Guide for Curing of Portland Cement Concrete Pavements, Volume II

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FOREWORD

There has been a considerable amount of research over approximately the last 70 years on the theoretical aspects of curing portland cement concrete. Early work focused principally on portland cement hydration chemistry and the physics of developing microstructure. Later work incorporated features of pozzolanic reactions and other supplemental cementing materials. Because of this work, there is sufficient understanding of the theoretical aspects of the curing process for concretes of conventional proportions using conventional materials to develop effective practical application rules. The causes of when and where problems exist while curing portland cement concrete pavement may be because of changes in concrete technology that developed since the curing guidance was written or from some details of paving construction practice that differed from the types of concrete construction around which curing guidance was developed.

This report contains information on the current state of knowledge of curing hydraulic-cement concrete and on current curing practice, gathered by means of a literature review and a review of current standard guidance. A separate report (FHWA RD-02-099 *Guide for Curing of Portland Cement Concrete Pavements, Volume. I*) was published in January 2005 and captures the details of the recommended guidance.

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16. Abstract
Information on the current state of knowledge of curing hydraulic-cement concrete and on current curing practice was gathered by means of a literature review and a review of current standard guidance. From this information, a draft guide for curing hydraulic-cement concrete pavements was developed. Draft guidance was based around type of curing used (water added, water retention by sheet, or curing compound) and around temperature effects. As a result of review by the project technical advisory panel, additional information was gathered from existing sources on several subjects. Laboratory studies were conducted on topics for which information was needed but not currently available. The result of the investigation was a set of guidelines that focused particularly on attention to details of moisture retention and temperature immediately after placing (initial curing period) and on details of selection of materials for final curing and determining when to apply final curing. Test methods for evaluating application rate of curing compound and effectiveness of curing were also reported. A separate report (FHWA RD-02-099 *Guide for Curing of Portland Cement Concrete Pavements, Volume I*) has been written that captures the details of the recommended guidance. That report is intended to be the principal technology transfer medium.

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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)

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CHAPTER 1: INTRODUCTION

BACKGROUND

Curing of concrete is defined by the American Concrete Institute (ACI) as maintaining of a satisfactory moisture content and temperature in concrete during its early stages so that desired properties may develop."[1] The need to cure portland cement concrete, including pavements, in order to develop its physical properties sufficiently for strength and durability has been appreciated for many years. Jackson and Kellerman (1939) of the U.S. Bureau of Public Roads wrote, "Thorough and complete curing has always been recognized as one of the most important single factors involved in the construction of concrete pavement."[2] Curing has been an item in the ACI Building Code (now ACI 318[3]) since 1904 (Meeks and Carino, 1999).[4]

There has been a considerable amount of research over approximately the last 70 years on the theoretical aspects of curing portland cement concrete. Early work focused principally on portland cement hydration chemistry and the physics of developing microstructure. Later work incorporated features of pozzolanic reactions and other supplemental cementing materials. Because of this work, there is sufficient understanding of the theoretical aspects of the curing process for concretes of conventional proportions using conventional materials to develop effective practical application rules. Features of the curing process of unusual concretes, such as extremely low water-cementitious concretes, have yet to be fully understood and still require significant research effort. Still, for the bulk of concrete placed, including portland cement concrete pavements, the existing theoretical knowledge is sufficient to support good practice. A substantial body of practice has been developed on curing that covers the critical steps that, if properly followed, result in properly cured concrete.

The major features of curing portland cement concrete pavements are not different from the major features of curing other portland cement concrete structures. The objective of all curing operations is to maintain a condition of moisture availability and temperature sufficient to allow development of physical properties before the structure is subjected to loading, abrasion, and excessive drying.

The problems related to curing portland cement concrete pavement may be due to changes in concrete technology that developed since the curing guidance was written or from some details of paving construction practice that differed from the types of concrete construction around which curing guidance was developed. In either case, the problems are in the details.

The most obvious changes in concrete practice since the development of standard curing practice are connected to the increased reactivity of cementitious materials, derived both from the more reactive chemical composition and from increased fineness. A practice that has changed is the common use of lower water-cementitious materials ratios.

CURING PROBLEMS SPECIFIC TO PORTLAND CEMENT CONCRETE PAVEMENTS

A major difference between concrete highway pavements and most other concrete structures is the large surface-area-to-volume ratio of the structure. This makes the pavement highly susceptible to environmental effects, such as drying or temperature extremes. Compounding this is the relatively large amount of such concrete that can be placed in a single workday and hence a large amount of surface area that must be managed without delay. For example, a kilometer (km) or more of concrete pavement can typically be placed in one shift using slip-form paving technology. This may represent as much as 10,000 square meters (m^2) of concrete surface that is exposed to prevailing climatic conditions. As a matter of economics, this amount of surface area strongly affects choices in curing methods and materials.

Use of liquid membrane-forming curing compounds (henceforth called curing compounds) is the only economical approach for curing large placements of concrete pavement. The principal advantage in using curing compounds to cure concrete is the relatively low labor requirements involved with application and inspection during the curing period. The major disadvantage to using curing compounds is the amount of detail involved in specification-compliance issues and of application procedures required to insure proper performance. One of the major objectives of this work is to develop useful guidance on curing compound selection and usage practices as they apply to pavements.

Another important and somewhat unusual feature of pavement concrete is the relatively low bleeding or absence of bleeding of the fresh concrete, particularly for mixtures suitable for slip-form paving. Because of the large surface-volume ratio, such concrete is particularly susceptible to drying soon after placing if drying conditions are high, potentially leading to plastic shrinkage cracking. This phenomenon makes selection of early curing practices particularly critical.

Another important feature of concrete in pavements is the near-surface zone. This zone of concrete within about 50 millimeters (mm) of the surface is the most susceptible to the effects of poor curing. Uncontrolled cracks in the near-surface zone can be the initiation point for deterioration processes that shorten service life of the concrete. Poorly cured near-surface concrete is also more permeable to water and less abrasion resistant.

Because of these qualities of pavement concrete, details of generally accepted curing practice may be not be appropriate for use on pavements. Problems such as knowing when paving concrete is susceptible to plastic shrinkage cracking, understanding how to effectively control this condition in the field when it potentially exists, recognizing when to apply curing compounds, anticipating the effects of climatic conditions on drying of curing compound, and knowing the effects of less-than-optimal placing temperatures may require different practices than are used in more common structural applications.

For example, during a recent placement of a U.S. Army Corps of Engineers (USACE) airfield pavement, the climatic conditions were relatively hot and windy. The project specifications directed that curing compound be placed as soon as the sheen had disappeared from the surface of the concrete and finishing was complete, which is relatively common guidance. The water-cement ratio of the concrete was relatively low, so bleed water was not abundant. In such concretes, bleed water is sometimes slow to appear on the surface of the concrete, so a no-sheen condition developed within a few minutes after placing was completed. Curing compound was then applied. Bleed water subsequently developed, apparently after the curing compound had dried, and resulted in the delamination of 1 to 2 mm of the surface of the concrete. Guidance exists cautioning about this situation, but the pavement engineer onsite had no quantitative information on which to make judgments on details of bleeding and timing of curing compound application. Following the simplest guidance concerning the disappearance of surface sheen, curing compound was applied too soon.

SCOPE AND OBJECTIVES

The scope of this guide is limited to pavements. It does not include curing of bridge decks or other structures associated with pavements. Curing for these types of structures depends on the same basic principles, but some details of execution differ significantly from pavements. References to work on the curing of bridge decks were found while researching this guide, and a summary of this literature is included in the literature review (appendix B).

The objective of this project is to develop practical, quantitative guidelines on curing of portland cement concrete pavements that will give the pavement engineer tools with which to anticipate the critical details of curing practice and to be able to plan for contingency conditions. Specific information includes recommendations on:

- Selection of curing procedures.
- Selection of curing materials.
- Accounting for climatic conditions.
- Duration of curing.
- Sequence of critical events.
- Verification of curing.
- Accounting for concrete materials and concrete mixture proportions.

PROJECT ORGANIZATION

The major tasks in the execution of the project are as follows.

- **Formation of a technical advisory panel (TAP).** A TAP was formed, comprised of individuals from State highway departments involved in concrete paving operations and familiar with the problems associated with curing practice. The purpose of the TAP was to advise on technical aspects of the project.

- **Information search.** Research literature and current guidance were reviewed to determine the existing understanding of technical matters involving curing and the state of current practice, at least as contained in guidance.

- **Synthesis of information and draft guide.** From the results of the information search, a description of current knowledge and practice was synthesized, and a draft guide for curing portland cement concrete pavements was developed. Deficiencies in the guide were identified.

- **Resolution of deficiencies and development of completed guide.** As a result of recommendations of the TAP, additional information was gathered as required to complete the guide.

- **Additional investigations.** Preparation of the draft guide suggested some areas that required laboratory work or other additional investigation to illuminate critical details of practice. Laboratory work was executed to evaluate these critical points of the guide.

- **Final draft.** A final draft of the guidelines was then developed and is printed as a separate report. (5)

CHAPTER 2: SYNTHESIS OF INFORMATION

This section represents the synthesis of information that supported the development of the draft guide presented in the interim report. Additional information required to complete the guide was identified as a result of ideas and suggestions made by the TAP and will be added in chapter 4. A full literature review is in appendix B.

TERMINOLOGY

ACI 308R[6] defines two phases of curing. For purposes of this project, it will be useful to refer to these. The initial curing period is the time between when concrete is placed and when final curing operations can be initiated. Final curing operations typically cannot be applied during this period because one or more properties of the concrete are not suitably developed, and the concrete could be damaged. The objective of curing activity during the initial curing period is to prevent excessive loss of mixing water from the plastic concrete, which can lead to plastic shrinkage cracking. Deliberate activity during this period is only required if drying conditions are sufficient to cause excessive water loss. This will be discussed in chapter 5.

The final curing period is the time between application of final curing procedures and the cessation of deliberate curing activity. The objective of curing activity during this period is to insure that necessary water is either retained or added and that temperature is maintained within a range that the hydration of the cementitious materials can progress sufficiently for development of necessary physical properties and that temperature is controlled sufficiently to avoid damaging thermal gradients.

SELECTING CURING METHODS

Initial Curing Period. If deliberate curing activity is required during the initial curing period, two methods are commonly cited in guidance for reducing evaporation rates—wind breaks and water misting devices. These are often considered impractical for large pavement construction projects because of the large amount of hardware and labor required.

Figure 1. Canopy used to protect fresh concrete.

