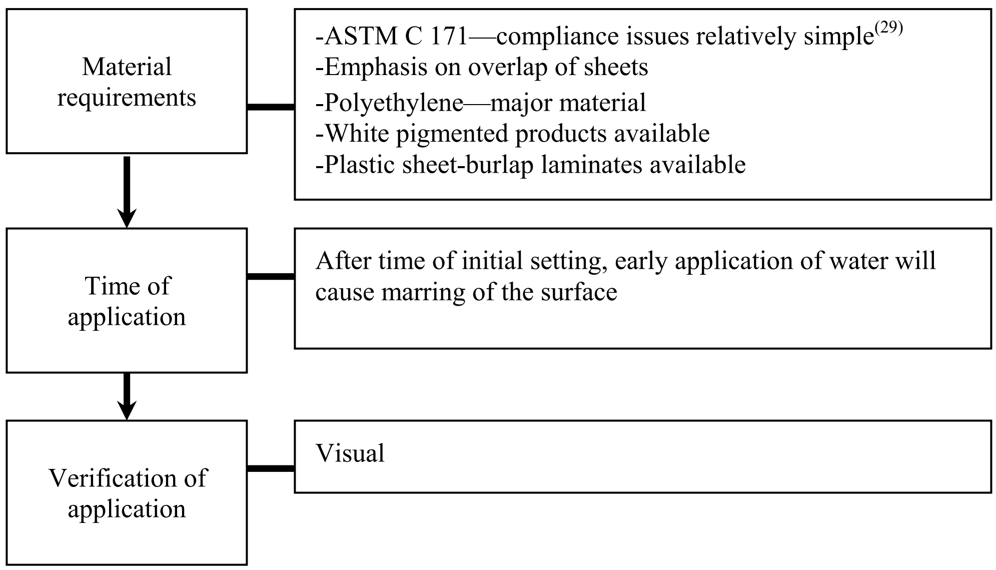

Figure 19. Chart. Major features of curing with water-retention methods.

Material Requirements and Compliance Issues

Specification compliance issues are simplest with this type of curing. AASHTO M 171[30] and ASTM C 171[29] both describe the specification covering plastic sheeting, and contain relatively simple requirements. A major feature of specifications on application has to do with overlap of sheets. Typically a 50-mm overlap is required. The sheet material must cover exposed edges of the concrete, be sealed so that moisture does not escape, and be weighted down so that wind will not lift the sheet off of the pavement, either by getting under the edges or by aerodynamic lifting.

Simple polyethylene sheets meeting AASHTO M 171 specifications work well for water retention, but use of this type of material may result in a mottled pattern on the concrete surface.[30] For this reason, some agencies do not allow curing with plastic sheets. Plastic sheet-burlap laminates are also manufactured that would avoid this problem.

White-pigmented sheeting is available, which helps with temperature control by reflecting sunlight.

Time of Application

Sheet materials should be applied after time of initial setting. Applying sheeting prior to initial time of setting is likely to cause marring of the surface.

Verification

As in water-added methods, daily visual inspection is the normal verification method. If drying areas are found, the problem is fixed and an additional day added to the curing time.

TEMPERATURE—CONTROL METHODS

The effects of temperature variations in concrete on events that occur during or at the end of the initial curing period have been described above. This section addresses problems associated with the volume changes in hardened concrete that occur within the first few days of placing.