Practice in the United Kingdom (UK) (Carroll, 1988) at one time included use of a long canopy that could be towed behind the paving operation that would protect from sun, wind, and rain (figure 1).[7] It is unknown if this practice is still used there. No mention of such a device was found in American literature or guidance.

Evaporation reducers (sometimes called evaporation retarders) are a relatively new product being marketed to protect concrete during the initial curing period. Mention of these is largely absent from standard guidance and the research literature. These products are being used in construction, but no information was found on the breadth of their use. No specifications or test methods are known to exist. Users are currently relying on manufacturer's instructions.

Evaporation reducers are gaining popularity because of the relative ease of use. Like curing compounds, their use requires a relatively small labor cost. Evaporation reducers can usually be applied with the same hardware used to apply curing compound or applied as a drip on a burlap drag, so the additional hardware costs are not high. This technology needs to be further investigated.

<u>Final Curing Period</u>. Standard guidance on choosing final curing methods for portland cement concrete allows for a number of options. Allowable methods can be broadly classified either as water-retention methods or as water-added methods. As the terms suggest, the objective of the former is simply to retain the mixing water in the concrete for the period of time necessary for curing to be completed. Water-added methods provide water in excess of the mixing water. Occasionally water-added methods are used as a matter of practicality—not because more water is needed.

For paving concrete, the choice of curing methods from among these is largely one of practicality and economics rather than quality of performance. However, a distinction is made in some guidance between water-added and water-retentive methods based on water-cement ratio, which may affect paving concrete is some cases.

Guidance featuring this distinction includes the USACE Standard Practice for Concrete (EM 1110-2-2000)[8] and Standard 3420, as reported in Meeks and Carino (1999)[4]. This distinction is also evident in the research literature. At water-cement ratios below approximately 0.40 (the exact number varies with the information source), water-added methods are recommended. This guidance is based on the fact that concretes can internally desiccate from consumption of water by hydration reactions at water-cement ratios lower than about 0.40, and additional water must be added if additional hydration is required. The 0.40 threshold is an approximate value, varying some with chemical composition of cementitious materials. It probably derives from Philleo's (1986[9], 1991[10]) calculations on the amount of water filled space in fresh cement paste and the volume occupied by reaction products in a fully hydrated paste. At a water-cement ratio greater than about 0.40 there is, initially, more mixing water filled space than can be filled with hydration products if all the cement hydrates. At a water-cement ratio less than about 0.40 there is initially insufficient mixing water filled space to allow all of the cement to hydrate. Hence at water-cement ratios greater than 0.40, some mixing water can be lost without jeopardizing maximum hydration of the cement, if this is desired. At a water-cement ratio less than 0.40, this is not the case.

Another, and probably more consequential, effect of internal desiccation due to complete consumption of mixing water is the development of shrinkage cracks. The same mechanism that causes drying (atmospheric) shrinkage cracks apparently causes cracking when the water is lost to hydration. This source of shrinkage strains is a form of autogenous shrinkage. This form of cracking is probably not a common problem in pavements since water-cement ratios are commonly above 0.40, but may be a substantial cause of cracking in bridge decks. Water-added methods are sometimes advised in this application.

One potential problem with water-added curing of low water-cement ratio concrete is that after a relatively short curing time, the capillary pores may be sufficiently disconnected that no appreciable amount of water from wet curing penetrates the concrete. Powers, Copeland, and Mann (1959)[11] report that capillary continuity of 0.40-water-cement ratio paste is lost at 3 days. For purposes of achieving adequate strength, it may not be very important that additional water get into low water-cement ratio concrete. Experience reported by the Iowa Department of Transportation showed that the concrete mixtures commonly used in paving achieve adequate strength even if all of the cement does not hydrate. However, for durability considerations, it may be important that additional water gets into the near-surface zone of the concrete. No research on the effectiveness of water-added methods on the near-surface properties of low water-cement ratio concretes was found.

With today's pavement technology, it is usually true that the most practical and economical method of curing large amounts of portland cement concrete pavements is by using water-retention methods, generally in the form of curing compounds. Water-cement ratios of paving mixtures are usually close to or greater than 0.40, so there is no important theoretical reason to recommend water-added methods, unless the economics are favorable.

Temperature management of large paving operations is difficult and mostly relies on selecting appropriate climatic conditions. The commonly used approach is to specify air temperature conditions considered suitable for paving. Allowable placing temperatures typically range from a minimum of about 5 degrees Celsius (°C) (with temperatures rising) to a maximum of about 30 °C. These limits on temperatures during placing are to minimize the possibility of damage due to early freezing events in the case of low temperatures or due to development of plastic shrinkage cracks in the case of high temperatures.

For the duration of the final curing period, protection from freezing is required and a minimum average concrete temperature of about 10 °C is typically required to insure strength development. If concrete temperatures fall below this, extended curing time is often required. No guidance was found that referenced a maximum curing temperature during the final curing period, although guidance does require use of reflective materials under hot weather conditions, as described in ACI 305R[12]. Not covered in standard guidance is the problem of thermal stresses that can develop within the first few days in pavements due to the combined effects of heat of hydration and environmental heating and cooling. This is the principal subject of new FHWA software called HIPERPAV®[13].

Temperature management of small areas of pavement in cold weather can be practically accomplished by using insulation. ACI 306R[14] gives extensive guidance on insulation required to maintain this temperature. A wide variety of guidance was found in State DOT requirements for protecting concrete from freezing. The major need here is to put this information into a format that is easily accessible to the user.

SELECTING CURING MATERIALS

Initial Curing Period. The major activity during the initial curing period is to control evaporation of bleed water. Bleed water can generally be lost without major detriment, but there is a fine line between losing only bleed water and loss of pore water, which causes shrinkage. For use in the initial curing period, options are limited to two materials: water (in the form of mist) and evaporation reducers. Water for application to prevent excessive loss of bleed water generally faces few serious specification compliance issues and may be a reasonable option when evaporation rates are such that one or two passes by the application equipment are sufficient to protect the concrete. At an application rate of 0.2 kilograms per meters squared (kg/m^2) and an evaporation rate of 1 kilogram per meter squared per hour ($kg/m^2/h$), water would need to be applied every 12 minutes (min) to avoid loss of mixing water. Evaporation reducers are a very practical option for extending this period between required applications. However, no published information or standard guidance was found on these products. The only information found was in the form of manufacturer's product literature. These products are potentially quite valuable for helping protect concrete pavements from excessive water under conditions of high evaporation rates. Their use fits easily into the construction practices already in common use and require little in the way of additional equipment. A major impediment to their use is the absence of test methods, specifications, and detailed guidance.

Final Curing Period. For final curing, several material options are available within each method of curing. Water-retentive methods include waterproof sheeting and curing compounds. Water-added methods include water, wet burlap, wet soil, and wet cotton mats. Waterproof sheeting, water, burlap, and curing compounds are covered by standard specifications. The specifications for water, waterproof sheeting, and burlap are relatively simple and compliance issues relatively easy to deal with. Compliance issues associated with the use of curing compounds are much more difficult, but, except for small areas, the economics of paving usually dictate using curing compounds as the material for final curing.

Curing water is limited only by staining materials or dissolved salts (American Society of Testing and Materials (ASTM)) [15], USACE CRD-C 400[16]). Sheet materials are specified by ASTM C 171[17], which limits water loss (ASTM C 156[18]), physical properties, and reflectance. The USACE, in CWGS 03300[19] limits use of impervious sheeting to plastic coated burlap. Simple plastic sheeting is not allowed because of the mottled appearance it can cause on the surface of the concrete. Burlap is specified by American Association of State Highway and Transportation Officials (AASHTO) M 182.[20] ACI 325.9R further requires that the fabric be water absorptive.[21] No other selection criteria among materials were found. Curing compounds are specified by AASHTO M 148[22] (ASTM C 309[23]) and ASTM C 1315.[24]

Curing compound selection, acceptance testing, verification of application and effectiveness probably present some of the greatest challenges in curing practice. The critical performance property limited by specifications is moisture loss, determined by ASTM C 156[18] or a similar method. State DOTs commonly use their own variation of ASTM C 156[18] for acceptance testing of curing compound, and some have more stringent moisture loss requirements than those in ASTM C 309.[23] For example, Minnesota DOT (Mn/DOT) allows a maximum of 0.15 kg/m^2 at 24 hours (h) and 0.40 kg/m^2 at 72 h. Virginia allows a maximum of 0.116 kg/m^2 at 24 h and 0.232 kg/m^2 at 72 h. Curing compounds are manufactured along several formats (waxes, resins, water-based, solvent-based), but there seems to be little guidance on selecting among these. Discriminating guidance that does exist is mostly based on practical problems. For example, the USACE (CWGS 03300[19]) directs use of styrene acrylate or chlorinated rubber curing compounds when paint or bituminous or waterproofing is to be applied to the cured surface later. USACE TM 5-822-7[25] directs that wax-based products are to be avoided if the concrete surface is to be painted. White pigmented curing compounds are required if use is in direct sunlight. ACI 305R[12] recommends that the moisture loss requirement for curing compounds be tightened in hot weather. A limit of 0.39 kg/m^2 is recommended.

ASTM C 1315[24] has more stringent requirements on curing compounds than does C 309.[23] Moisture loss is limited to 0.40 kg/m^2 (at a lower application rate than allowed in C 309[23]), and a minimum solids content of 25 percent is required. The purpose of the solids content requirement is to insure a membrane thickness of at least 25 microns (µm). This standard has not become common practice in specifying materials for use in pavement construction, although ACI 308R[6], a relatively new committee report, does recognize this specification.

Recent developments in environmental regulations governing volatile organic compounds (VOCs) are expected to have substantial effects on choice of curing compounds. Manufacturers' literature has already started to show a classification of VOC-compliant materials. VOC-compliant materials are largely water-based, which means their rate of drying could be affected by very humid conditions. Application of water-based compounds when relative humidity is near 100 percent would interfere with formation of the membrane, which is dependent on evaporation of the water from the curing compound. The application might then be susceptible to washing away or damage by rainfall for many hours after application. Essentially no information was found on practical matters associated with use of low-VOC curing compounds.

There is some variation among curing compounds from different manufacturers in the chemical composition and principle of action. Except for the guidance that cautions against some products if the concrete is to be painted or when surface adhesion is important, there is not much information available on the relative strengths and weaknesses of the competing technologies. The differences may not be important in the performance of the materials, but it would be useful to have some information gathered on the logic of the competing materials.