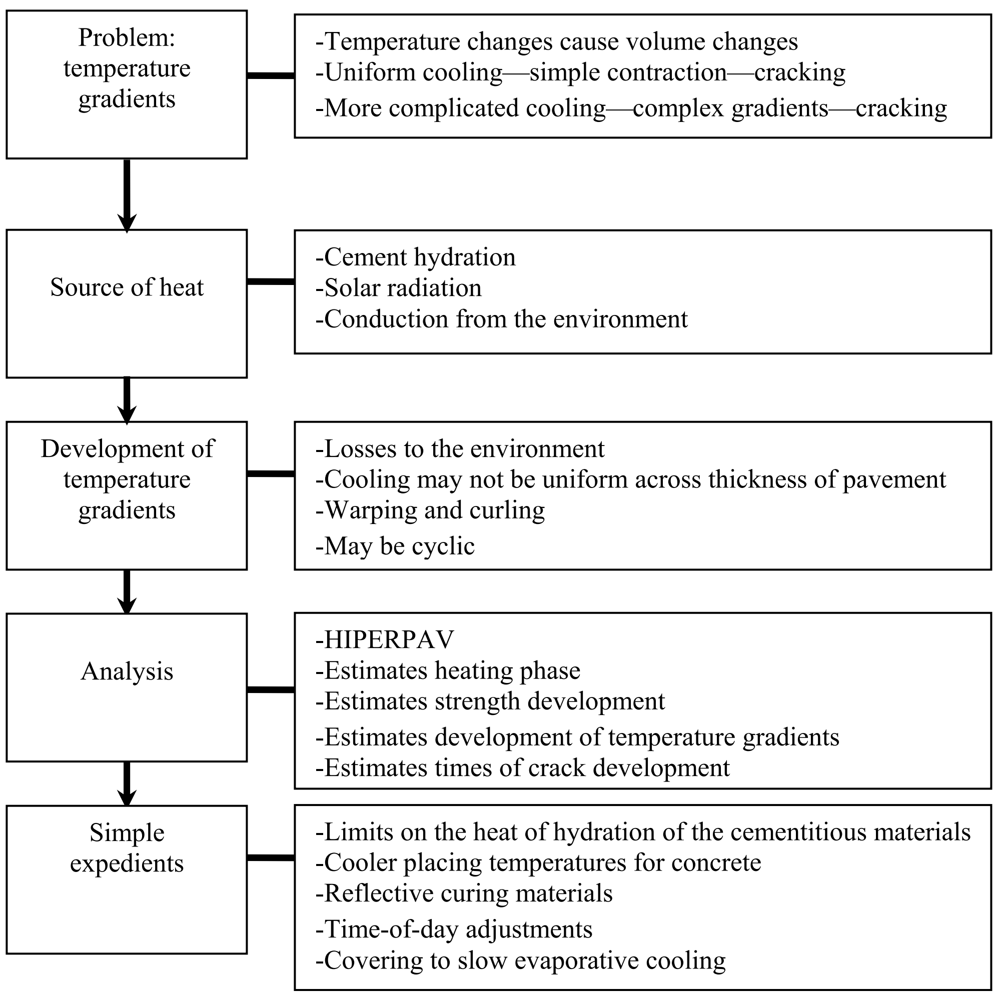

Figure 20. Chart. Thermal effects.

Temperature changes cause volume changes in concrete. A typical coefficient of thermal expansion for concrete is $10^{-5}/^{o}C$ (i.e. in/in/^{o}C, cm/cm/^{o}C etc) ± $2x10^{-5}/^{o}C$. The coefficient of thermal expansion is dominated by the type of aggregate. Carbonate aggregates have a lower coefficient of expansion than do silicate aggregates. The volume changes caused by temperature changes are not a problem per se, unless the concrete is not free to expand or contract due to some physical limitation. For considerations of curing practice, it is the early heating, then cooling, along with environmentally induced warming and cooling cycles and accompanying volume change of the concrete that is the immediate problem.

Concrete generates heat internally starting soon after placement due to the hydration of the cementitious materials. The most intense heating from this source occurs in the first 24 hours, reaching a peak approximately 6-8 hours after placing, depending on the environment and the chemistry of the cement. In thin pavements, this heat is usually dissipated to the environment about as fast as it develops, and does not contribute significantly to the overall heating of the pavement. In thick highway pavements, some of the heat can accumulate.

Concrete can also warm if the air temperature is higher than the placement temperature and if there is significant solar radiation. Cool atmospheric conditions and evaporation of water from the surface of the concrete act against the warming.

The typical pattern in warm-weather placements is for the concrete to warm up at least a little. However, if the heat of hydration of the cement, peak air temperature, and peak solar radiation occur at the same time, then temperatures as high as about 60 ^{o}C (140 ^{o}F) can be reached if measures are not taken to prevent this.