The current status of acceptance testing of curing compounds is, at best, inadequate. The between-laboratory precision in ASTM C 156[18] is so poor that buyer/seller agreement or disagreement on the acceptability of a product is strongly affected by testing error. Either this test method needs substantial improvement or a more precise test method needs to be developed.

Improving this test method would be the preferable solution, given the degree to which it is embedded in current practice.

As published in the precision and bias statement of the test method, the between-laboratory standard deviation is 0.30 kg/m^2. This equates to a coefficient of variation of 54.5 percent, at a water loss rate of 0.55 kg/m^2 at 72 h (the specification limit of ASTM C 309[23]). Two laboratories might reasonably be expected to differ in comparing single test results by as much as 0.84 kg/m^2 in 95 percent of 2-laboratory comparisons. (This statistic is called the D2S limit, as described in ASTM C 670[26]). This level of uncertainty makes it almost impossible for a manufacturer to be assured that a material meeting the moisture loss requirement by a seemingly comfortable margin will be found to comply consistently with specification requirements by a user's testing laboratory. The small difference between ASTM C 309[23] and C 1315[24] requirements for moisture loss (0.55 kg/m^2 versus 0.40 kg/m^2) would be very difficult to verify with this test method.

The within-laboratory precision of the method is considerably better than the between-laboratory precision, and other methods have been presented that claim to have considerably better within-laboratory precision than C 156[18]. ASTM C 1151[27](now withdrawn), BS 7542[28], and a method published by Dhir, Levitt, and Wang (1989)[29] are examples. But, it is the between-laboratory precision that controls acceptance of a material and ultimately has the most effect on it use. The practice of some State DOTs noted above, of setting more restrictive specifications on this property, may be partially attributable to the precision issue.

It is difficult to know how much of the between-laboratory precision problem is due to poorly described details of the test method and how much is lack of operator attention to the details of the test method. A formal ruggedness analysis of this procedure (ASTM C 1067[30]) would probably contribute significantly to an understanding of the sources of variation and their relative contribution to the current precision. The major variables either are known or can reasonably be anticipated. These include temperature, relative humidity, wind velocity, time of application of curing compound, and surface finish of cement specimen. A between-laboratory coefficient of variation of about 10 percent is probably required for the method to be effective in distinguishing materials.

ACCOUNTING FOR CLIMATIC CONDITIONS

Climatic conditions, particularly when at extremes, can have significant impacts on moisture balance, rates of hydration of cementitious materials, damage due to freezing and thawing, and can contribute to damage due to excessive thermal gradients. These effects constitute the principal need for deliberate curing activity.

Initial Curing Period. Concrete is particularly sensitive to the effects of excessive losses of mixing water, although it is not usually necessary to conserve all mixing water. Mixing water that appears as bleed water on the surface of concrete is generally considered to be in excess of water needed for sufficient hydration and for protection from shrinkage effects. However, as a practical measure, it is best not to push too close to the limit of the bleed water and to accidentally lose critical pore water.

The rate of evaporation of bleed water is commonly estimated using the nomograph in ACI 308[31] (also 305R[12], 308R[6], and other sources). This nomograph provides a graphical calculator of evaporation from a free-water surface given inputs for concrete temperature, air temperature, relative humidity, and windspeed. ACI 308R addresses the issue of agreement between rates of evaporation predicted by the nomograph and rates actually measured and concludes that the nomograph is accurate to within approximately 25 percent for actual evaporation rates near 1.0 $kg/m^2/h$ or lower, but that it tends to over represent the evaporation rate at higher levels.[6] The committee report also describes in detail the measurement of evaporation rates used to collect the data on which the nomograph is based. Wind velocity appears to be the most critical variable.

Losses of water to evaporation in excess of bleed water during the initial curing period are particularly critical. Under climatic conditions particularly favorable to drying, evaporation of bleed water can be quite rapid because a free-water surface is exposed to the environment. When evaporation exceeds bleeding, then the near-surface zone of the cement paste starts to dry, which results in shrinkage and development of tensile strains. Tensile strength at such early ages is very low, and the fresh concrete easily then develops plastic shrinkage cracks.

The single most critical activity during the initial curing period is in accurately anticipating this evaporation-to-bleeding water balance and taking adequate steps to shift it to a more favorable position. The current guidance suggests either setting limits on the length of time concrete can be left in an unprotected condition or setting upper limits on evaporation rates.

Some State highway departments set a maximum time that concrete can be left unprotected during the initial curing period of 30 min. This guidance assumes that evaporation of bleed water cannot reasonably exceed formation of bleed water in that time frame, at least to the point of being critical. No information was found that comments on this assumption.

Until recently, the major guidance on maximum tolerable evaporation rates was to be found in the caption to the ACI 308 nomograph.[31] The values returned from the calculation do not apply to evaporation rates when a free-water surface is not present, although the values are sometimes used as an indicator of drying potential in such situations. The guidance in the caption directs that when evaporation rates exceed 0.5 $kg/m^2/h$ precautions are recommended to reduce evaporation rates, and when evaporation rates exceed 1.0 $kg/m^2/h$, action to reduce evaporation rates should be required. USACE TM 5-822 directs that paving operations be avoided if evaporation rates exceed 1.0 $kg/m^2/h$ and perhaps even at 0.75 $kg/m^2/h$ if plastic-shrinkage cracks must be prevented.[25]

Al-Fadhala and Hover (2001)[32] comment on the history of the ACI 308[31] guidance. When these limits were established, typical bleeding rates for concrete were believed to usually fall between 0.5 and 1.5 $kg/m^2/h$. It can be deduced that most bleeding rates exceeded 1.0 kg/m2/h since the prescriptive limit in ACI 308 for required action was set at this level. Recognizing that this range may not represent some modern concretes, the recently published ACI 308R[6] contains the following guidance. For concretes that show little tendency to bleed, it may be necessary to set a requirement on evaporation rate below 1.0 $kg/m^2/h$. Limits of 0.25 $kg/m^2/h$ for silica fume concrete and 0.50 to 0.75 $kg/m^2/h$ for other low-bleed concretes are recommended.

Air temperature is an important climatic variable during the initial curing period beyond its direct effect on evaporation rates. High air temperatures tend to result in higher fresh concrete temperatures unless deliberate steps are taken to cool concrete materials stockpiles. However, temperature of fresh concrete and wind are more important variable driving evaporation of bleed water than is air temperature. High temperatures of fresh concrete also accelerate hydration of cement, affecting working times and the length of the initial curing period.

Final Curing Period. Losses of water from concrete due to evaporation after the end of the initial curing period are much lower regardless of curing activities. After bleeding has stopped and any residual bleed water is lost, evaporation rates slow down considerably because the free-water surface exposed to the atmosphere is now below the surface of the concrete. The near-surface zone acts to protect the bulk of the concrete by reducing windspeed at the water surface and maintaining a relatively high humidity near the surface of the concrete. ACI 308R reports that actual evaporation rates from concrete that has no bleed water are 10 to 50 percent less than evaporation rates from a free-water surface.[(6)] However, even though rates are lower, total water loss can accumulate over a period of several days to the point of being significant and affecting cement hydration, possibly causing damaging shrinkage. The purpose of curing in the final curing period is to conserve this water.

Limits on the amount of water that can be lost during the final curing period without detriment were determined early in the development of curing compounds. Information in the older literature seems to converge on a loss figure of about 0.6 kg/m^2 at 3 days as being a useful upper limit, although other work suggests that losses as high as 1.0 kg/m^2 can be tolerated. A loss of 0.6 kg/m^2 in 72 h equates to an average rate of water loss rate of 0.008 $kg/m^2/h$ during the time interval. This rate is two orders of magnitude lower than the limits on evaporation of bleed water allowed during the initial curing period.

There does not seem to be a simple way to determine what levels of evaporation, as estimated by the nomograph, would result in this kind of water loss potential when no free-water surface exists. The evaporation rate probably is not a constant, but plausibly varies considerably with concrete materials and mixture proportions and is a declining function with time as more of the mixing water becomes chemically combined during hydration. ACI 305R recommends using a high performance curing compound in hot weather conditions.[(12)] This report does not precisely define hot weather conditions, but it might be reasonably deduced from other information in 305R to be conditions that equate to a drying condition of 1.0 $kg/m^2/h$ or more.[(12)] ASTM C 156 (method for testing water loss through a curing compound) uses a set of test conditions that result in an evaporation rate in the range of 0.65 to 1.2 $kg/m^2/h$.[(18)] It can be deduced from this information that drying conditions considered dangerous to fresh concrete would also be dangerous to hardened concrete within the first few days after placing.

Establishing an exact limit on drying conditions that require attention for hardened concrete is not critical in most practices since the standard practice in construction for most concrete pavements is to execute curing actions, regardless of the anticipated weather conditions.

Air temperature is an important climatic variable during the final curing period beyond its direct effect on evaporation rates. High temperatures affect strength development and can contribute to peak concrete temperatures, particularly in the first 24 h after placing. High peak temperatures can lead to a thermal stress problem. Low air temperatures are primarily a matter of concern because of the reduced rate of strength gain and because of the potential for damage due to freezing.

Upper limits on air temperature are common in standard guidance. For example, the AASHTO Guide Specification(33) recommends against concreting at temperatures higher than 30 °C. Other agencies have lower limits. For example, Arizona requirements limit placing to temperatures of 29 °C or lower. A bridge deck replacement in Nebraska was limited to 27 °C maximum temperatures (Beacham, 1999).(34) ACI 305R does not give any maximum allowable placing temperatures.(12) Army TM 5-822(25) directs that the precautions in ACI 305R(12) should be invoked if temperatures exceed 32 °C, but also advises that concreting should be avoided above this temperature, if possible. This limit is based on concerns for high evaporation rates.

Regarding temperature gradients, ACI 305R directs that curing water must be within 10 °C of concrete temperature.(12) The USACE Guide Specification for Structural Concretelimits the temperature difference between a point 50 mm into the concrete and the ambient temperature to be less than 13 °C.(35)

Three reports in the literature identified temperature rise in summer placements as potentially important even when ambient conditions did not involve high temperatures (Okamoto and Whiting, 1994(36); Healy and Lawrie, 1998(37); Mohsen, 1999(38)). Portland cement hydration characteristically has a major heat of hydration peak that starts at about the same time as time of setting and continues to be a significant source of heat during the first 24 h after placing. The peak rate of heating normally occurs 8–10 h after placing, but exact timing and duration are cement specific and are strongly affected by temperature and admixtures. This heat can accumulate in thick pavements and, together with heating from solar radiation, can result in a significant temperature rise, which can further accelerate the hydration of the cement, contributing more heat, and thus setting up a self-stoking cycle of temperature rise. Peak temperatures of 60 °C can develop. Determining the early age heat of hydration patterns may be very useful in specifying a construction schedule that would avoid this synergistic effect of autogenous and climatic heating, thus reducing the peak temperature that a pavement experiences.