Problems do not usually occur during this heating phase, but as the concrete develops strength and becomes somewhat brittle, the shrinkage associated with cooling can cause cracking. An exception to this occurs if warming and cooling cycles of sufficient intensity occur early in the history of the pavement. Under such conditions, the rapid warming of the surface of the concrete can cause a warping reaction that can result in cracking. A temperature change of about 15 ^{o}C (27 ^{o}F) in concrete that is restrained from shrinking is sufficient to cause cracking.

The restraint that prevents free shrinkage of the pavement may be the friction with the road base, or be deep-lying concrete may experience slower cooling because it is not in contact with cool air.

The purpose of joint cutting is basically to anticipate these cracks and to cause them to form in a controlled location. The art in joint cutting is determining when the concrete is mature enough to withstand the sawing operation without damage, but not to wait too long so that significant cooling shrinkage occurs, causing cracks to form in uncontrolled locations.

Because of the number of variables involved in the final curing process, anticipating problems is a very complicated process. FHWA has developed a calculation procedure that captures all of these effects and anticipates these kinds of problems. This procedure is captured in a software product called HIPERPAV. This software accepts inputs on the concrete properties, pavement properties, and environmental conditions, then calculates temperature changes and gradients. The output is a time-dependent graph that displays development of compression and tension in the pavement, and anticipates points at which cracking is likely to develop.

In the absence of this computational tool, the pavement engineer's best option is to try to minimize the maximum temperature difference between the average ambient temperature and the peak temperature of the pavement. This method will also limit the size of the temperature gradients during cooling. In searching standard guidance, no limits were found that address this feature, although a maximum temperature difference of about 20 ^{o}C is commonly applied to large-section bridge elements.

Another approach commonly used in construction of mass concrete structures is to cool the concrete to a temperature below the average ambient temperature, so that the temperature increase caused by the heat of hydration and environmental heating will result in a smaller ambient-peak value (i.e., the concrete will have less cooling to do, and hence the gradients should be smaller).

Fresh concrete is cooled most effectively by keeping the aggregates cool by sprinkling the stockpile. Aggregates normally comprise 75-80 percent of the mass of concrete, so their temperature dominates the temperature of the fresh concrete. However, cooling stockpiles may be impractical in some paving operations. The fallback method is to use ice as partial replacement for mixing water, or to use liquid nitrogen injections.

CHAPTER 5. TERMINATION OF CURING AND VERIFICATION OF CURING EFFECTIVENESS

Figure 21 summarizes major considerations involving length of curing required and verification of effectiveness of curing.

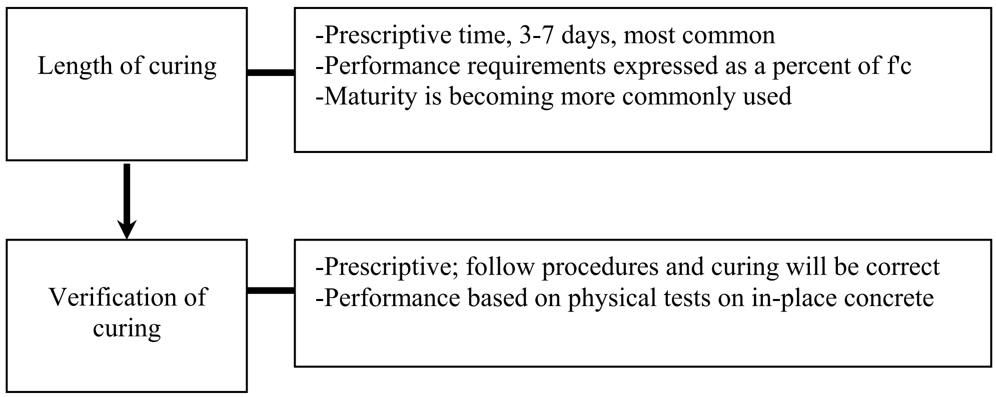

Figure 21. Chart. Considerations pertinent to the termination of curing.