ACI 306R(14) covers the slow strength-gain effect of low temperatures and gives guidance on managing the problem, as discussed above in the section on “Selecting Curing Methods.” The maturity method (ASTM C 1074(39)) is an effective way to anticipate the rate of strength gain in low temperature conditions.

The guidance on avoiding freezing is inconsistent. The AASHTO Guide Specification[33] directs that concrete be protected from freezing for 10 days or until compressive strength reaches 15 megapascal (MPa). ACI 306R[14] and 308[31] direct that a single freezing event must be avoided until concrete has reached a strength of 3.5 MPa. The USACE Standard Practice (EM 1110-2-2000) cautions avoidance of freezing-and-thawing cycles until strength reaches 24 MPa.[8] Avoidance of freezing conditions and use of insulation are the two major features of standard guidance. There is no mention of using antifreezing admixtures. The AASHTO Guide Specification recommends avoiding concreting at ambient conditions less than 10 °C and directs that concrete be protected with blankets if ambient temperatures are expected to fall below 2 °C.[33] ACI 306R gives guidance on how to use insulation to maintain a minimum temperature of 10 °C in concrete for ambient temperatures below 10 °C.[14] Moisture retention is often not a serious issue because of the low evaporation rates associated with cold weather, unless heated enclosures are used, in which case moisture retention practices for warmer conditions are applied.

Both the British standard (BS 8110: Part 1[40]) and the European standards (CEB-FIP[41] and EN 206[42]) account for climatic conditions during curing, but neither use evaporation rate. Both use relatively nonquantitative measures, such as amount of direct sun (none, medium, and strong) and wind (low, medium, and high), but there is quantitative guidance on relative humidity (RH), with RH less than 50 percent being severe, RH between 50 and 80 percent being moderate, and RH greater than 80 percent being mild.

START OF CURING

Typical guidance states that curing should start after concrete is placed, finishing is complete, and the surface sheen has disappeared. In conventional concrete construction, finishing is typically not completed until sometime near time of initial setting. In pavement construction, finishing is essentially completed when the paving machine passes, although there may be some touch-up work executed within a few minutes. Surface sheen may disappear soon after that, given the tendency of slip-form mixes to bleed very little.

Using the concepts of initial and final curing period, as described in ACI 308R[6], the start and duration of these periods is quite different for slip-form paving and for more conventional concrete placements. In the case of conventional concrete, the initial curing period would start immediately after placing, then would end, and the final curing period would start at approximately the time of initial setting. This would normally be 2–4 h, although it could extend for several more h if admixtures cause retardation. In the case of slip-form paving, the initial curing period would start immediately after the paving machine passes, and the transition point to the final curing period is unclear.

In the case of the slip-form paving, the concrete probably would not have reached time of initial setting when final curing procedures are applied. If water added and/or sheet materials were used for final curing, a problem might develop because the concrete is not strong enough to resist washing out or marring. Since these techniques are not commonly used in large slip-form applications, the problem really does not present itself. Curing compounds can be applied at almost any time without either washing out cement paste or causing mechanical damage.

However, the question of curing compound performance is unresolved. Do curing compounds applied before time of setting perform as well as when applied after time of setting?

ACI 308 contains a short section cautioning application of curing compounds before bleeding has stopped.[31] Interviews with project engineers indicate that the concrete used in slip-form paving does not bleed, or if it does, it is so slight as to be insignificant. If this is true, then it appears that curing compounds could be applied very early without detriment. This detail needs to be verified.

CURING DURATION

Requirements on duration of curing are mostly based either directly or indirectly on strength-gain rate, which is determined by temperature, properties of cementitious materials, and concrete mixture proportions. This is simplified in most U.S. guidance (ACI, FHWA, and DOT) to specifying curing duration as a required fixed-time interval, with some adjustment for rate of expected strength gain of the concrete (e.g., high early strength versus normal strength). There is some inconsistency in the prescribed curing times, even among the various ACI guidance. As a secondary position, many standards allow curing duration requirements to be based on time required for strength to reach some minimum fraction of the specified strength (f_c'), as measured by c specimens.

The AASHTO Guide Specification[33] requires 3-day curing for pavements and 7 days for structures, including bridge decks. The latter is increased to 10 days if more than 10 percent pozzolan is used. There is a provision on structures that curing may be terminated if 70 percent of f_c' is reached. This is the only standard guidance that requires extra curing for concrete containing a slowly reacting cementitious material, such as pozzolan. A limited survey of State DOTs indicates that curing duration largely follows the AASHTO guidance.

ACI guidance typically sets a fixed time period provided concrete temperatures are maintained at greater than or equal to 10 °C. Sometimes there is the caveat that earlier termination can be allowed if testing shows a prescribed percentage of f_c' (typically 70 percent) at an earlier age.

The guidance in the ACI Building Code (ACI 318[3]) of 3 days for high-early strength concrete and 7 days for normal strength concrete at temperatures greater than or equal to 10 °C is an example of the simplest form of this kind of guidance. High-early strength and normal strength are not defined. The Standard Specification for Structural Concrete (ACI 301[43]) prescribes 7 days curing (3 days for high-early strength concrete) with the provision that curing can be terminated if 70 percent f_c' is reached in field-cured specimens; or if temperatures are greater than or equal to 10 °C (50 °F) for the length of time required to reach 85 percent of f_c' in laboratory-cured specimens; or if strength reaches f_c', as determined by nondestructive methods, which are not specified. The Standard Practice for Curing Concrete (ACI 308[31]) bases duration of curing on the types of cement (ASTM C 150[44]) used: 3 days for Type III, 7 days for Type I, and 14 days for Type II. The most recent ACI guidance, Standard Specification for Curing Concrete (ACI 308.1-98[45]), gives a default duration of 7 days, but allows for curing to be terminated early if strength reaches 70 percent of f_c' or if desired levels of durability are reached early. There is no additional guidance on the latter criterion. ACI 325.9R[21] on concrete pavements requires 7 days at temperatures above 4 °C or 70 percent f_c'. ACI 330R on concrete parking lots requires 7 days at temperatures above 15 °C or 21 MPa compressive strength.[46] ACI 306R accounts for the longer curing times needed in cold weather with a sliding scale, depending on the extent of cold.[14]

The ACI 308 guidance that is based on cement type is obsolete in the case of Type II cement.[31] When ACI 308 was first written, most Type II cements on the market were slow to hydrate compared to Type I cement, because they are formulated to meet moderate heat of hydration cements.[31] Type II cement is now almost undistinguishable from Type I cement in its rate of hydration, except in the rare instance when the cement is manufactured to meet the optional heat of hydration requirement in ASTM C 150[44] (Poole, 1998).[47]

The British Standards Institution (BSI) and the European Committee for Standardization (CEN) guidance is very prescriptive in nature and considerably more complicated than the guidance in U.S. standards. BSI 8110, Part 1, bases curing duration on specific lengths of time, but these times are determined as a function of the cement's rate of strength gain, climatic conditions after casting, and surface temperature of concrete during curing (details are reproduced in appendix B).[40] A maturity function is used to account for concrete temperature effects. EN 206 accounts for strength gain of concrete, water-cement ratio, ambient temperature, and climatic conditions to give variable curing times, but maturity does not appear to be used.[42]

Australian guidance (AS 3600[48]) is based strictly on durability considerations. Climatic zones and environmental aggressiveness within the zones are the major variables. Curing duration ranges from 3 days for the mildest exposures to 7 days for the most aggressive, with some adjustments made for accelerated curing.

Very little of the U.S. guidance accounts for the slower rates of hydration of concretes containing cementitious materials other than portland cement, particularly in paving concrete. Although it is well documented that pozzolans and slag, two of the most commonly used supplemental cementing materials, can cause strength gain to be significantly retarded, the phenomenon is so variable that a prescriptive specification would need to be extremely conservative to account for all of the possibilities.

Perhaps a better approach would be to rely totally on performance testing. Once a concrete has reached 70 percent of its required strength, then deliberate curing efforts could cease. Maturity (ASTM C 1074[39]), temperature-matched curing, and field-cured specimen methods are sufficiently well understood to serve as reasonably practical ways of determining when to cease curing operations. If, as a matter of practicality, a user wanted to develop and follow a prescriptive time-based specification, then laboratory testing could be used to determine conservative time-base limits for the job concrete.

Some concern is occasionally expressed over use of strength as an indicator of development of other physical properties critical to paving, such as abrasion resistance and water permeability. Strength, however, is a good measure of degree of hydration of the cement, and represents development of other physical properties reasonably well. So, using strength as an indicator criterion is a reasonable practice.

PROCEDURES FOR VERIFICATION OF CURING

Initial Curing Period. Procedures for verifying application of curing procedures during the initial curing period are not well developed. Several State departments of transportation direct that if cracking starts to appear during this period, then measures to reduce evaporation or to compensate the concrete for water lost to evaporation be implemented. If possible, it would be preferable to identify or develop a method that would detect deficiencies before damage starts to develop.

A plausible approach would be to monitor the surface sheen until the end of the initial curing period. Loss of sheen during this period is an indication that evaporation is exceeding bleeding, potentially conditioning plastic shrinkage cracking. Observation of laboratory specimens indicates that in the absence of surface evaporation, a surface sheen is present until approximate time of initial setting even if there is essentially no detectable bleeding.

It would be a very useful feature of this guide if it could give the user a way to anticipate that this condition is possible under expected project conditions. Construction crews could then be prepared with equipment and materials in case critical conditions develop.

Final Curing Period. Verifying water-added and methods that use waterproof sheets is mostly a matter of inspecting at prescribed intervals for evidence of dry spots or areas uncovered by sheet material. Verification procedures for the curing compound application are not well developed.

The basic approach to verifying effectiveness of curing is prescriptive. All of the standard guidance prescribes curing compound application rate, either as the manufacturer's recommended rate or according to a prescriptive value. USACE guidance has additional prescriptive items. TM 5-822-7 prescribes equipment for applying curing compound for pavements.[25] It directs that equipment must be power driven, straddle the newly paved lane, and give uniform coverage. Nozzles must be surrounded by hoods to prevent wind blowing curing compound. There is no guidance on how to ensure that uniform coverage is actually achieved. Guide Specification CWGS 03300 directs that curing compound must be applied in a two-coat operation at a minimum pressure of 500 kilopascals (kPa).[19] If it rains within 3 h of application, then the application must be repeated. Application rate of curing compound is verified by documenting the amount of curing compound used and estimating the covered area.

Another concept in use by at least one State for estimating the amount of application is to relate flow rate through nozzles (by direct measurement) to pressure, then to monitor pressure and rate of travel of the application equipment. From this information, a calculation of the rate of application is possible.

Another common practice is direct visual inspection when pigmented curing compounds are used. This is based on the concept that an uneven appearance of color or whiteness will indicate problems in curing compound application. No information was found on the sensitivity of visual inspections to variation in application rates. Reflectance measurements may also be a plausible way to estimate coverage of white pigmented curing compounds. Portable instruments developed for measuring reflectance of paint are available and may have application for evaluating pavements.

ACI 308R cautions that estimating application rates on highly textured surfaces from using calculation methods can be misleading because the actual area of a highly textured surface can be grossly underestimated by a calculation based on simple dimensions.[6] No information was found either in standard guidance or in the literature on direct verification of application of curing compounds.

In theory, a pavement on which curing compound has been improperly applied or on which it is not functioning properly should be cooler than a well-covered pavement, due to evaporative cooling. Infrared imaging of the surface could be effective here. This approach could give results quickly for quality control purposes.

VERIFICATION OF EFFECTIVENESS OF CURING

There are a number of test methods for verifying that expected curing levels have occurred, including measuring strength, both directly and or by use of nondestructive methods, and by measuring surface or near-surface physical properties. Strength methods are covered in ACI 228[49] and include in place curing of test cylinders, ultrasonic pulse velocity, rebound hammer, pull out, and penetration resistance. These are all covered by ASTM standard test methods. Tests of near-surface properties that develop with curing are covered in Kropp and Hilsdorf (1995)[50] and include methods that measure permeability, water absorption, relative humidity, abrasion resistance, and hardness.

Standard guidance still heavily relies on strength or strength correlates. The current trend in the literature of the last 10 years is to rely on the surface or near-surface properties, but this has not appeared much in practice. Permeability and water absorption methods are generally favored. A number of these claim to be useful for field-testing, but most are not simple. One recurring problem with near-surface test methods applied to field concrete is the effect of concrete's moisture condition on the determination. Most of these methods work best when test specimens are prepared and analyzed in the laboratory because the methods include a drying period to remove this effect. However, some of the field methods give moisture correction procedures. The simplest test found was based on a relative humidity button containing moisture sensitive dye, allowing visual verification that the surface of the concrete was wet (Carrier and Cady, 1970).[51] To our knowledge, this device has not been widely used (Senbetta, 1994)[52], but there was no information on whether this was because of technical problems or a general disregard for this kind of verification.

Some of the methods described in ACI 228 potentially could be adapted for measuring changes in near-surface properties as an indicator of curing.[49] The rebound hammer appears to have promise here. This method has been commonly criticized as a measure of in place strength because of the very large effect of surface features on readings. One of these problems, near-surface aggregate particles, can be averaged out statistically, so that the method should have potential for measuring quality of near-surface curing, particularly if calibrated properly with a section of field concrete known to be well cured.

ACCOUNTING FOR CONCRETE MATERIALS AND MIXTURE PROPORTIONS

Four properties of a concrete mixtures and concrete materials that affect curing practice are addressed in standard guidance: (1) type of cement, (2) presence of pozzolan or slag, (3) water-cement ratio and, (4) rate of strength gain. The variables are not independent. In the main, these variables affect the duration of curing, and have been addressed in that section of this report. The presence of some pozzolans, notably silica fume, and water-cement ratios less than 0.40 requires water-added curing, which was discussed in the section "Selecting Curing Methods." One of the most critical features of a mixture design with respect to the way it affects curing practice may be the amount of bleeding that occurs.

Type of cement. ASTM C 150 Type I, Type II, and Type V cement is used for paving.(44) Many cements meet both Type I and II requirements and are called Type I/II. This is not an ASTM recognized category. Types II and V are usually cited for their sulfate resisting properties. Type III is sometimes used for small areas when rapid early strength development is required. Type IV cement is largely unavailable and not of interest for paving. Equivalent cements defined under ASTM C 1157 are Type GU (equivalent to Type I), Type MS (equivalent to the moderate sulfate resisting feature of Type II), and Type HS (equivalent to Type V).(53) At least one State (Florida) imposed a heat of hydration requirement on Type II cement used in summer paving of 80 calories per gram (cal/g) at 7 days.

As discussed above, ACI 308 makes a significant distinction between Type I and Type II cement with respect the length of curing required (7 versus 14 days, respectively).(31) There was once a significant basis for this distinction, but strength-gain rates in modern Types I and II cement are very similar. Type V cement typically does gain strength somewhat more slowly than Types I and II, but little distinction is made in curing guidance.

Pozzolans. Pozzolans typically have two effects on portland cement concrete that pertain to curing. One is that time of setting is sometimes retarded as much as several hours. This mostly affects the timing of application of curing procedures. The other property is that strength gain is slower than with pure portland cement concrete. This is particularly acute with Class F fly ash. Some research has recommended 3–7 days extra curing to get desired strength properties when using this type of pozzolan as a replacement for portland cement (See appendix B). In some practices pozzolan is simply added to the cementitious content, requiring adjustments to the other ingredients of the concrete. This practice effectively results in an increase in the total cementitious materials. Additional curing is probably not required to reach target strengths when this practice is employed.

Fineness of cementitious materials. Very finely divided cements and pozzolans are noted for contributing to reduced bleed and increased susceptibility to plastic shrinkage cracking. Typical values of fineness for cements are 350 to 400 m^2/kg (squared meters per kilogram) (ASTM C 204) , and for pozzolans are 10–30 percent retained on a 45 micrometer (µm) sieve.[(54)] Values much finer than these may contribute significantly to these problems. Type III portland cements typically have a fineness of 500 m^2/kg, or more. Silica fume is about an order of magnitude higher still. Slag tends to be a little finer than Types I or II cement, particularly Grade 120, which may reach a fineness of 500 m^2/Mg (squared meters per megagram) (ASTM C 204).[(54)]

Retarders. As with pozzolans, excessive retardation of time of setting may impact susceptibility to plastic shrinkage cracking by extending the initial curing period. This should not be a problem if evaporative losses are managed properly, but any retardation increases the length of time during which this must happen.

Water-Cement Ratio. Concretes with water-cement ratios less than about 0.45 tend to be more susceptible to plastic shrinkage cracking because of the reduced amount of bleed water that is formed. On the positive side, the more rapid strength gain of low water-cement ratio concretes shortens the time of setting and the total curing time required.

Cement Content. Concretes containing high levels of cementitious materials tend to show lower bleeding rates (although water-cement ratio is the major variable here). High cement contents are also associated with higher ultimate drying shrinkage. Long-term drying shrinkage is related to the amount of hydrated cement paste in a concrete. Reducing cement contents, if compatible with development of other properties is sometimes recommended as a way to reduce ultimate shrinkage.

Amount of pozzolan. As noted above, portland-pozzolan mixtures hydrate slower than pure portland cement, and setting times are often extended. These effects appear approximately in proportion to the amount of pozzolan. Pozzolan is commonly limited to about 20 percent by mass of total cementitious materials in paving concrete because of these effects.

CHAPTER 3: DRAFT GUIDELINES

A draft guide for curing portland cement concrete pavements is presented in figures 2 through 9. Figure 2 gives an overview of the entire guide. Figures 3 through 9 give details of subsections of the guide, with figures 3 through 7 covering choices among materials and methods, and figures 8 and 9 covering temperature management. The guide was developed principally from existing U.S. standards, with some features added for which U.S. standards provide little or no guidance.

As a result of review by the TAP, some features of the guide were identified as poorly developed, needing additional work to develop the information necessary. Text accompanying each figure covers pertinent details and subjects that needed more work in subsequent tasks in the project.

GENERAL OUTLINE OF THE GUIDE

Figure 2 presents a general summary of the draft guide. The guide is organized around three moist-curing procedures and a separate section on temperature management. The three moist-curing procedures are curing compound methods, water-added methods, and water-retention methods other than curing compounds.

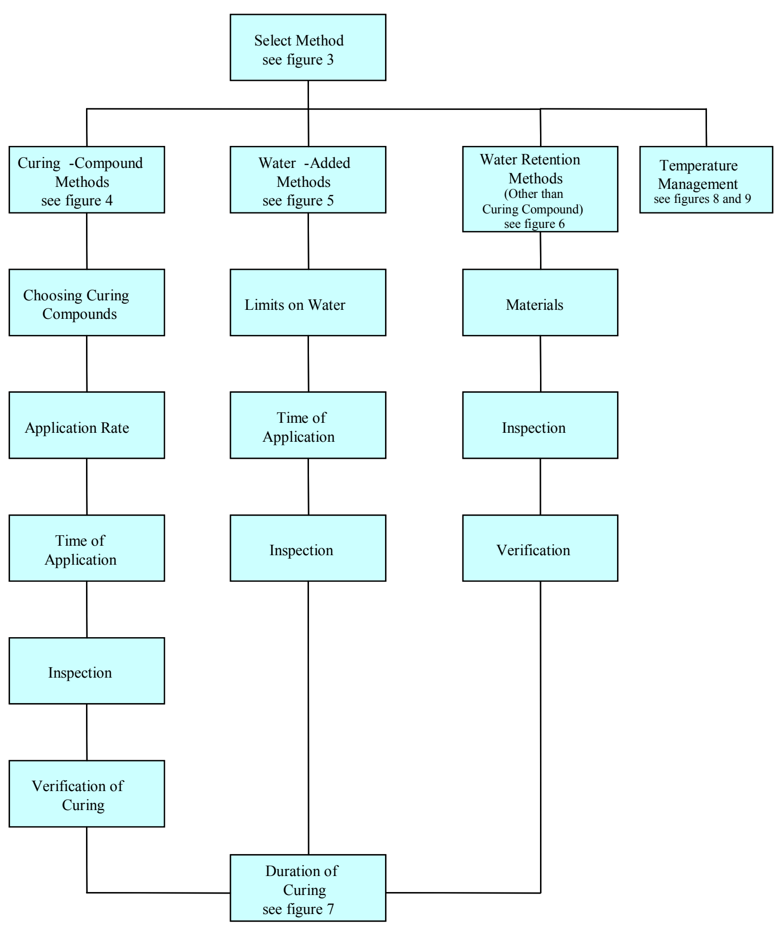


Figure 2. General layout of the draft guide.