LENGTH OF CURING

Fixed Time Intervals

The traditional prescriptive way of specifying length of curing is with fixed time periods. The requirement is usually accompanied by a minimum temperature during the specified time interval, typically 10 ^{o}C.

AASHTO

The *AASHTO Guide Specifications for Highway Construction* requires 3 days of curing, without comment on temperature.[14]

State DOTs

More than half of State guidance reviewed requires 3 days of curing, with no requirements on temperature during the curing period, although some DOTs had cold-weather provisions requiring concrete temperatures be ≥ 10 °C. One DOT requires the temperature during those 3 days to be at ≥15 °C. Several States require 4 days, without qualifications on temperature. About 25 percent of States require 7-14 days of curing, but most of these DOTs allow for a shorter period if strength reaches a prescribed level, as determined by field-cured cylinders or maturity methods.

ACI

ACI guidance is quite variable, and some standards provide for several options.

- ACI 318 (*Building Code*)—7 days at T≥10 ^{o}C, or 3 days at T≥10 ^{o}C for high early-strength concrete (not specifically defined).[31]

- ACI 301 (*Standard Specification for Structural Concrete*)—7 days or 3 days for high early strength concrete.[32]

- ACI 308 (*Standard Practice for Curing Concrete*)[4]
  - 3 days with type III cement.
  - 7 days with type I cement.
  - 14 days with type II cement.
  - Types IV and V, or w/ pozzolan—no recommendation.
  - Pavements—7 days at ≥5 ^{o}C.

- ACI 325.9 R (*Guide for Construction of Concrete Pavements and Concrete Bases*)—7 days at ≥ 4 ^{o}C.[33]

- ACI 330 R (*Guide for Design and Construction of Concrete Parking Lots*)—3 days for auto traffic, 7 days for all other traffic.[34]

Time to a Specified Strength

The option to cure until a certain fraction of design strength is attained is common in ACI guidance, summarized as follows.

- ACI 301 (*Standard Specification for Concrete*).[32]
  - Time to 70 percent f'c using field cured specimens.
  - Time to 85 percent f'c using lab specimens, with field temperatures ≥10 ^{o}C.
  - Time to 100 percent f'c using NDT methods (methods unspecified).

- ACI 308 (*Standard Practice for Curing Concrete*)—time to 70 percent f'c—option for pavements.[4]

- ACI 325.9 R (*Guide for Construction of Concrete Pavements and Concrete Bases*)—time to 70 percent f'c.[33]

- ACI 330 R (*Guide for Design and Construction of Concrete Parking Lots*)—until compressive strength ≥ 21 MPa.[34]

Maturity

The maturity method is a calculation based on the concept that time-temperature history, rather than simple time, determines the strength development of concrete. By monitoring time-temperature histories of in-place concrete, real-time strength development can be indirectly monitored. The method is calibrated using strength development of laboratory- or field-cured specimens with a known time-temperature history. ASTM C 1074 describes the method.[35] Hardware and software are manufactured that automates much of the work, and consulting firms specializing in this procedure exist.

Equations in ASTM C 1074 can be written into a spreadsheet to simplify exploratory calculations.[35] Exploratory calculations are useful for approximate planning purposes and investigating likely effects of different temperature histories. For exploratory work, inputs of daily high and low concrete temperatures and of standard laboratory strength determinations can be used to estimate strength development for the first 7 days after placing. Predictions become more prone to error at later ages and should not be used.

In actual field application, the maturity method normally takes temperature input from in-place thermocouples located at critical points in the pavement. Determining critical locations is an important part of the application. Pavement corners, sections of elevated pavement, and most recently placed pavements are particularly sensitive to low temperature events.

VERIFICATION OF CURING

Although strength is the primary variable around which curing specifications are based, verifying adequacy of a curing program on pavements may not be best measured by strength. Several approaches are described below.