SELECTION AMONG MOIST-CURING METHODS

Figure 3 depicts the decision tree associated with selection among moist-curing methods. Use of curing compounds for curing large placements of highway paving is usually the most practical and economical method. This may also be true for smaller pavement projects due to unavailability of materials for other curing methods or because of the impracticality of maintaining inspection.

Concretes with water-cement ratios less than 0.40 are known to desiccate internally due to consumption of water during hydration. More water must be added if additional hydration is thought necessary and/or to prevent the shrinkage associated with internal desiccation. There is considerable doubt expressed in the literature about whether water-added curing is effective in penetrating low water-cement ratio concretes, and so it may be a wasted effort from the perspective of improving strength. However, it is plausible that the added water has positive effects on the near-surface concrete. There is not much in the literature on this detail. Expansive cements are also believed to benefit from added water, but these are rarely used in concrete paving.

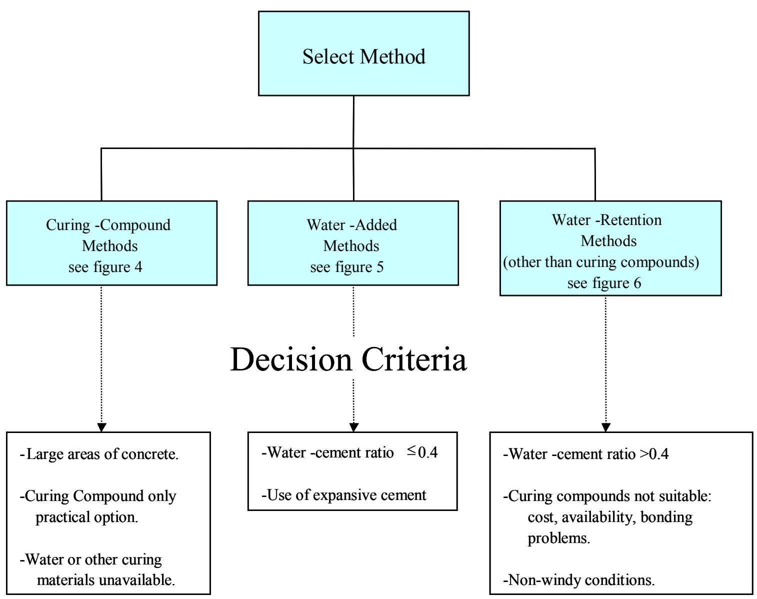


Figure 3. Selection among moist-curing methods.

If the water-cement ratio is greater than 0.40, more than sufficient mixing water exists to completely hydrate the cement and to prevent internal desiccation, so no added water is required. This branch of the guide also includes guidance on water-retention methods to use when curing compounds are not suitable. The most likely reasons this might occur would be unavailability (small jobs, short notice), anticipated problems with bonding of paint or adhesives to the pavement surface, or a desire to dry the concrete as rapidly as possible after curing is completed, such as if some kind of covering is to be applied that is intolerant of residual moisture in the concrete. This method may not be suitable under windy conditions.

SELECTING AMONG CURING COMPOUND METHODS

The outline of decision criteria pertinent to curing compound methods is shown in figure 4.

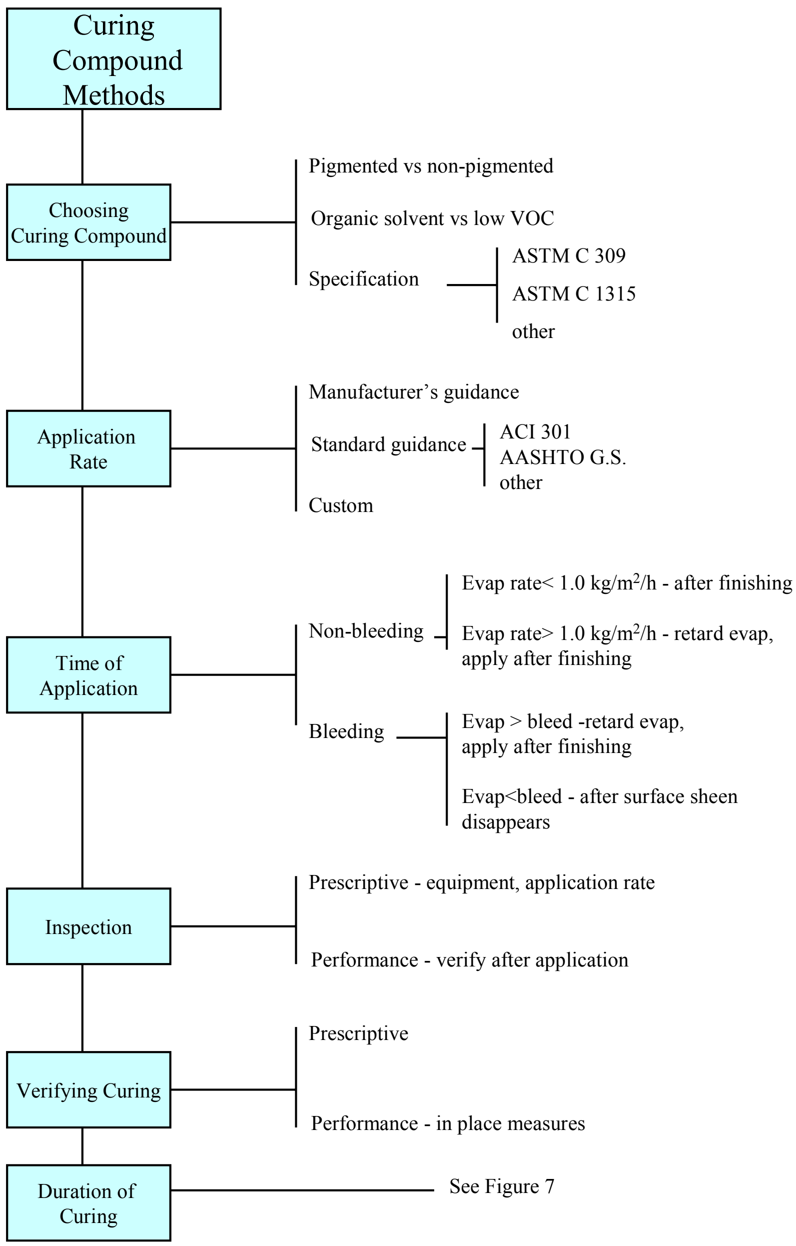


Figure 4. Decision criteria for curing-compound methods.

<u>Choosing curing compounds</u>. White pigmented curing compounds are normally required when exposure to sunlight is anticipated. Either white pigmented or fugitive dye compounds are required when visual inspection of the quality of the application is required.

Environmental regulations limiting the amount of VOCs released during construction activities are currently being implemented by some organizations. More information on these regulations needs to be obtained so additional details can be added to this branch. Also, information on any differences in practices required of low VOC versus conventional curing compounds needs to be obtained and incorporated into the guide.

AASHTO M 148[24] (ASTM C 309[23]) is the most commonly referenced specification for curing compounds for highway paving. Some State transportation departments have developed their own standard, which limits moisture loss measured using AASHTO T 155[55] (ASTM C 156[18]) or similar test, to values lower than those found in M 148[24] (0.55 kg/m^2 at 72 h). ACI 305R[12] recommends lower limits in hot weather (0.39 kg/m^2 at 72 h). ASTM C 1315[24] limits moisture loss to 0.40 kg/m^2 at 72 h, but is not referenced in any current paving guidance found. Additional information on the relationship between the moisture loss requirement and performance needs to be developed. The precision of test methods is also a problem with respect to user-producer agreement on acceptance.

<u>Application rate</u>. ACI 301[43] requires a curing compound application rate of no more than 5 meters squared per liter (m^2/L) , with two applications at right angles on rough surfaces, not to exceed 5 m^2/L for the total application. The AASHTO Guide Specification[33] requires 3.5 m^2/L, applied by fully atomized spray equipment with a tank agitator and wind guard. USACE requires two applications of 10 m^2/L each.[34] Manufacturer's recommendations are typically 5–10 m^2/L. This information needs to be supplemented with information on practices from State departments of transportation.

It seems plausible that an application rate could be based on the physical properties of the pavement surface, the performance properties of the curing compound, and the climatic conditions anticipated during use. Additional work needs to be done to explore this possibility.

<u>Start of curing activity</u>. Guidance typically directs application of final curing after finishing is complete and sheen has disappeared. If evaporation rates are high and the concrete does not bleed, protection against excessive evaporation must be provided until this point is reached. According to guidance in ACI 305R[12] and ACI 308[31] evaporation rates of ≥1.0 kg/m^2/h seem to be the upper limit for acceptable conditions for requiring no action. Other guidance recommends consideration of action at lower rates. ACI 305R[12] says that precautions should be taken if evaporation rates approach this limit. Army TM 5-822[25] says that 0.75 kg/m^2/h may be problematic. ACI 308[31] says that precautions may be needed at 0.5 kg/m^2/h. Additional work may be needed on this limit.

If concrete is bleeding, then a negative interaction between bleeding and early application of curing compound can result. ACI 308-92[31], paragraph 2.3.3 cautions:

> If ambient evaporation rate exceeds 0.2 lb/ft^2/h (1.0 kg/m^2/h) … the concrete may still be bleeding even though the surface water sheen has disappeared and steps must be taken to avoid excessive evaporation. If membrane-forming compound is applied to a dry-appearing surface, one or the other of two undesirable conditions may follow: a) evaporation will be effectively stopped but bleeding may continue, resulting in a layer of

water forming below the layer of cement paste to which the membrane is attached (such a condition promotes scaling); b) evaporation will be temporarily stopped but bleeding may continue resulting in map cracking of the membrane film, requiring reapplication of the curing compound.

This problem can be avoided by maintaining the surface moisture, either by misting or applying evaporation retarding compounds.

Inspection. Current guidance is to inspect application equipment (Army TM 5-822[25], ACI 305R[12]) to ensure proper function and to estimate the rate of application by measuring the amount of curing compound used to cover a known surface area at the end of each operation (USACE Guide Specification, CWGS 03300[19]). In the case of pigmented curing compounds, visual inspection for uniformity is recommended (CWGS 03300[19]). No information was found on the reliability of visual inspections to detect poor application of curing compound. Work may need to be done here.