Strength of Cores (ASTM C 42)[36]

The strength of concrete is strongly affected by inadequate curing, and, in theory, could be detected by measuring strength of cores taken from a concrete pavement. However, the effects of poor curing are only strongly apparent in the properties of the top 50 mm of concrete, and sometimes even less. Therefore, only thin pavements are likely to be well represented by strength testing. Compressive strength is not likely to be an effective procedure for typical highway pavements.

Rebound Hammer (ASTM C 805)[37]

The rebound hammer method basically measures the modulus of elasticity of the near-surface concrete. It is often criticized as being unduly affected by near-surface properties and insensitive to the strength of the entire section of concrete under the test point. This may actually recommend the method for use in evaluating the curing of concrete pavements, where near-surface effects are considered most important. The test method is suitable for in-place measurements and has been found in laboratory tests to be well suited for detecting curing deficiencies in near-surface pavement. There is a considerable amount of scatter in rebound numbers because of the heterogeneous nature of near-surface properties (principally due to near-surface aggregate particles). The method directs that an average over 10 readings be taken to smooth out this effect. The method requires at least modest maturity of the concrete for the instrument to register readings, typically 1–2 days depending on the concrete mixture and temperature.

A reasonable approach to using this technique for field verification of pavements would be to select one or a few small sections of pavement over which strict curing control could be maintained. Then, using the rebound numbers in these well-cured sections as a reference, the near-surface development of the remainder of the pavement could be evaluated through a random sampling scheme.

Laboratory work has shown that rebound numbers of uncured concrete exposed to modestly severe drying are reduced by about 50 percent at 7 days relative to well-cured concrete.

Surface Water Absorption (ASTM C 1151, withdrawn)[38]

It has been well established in laboratory work that the amount of water a dry concrete specimen absorbs in the first minute or so after contact with liquid water is related to the quality of the curing of the near-surface zone of the concrete. In theory, then, this method should have direct applicability to verifying curing. A number of field methods have been developed, but most suffer because of lack of control over the moisture content of the in-place concrete. The method is reasonably applied to cores, which can be dried to a constant low moisture content before testing.

The procedure is relatively simple. The top 50 mm of concrete pavement is removed by coring or sawing. The water applied during the short interval of taking the core is not significant if the core is dried in an oven (>60 ^{o}C) within no more than a few hours after extraction. The core is so dried for 24 hours, cooled, and weighed, and then the surface of the core representing the surface of the pavement is placed on a towel saturated with water. Sixty seconds is a reasonable exposure time. The core is then reweighed and the mass of water absorbed and the surface area of the concrete are calculated. The result is expressed in units of kg/m^2. If curing compound is on the surface of the core, it must be removed prior to testing. A powered wire brush is suitable for this. Sometimes a surface cut more than 50 mm from the finished surface is used as a well-cured standard. Although such a surface is probably well cured, it has probably experienced a different type of mechanical action during placing and finishing that make it not strictly comparable with the finished surface.

Well-cured concrete can serve as a control. As with the rebound hammer method, described above, select a small section of concrete over which control of curing can be assured, then take cores and use them as a reference.

Ultrasonic Pulse Velocity

The ultrasonic pulse velocity (UPV) method is an indirect measure of the modulus of elasticity of concrete. The modulus of elasticity of concrete tends to increase with increasing hydration (or quality of curing) of the cement paste fraction of the concrete. UPV testing can be set up in a number of configurations, each of which tends to focus on slightly different features of the concrete. A simple pulse velocity taken through a piece of concrete, which is the traditional way of using UPV to investigate concrete properties, gives information on the average quality of the concrete. This method would be difficult to apply to concrete pavements. UPV testing can be configured to measure the speed of wave propagation in the near-surface zone of the concrete. This configuration should be quite useful for monitoring curing.

Equipment for executing the latter type of analysis is not widely available at the commercial level, but has been mostly used in research applications. The hardware and analysis software could be developed into a practical technology if there were sufficient interest to warrant the commercial development.

Abrasion Resistance

The degree of curing has been shown in numerous research publications to be strongly reflected in the abrasion resistance of the cement-paste fraction of concrete. This truth is easily verified qualitatively using an electrically powered wire brush and observing the ease with which the near-surface mortar can be removed from a small spot of concrete. Poorly cured concrete is easily abraded away, while well-cured concrete is quite difficult to abrade away with such equipment. One major difficulty with this technology is in quantifying the forces involved and the results on the concrete. The test is also sensitive to the moisture condition of the concrete.

These shortcomings could be overcome if cores were taken and standard procedures were developed for laboratory testing, but it is doubtful that the results would be a better indicator than those derived from the other tests described above.

REFERENCES

1. American Concrete Institute (ACI). ACI 308 R. "Guide for Curing Concrete." *ACI Manual of Concrete Practice.* Farmington Hills, MI.

2. American Association of State Highway and Transportation Officials (AASHTO). AASHTO T 158. *Specification for Bleeding of Concrete*. Washington, DC.

3. AASHTO T 197. *Specification for Time of Setting of Concrete Mixtures by Penetration Resistance*. Washington, DC.

4. ACI 308. "Standard Practice for Curing Concrete." *ACI Manual of Concrete Practice.* Farmington Hills, MI.

5. ACI 305 R. "Hot Weather Concreting." *ACI Manual of Concrete Practice.* Farmington Hills, MI.

6. AASHTO M 85. *Specification for Portland Cement*. Washington, DC.

7. American Society for Testing and Materials (ASTM). ASTM C 150. "Standard Specification for Portland Cement." *Annual Book of ASTM Standards.* Vol. 04.01. West Conshohocken, PA.

8. AASHTO M 240. *Specification for Blended Hydraulic Cement*. Washington, DC.

9. ASTM C 597. "Standard Test Method for Pulse Velocity Through Concrete." *Annual Book of ASTM Standards.* Vol. 04.02. West Conshohocken, PA.

10. ASTM C 1157. "Standard Performance Specification for Hydraulic Cement." *Annual Book of ASTM Standards.* Vol. 04.01. West Conshohocken, PA.

11. AASHTO M 295. *Specification for Coal Fly Ash and Raw or Calcined Pozzolan for Use as a Mineral Admixture in Concrete*. Washington, DC.

12. ASTM C 618. "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete." *Annual Book of ASTM Standards.* Vol. 04.02. West Conshohocken, PA.

13. Poole T.S. *Curing of Portland Cement Concrete Pavements, Volume II Final Report*. FHWA-HRT-05-038. 2004.

14. *AASHTO Guide Specifications for Highway Construction*. Publication code GSH-8. Washington, DC, 1998.

15. Malhotra, V.M. and A.A. Ramezanianpour. 1994. *Fly Ash in Concrete.* 2nd Ed. CANMET MSL 94-45(R), Canadian Center for Mineral and Energy Technology, Ottowa, Canada.

16. ASTM C 232. "Standard Test Method for Bleeding of Concrete." *Annual Book of ASTM Standards.* Vol. 04.02. West Conshohocken, PA.

17. AASHTO T 23. *Specification for Making and Curing Concrete Test Specimens in the Field*. Washington, DC.

18. ASTM C 31. "Standard Practice for Making and Curing Concrete Test Specimens in the Field." *Annual Book of ASTM Standards.* Vol. 04.02. West Conshohocken, PA.

19. ASTM C 403. "Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance." *Annual Book of ASTM Standards.* Vol. 04.02. West Conshohocken, PA.

20. AASHTO M 148. *Specification for Liquid Membrane-Forming Compounds for Curing Concrete*. Washington, DC.

21. ASTM C 309. "Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete." *Annual Book of ASTM Standards.* Vol. 04.02. West Conshohocken, PA.

22. ASTM C 1315. "Standard Specification for Liquid Membrane-Forming Compounds Having Special Properties for Curing and Sealing Concrete." *Annual Book of ASTM Standards.* Vol. 04.02. West Conshohocken, PA.

23. AASHTO T 155. *Specification for Water Retention by Concrete Curing Materials*. Washington, DC.

24. ASTM C 156. "Standard Test Method for Water Retention by Concrete Curing Materials." *Annual Book of ASTM Standards.* Vol. 04.02. West Conshohocken, PA.