No standard test methods were found that are suitable for determining in place rates of curing compound application. Additional work is required.

Verify curing. The basic approach to verifying that proper curing has occurred is to ensure that proper curing procedures have been applied (ACI 308[31]). No standard procedures for performance testing currently exist. Potential performance measures of the adequacy of curing include measuring near-surface properties of concrete and/or measuring the amount of moisture on the surface of the concrete. Work needs to be done here.

WATER-ADDED METHODS

Figure 5 shows the decision tree and criteria for water-added methods.

Specifications on water. Temperature of curing water must be no more than 10 °C cooler than the surface of the concrete (ACI 308[31], ACI 308.1[45], ACI 305R[12]). Requirements on dissolved materials mostly pertain to the staining potential of curing water. ACI 308.1[45] directs that curing water be either potable or meet requirements of ASTM C 94[15]. The requirements in this standard purport to address mixing water, not curing water. USACE standard CRD-C 400 addresses staining in curing water, but in a relatively qualitative way.[16]

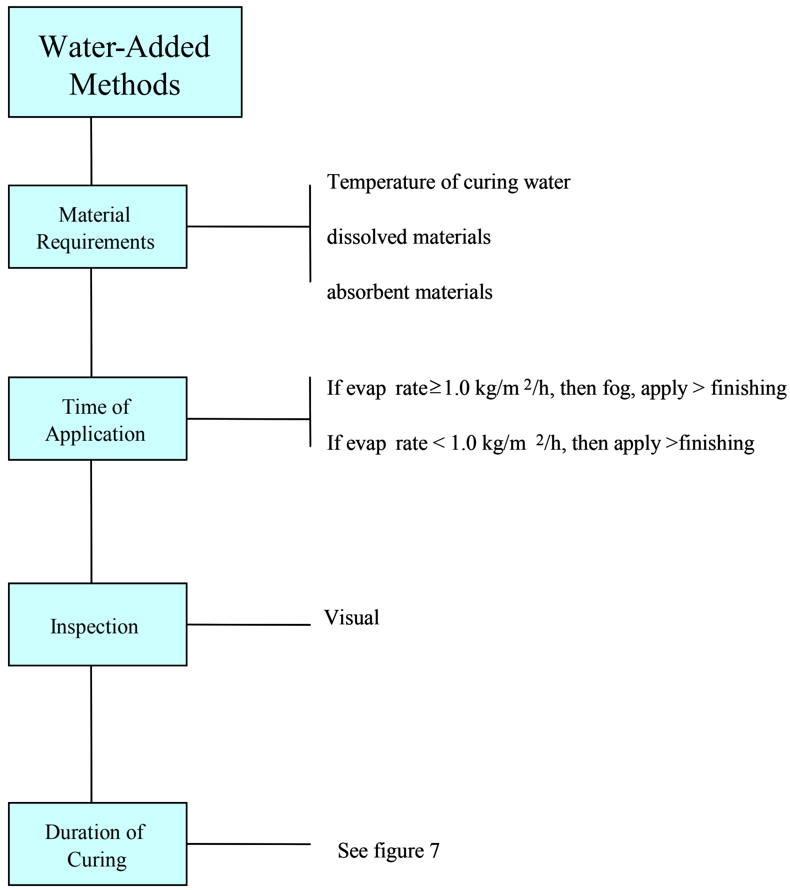


Figure 5. Decision criteria for water-added methods.

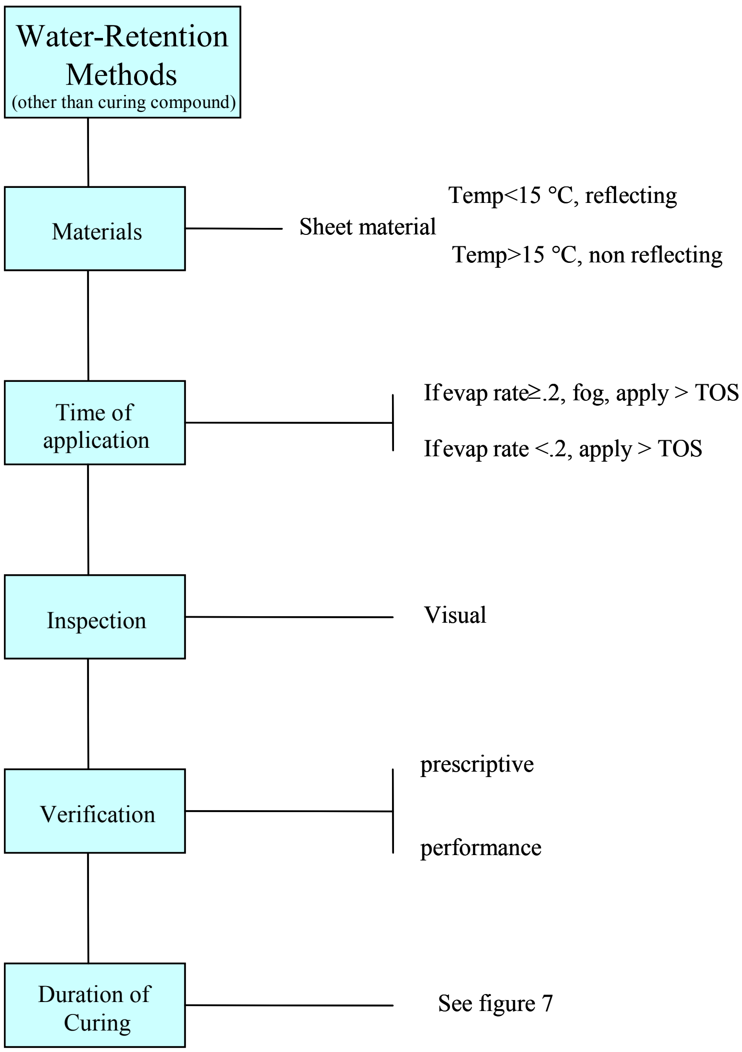
Specifications on absorbent materials**.** Absorbent materials are useful for holding water on the concrete surface, either vertical or horizontal. They are required to be nonstaining (ACI 308.1[45]) or free of sugar or fertilizer (ACI 308[31]), but no quantitative criteria are cited. Earth materials must be free of organic matter and free of particles larger than 25 mm. Straw or hay should be at least 150 mm thick (ACI 308).[31] Burlap must meet AASHTO M 182-91[56].

Start of curing. Guidance on delaying application of water until after final finishing is taken from ACI 308.1.[45] ACI 308[31] directs that even more strength is required for heavier mats, but no quantitative guidance is given. As with curing compounds, excessive evaporation must be avoided before application of curing to avoid plastic shrinkage cracking.

Inspection. Moist curing inspection shall occur once per shift or not less than two times per day, including nonworkdays. Moisture conditions of the concrete are recorded. If an area is found to be dry, corrective action is taken and curing is extended one day (USACE CWGS 03300).[19] ACI 308.1 allows that the architect may specify the frequency of inspections.[45]

WATER-RETENTION METHODS (OTHER THAN CURING COMPOUNDS)

Figure 6 shows the decision tree and criteria for water-retentive methods other than those that use curing compounds.



TOS = time of initial setting

Figure 6. Decision criteria for water-retentive methods other than those using curing compounds.

Specifications. Sheet materials are covered by ASTM C 171.[17] The sheet color requirement is in ACI 308.1.[45] The USACE Guide Specification (CWGS 03300) only allows plastic covered burlap sheeting.[19]

Start of curing. The same information applies as described above for application of water absorbent materials.

Inspection. Inspection must include verification that the concrete surface is wet under the sheet. Inspection frequency is the same as for water-added methods.

Verification of curing. Verification methods are the same as described under curing- compound methods.

DURATION OF CURING

Figure 7 shows the decision tree and criteria for duration of curing.

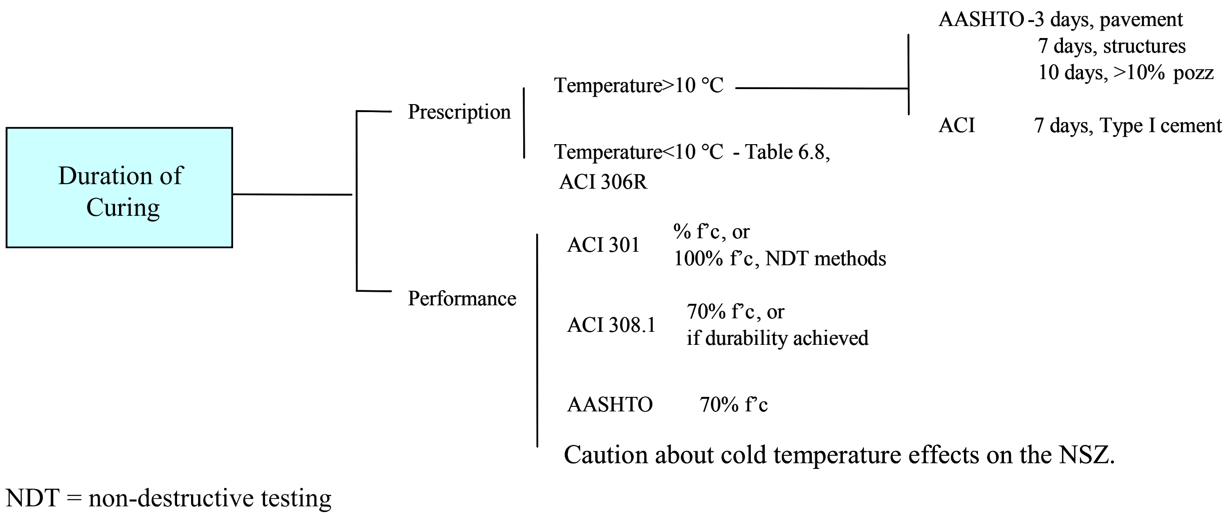


Figure 7. Decision criteria for duration of curing.

Prescriptive times. Additional work needs to be done here. There seems to be conflicting guidance when strength is the property on which curing duration is based. Durability may require even longer times.

Performance-based, strength. ACI 301 gives three alternative criteria:[43]

(1) 70 percent f_c'.
(2) Curing time equal to lab time required to achieve 85 percent f_c'.
(3) 100 percent f_c' when using NDT methods for estimation.

Performance-based, durability. Work needs to be done here. There is no additional guidance on durability.