25. Texas Department of Transportation, Departmental Material Specification: DMS-8120, "Liquid Membrane-Forming Compounds for Curing Concrete." Austin, TX. 1998.

26. Poole, T.S. “Methods for Measuring Application Rate of Liquid Membrane-Forming Curing Compounds on Concrete Pavements.” *Proceedings of 7th International Conference on Concrete Pavements*, International Society for Concrete Pavements, September 2001, pp. 351-360.

27. ASTM C 94. “Standard Specification for Ready-Mixed Concrete.” *Annual Book of ASTM Standards.* Vol. 04.02. West Conshohocken, PA.

28. AASHTO M 182. *Specification for Burlap Cloth Made from Jute or Kenaf*. Washington, DC.

29. ASTM C 171. “Standard Specification for Sheet Materials for Curing Concrete.” *Annual Book of ASTM Standards.* Vol. 04.02. West Conshohocken, PA.

30. AASHTO M 171. *Specification for Sheet Materials for Curing Concrete*. Washington, DC.

31. ACI 318. Building Code Requirements for Structural Concrete. *ACI Manual of Concrete Practice.* Farmington Hills, MI.

32. ACI 301. “Standard Specification for Structural Concrete.” *ACI Manual of Concrete Practice.* Farmington Hills, MI.

33. ACI 325.9 R. “Guide for Construction of Concrete Pavements and Concrete Bases.” *ACI Manual of Concrete Practice.* Farmington Hills, MI.

34. ACI 330 R. “Guide for Design and Construction of Concrete Parking Lots.” *ACI Manual of Concrete Practice.* Farmington Hills, MI.

35. ASTM C 1074. “Standard Practice for Estimating Concrete Strength by the Maturity Method.” *Annual Book of ASTM Standards.* Vol. 04.02. West Conshohocken, PA.

36. ASTM C 42. “Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete.” *Annual Book of ASTM Standards.* Vol. 04.02. West Conshohocken, PA.

37. ASTM C 805. “Standard Test Method for Rebound Number of Hardened Concrete.” *Annual Book of ASTM Standards.* Vol. 04.02. West Conshohocken, PA.

38. ASTM C 1151. “Test Method for Evaluating the Effectiveness of Materials for Curing Concrete.” Now withdrawn. Last existed as ASTM C 1151-91 in *Annual Book of ASTM Standards.* Vol. 04.02. West Conshohocken, PA.

OTHER SOURCES

AASHTO Quality Assurance Guide Specification. Publication code QA-1. Washington, DC, 1996.

AASHTO Construction Manual for Highway Construction. Publication code CM-4. Washington, DC, 1990.

ACI 228.1 R. "In-Place Methods for Determination of Strength of Concrete." *ACI Manual of Concrete Practice.* Farmington Hills, MI.

ACI 306 R. "Cold Weather Concreting." *ACI Manual of Concrete Practice.* Farmington Hills, MI.

HIPERPAV

McCullough, B.F. and R.O. Rasmussen. *Fast-Track Paving: Concrete Temperature Control and Traffic Opening Criteria for Bonding Concrete Overlays, Volume I: Final Report.* Publication No. FHWA-RD-98-167, Washington, DC, October 1999.

McCullough, B.F. and R.O. Rasmussen. *Fast-Track Paving: Concrete Temperature Control and Traffic Opening Criteria for Bonding Concrete Overlays, Volume II: HIPERPAV User's Manual*. Publication No. FHWA-RD-98-168, Washington, DC, November 1999.

McCullough, B.F. and R.O. Rasmussen. F*ast-Track Paving: Concrete Temperature Control and Traffic Opening Criteria for Bonding Concrete Overlays, Volume III: Addendum to the HIPERPAV User's Manual.* Publication No. FHWA-RD-99-200, Washington, DC, November 1999.

Additional information on HIPERPAV can be found at *www.hiperpav.com* and *www.fhwa.dot.gov*

Recycled
Recyclable

HRDI-11/01-05(400)E