TEMPERATURE MANAGEMENT, HOT WEATHER

Figure 8 shows the decision tree and criteria for temperature management in hot weather.

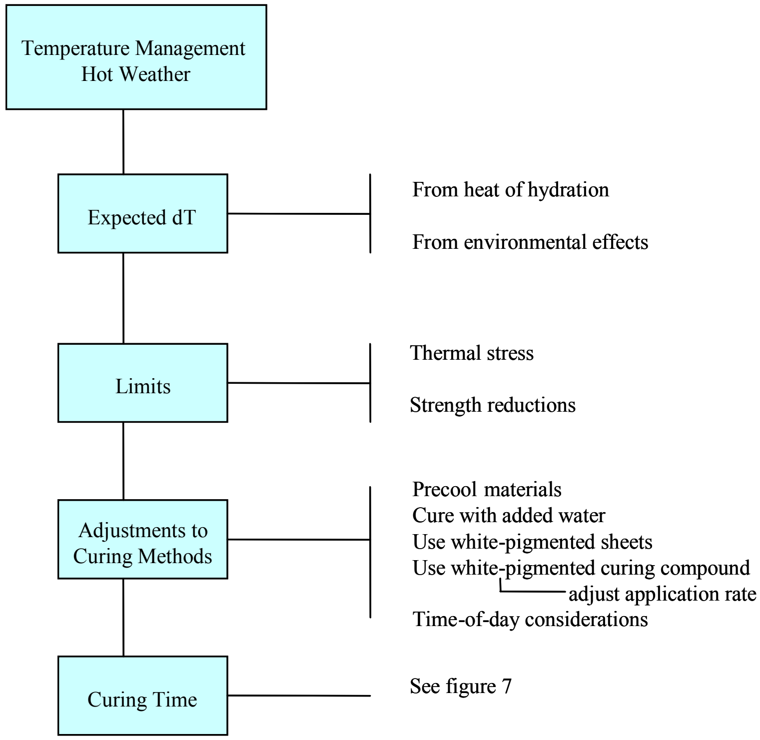


Figure 8. Decision criteria for temperature management in hot weather.

Temperature rise. Information on calculating heat rise in concrete pavements based on heat of hydration and environmental conditions exists. HIPERPAV(13) software (McCullough and Rasmussen (1999)(57, 58, 59)), for example, uses these kinds of input data as part of a calculation of strains in pavement concrete. The temperatures of the concrete are not currently part of the output of the program. Kapila, Falkowsky, and Plawsky (1997) have developed a computer program that executes this calculation.(60) The program is reported to be personal computer compatible. This paper also references other such programs. Predicting concrete temperature rise is reasonably outside of the scope of this work.

Thermal stress. Several items in current standard guidance apply to the problem of thermal stress that can result if cooling of concrete during curing is too severe. ACI 305R directs that water used in curing should not be more than 10 °C cooler than the concrete.(12) The USACE Guide Specification (CWGS 03300) limits the temperature difference between the concrete surface and a depth of 50 mm to no more than 13 °C.(19) A thermal stress analysis using finite element methods would be suitable for detailed analysis of this problem, but it is reasonably outside of the scope of this work.

Strength reductions at high temperatures. There does not seem to be a simple calculation for estimating the effect of high curing temperatures on ultimate strength, and this phenomenon probably does not lend itself to a simple calculation. This effect was not included in the literature search that was executed for this preliminary work, so an additional effort was required to identify this information (see chapter 4).

Adjustments to Curing Methods. Curing compound application rate or water-retention specification limits may need to be adjusted for hot weather conditions. There is a strong heat of hydration exotherm of portland cement-based concretes that starts at time of setting and continues for several hours. The exact timing and size of the exotherm depends on the cementitious materials (there is quite a bit of variation even among portland cements) and type and amount of chemical and mineral admixtures. If this exotherm occurs simultaneously with the peak in solar radiation, then there could potentially be a synergistic effect, resulting in a very large temperature rise. The timing of this exotherm does not seem to lend itself to prediction by simple calculation, but the effect is relatively easy to measure. At least one commercial manufacturer of equipment for measuring "heat signatures" exists. This information would probably be very useful in scheduling construction so as to avoid the confluence of autogenous heating and solar heating. HIPERPAV(13) software (McCullough and Rasmussen, 1999)(57, 58, 59) addresses these issues.

TEMPERATURE MANAGEMENT, COLD WEATHER

Figure 9 shows the decision tree and criteria for temperature management in cold weather.

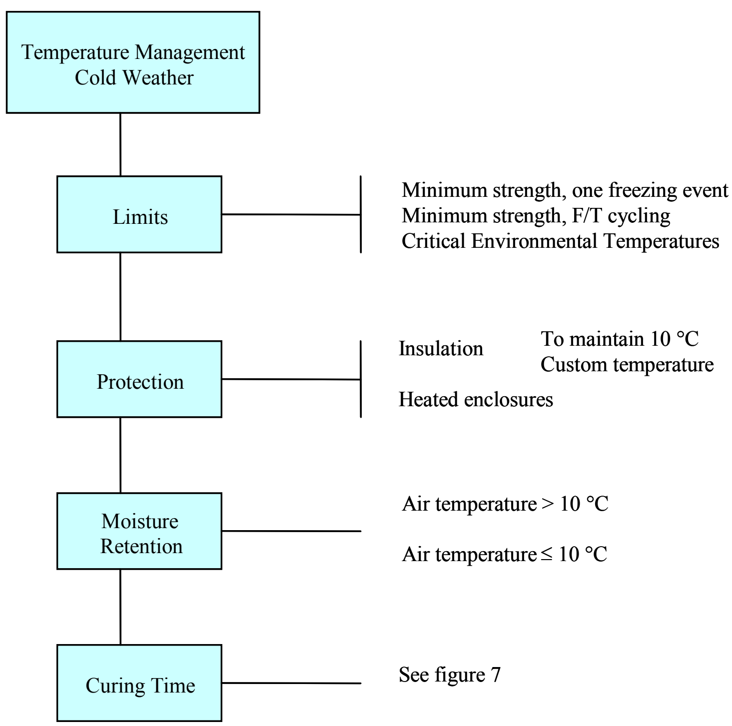


Figure 9. Decision criteria for temperature management in cold weather.

Strength limits for exposure to freezing. Various guidance on freezing exists. AASHTO Guide Specification(33) directs that concrete be protected from freezing for 10 days or until strength reaches 15 MPa. ACI 306R(14) and 308(31) direct that a single freezing event must be avoided until concrete has reached a strength of 3.5 MPa. The USACE Standard Practice (EM 1110-2-2000) cautions avoidance of freezing and thawing cycles until strength reaches 24 MPa.(8)

Insulation. ACI 306R gives insulation constants (R values) required to maintain a temperature of 10 °C for various ambient conditions.[14] This concept could be extended to include insulation constants required to maintain higher temperatures. This should lend itself to standard engineering calculations on heat transfer.

Need for moisture retention measures in cold weather. Paragraph 8.2 of ACI 306R on curing during the protection period applies here.[14] If concrete is warmer than 16 °C and air temperature is 10 °C or higher, then drying can be a problem. Use of steam for both heating and moisture maintenance is the preferred method, otherwise a curing compound is required. Water-added methods are not recommended because of the practical problems of ice forming outside of the enclosure. When the enclosure temperature is 10 °C or lower, then no moisture maintenance is required if the relative humidity is less than 40 percent.

ADDITIONAL INFORMATION AND MODIFICATIONS NEEDED FOR COMPLETION OF THE GUIDE

The following list summarizes items in the draft guide that need some additional attention, along with notes on how this will be accomplished.

Concrete materials and mixture proportions. A section needs to be added to the guide on concrete materials and mixture proportions. Concrete materials and mixture proportions are not normally chosen with respect to maximizing or even optimizing curing procedures. Specifications for materials tend to be rather monotonous. Cements, pozzolans, aggregates, admixtures, and mixing water are required to meet standard specifications. However, within the limits imposed by the standard specifications, there are a few places where some choice can be made that will have some impact on curing practices. Mixture proportions are an area in which quite a bit of latitude in choice exists. This information will be put together from existing knowledge of the relationship between materials and mixture properties and performance properties that are pertinent to facilitating curing. Agency guide specifications will be reviewed since these typically set outer boundaries on materials and mixture proportions.

Protection between placing and final curing. Details on options during the time between placing concrete and start of curing needs to be developed more fully. A considerable amount of information is currently under development in ACI 308Ron this period (referred to as “initial curing period” in their guides).[6] Research literature on plastic shrinkage was examined in more detail for information that might be useful in developing guidance. State DOT guidance was reviewed to see how this period is handled in various localities (see chapter 4).

Evaporation rate nomograph. The draft guide contains little information on the use of the evaporation rates, as calculated from windspeed, air temperature, concrete temperature, and relative humidity. There has been some criticism of the information derived from this calculation. Considerably more information has been developed recently in the new ACI 308R and in recent literature.[6] The limits of 0.5 and 1.0 kg/m^2/h for caution and definite action (respectively) may need to be revised.

Time of setting. Knowledge of the time of setting of concrete is useful for planning curing operations. It is well known that time of setting has a strong temperature dependency, and it has been suggested that it should follow the same Arrhenius relationship that is the basis of one of the maturity methods. A calculation will be developed based on this concept.

Curing compound technical information. More information on the diversity of curing compounds that are available needs to be developed and worked into the selection of materials section of the Guide for Curing Compound procedures. There does not seem to be much information on this in the research literature, so we will have to rely on information that can be extracted from curing compound manufacturers. Some of this information is expected to be proprietary and not available, particularly details of the formulation. Also details on application practices need to be filled out and organized in one place. This was obtained later from manufacturers and by comparing experiences and guidance manuals of various agencies.

Effectiveness of Water Curing of Low Water-Cement Ratio Concretes. Water curing is not a major method for curing concrete pavements, but it is sometimes used in curing small sections. If concrete is low water-cement ratio (<0.40), then internal desiccation may be an important source of shrinkage strains. Water curing can, in theory, relieve this form of drying shrinkage. Additional information will be located that comments on the plausibility that water applied to the surface of a low water-cement ratio concrete will actually penetrate far enough into the concrete to be effective.

Evaporation reducers. More information on evaporation reducers will be developed. Extensive literature on this technology does not exist, so information will have to be located in nonstandard places, such as through anecdotal information. As part of the evaluation of the guide, some evaporation reducers will be evaluated in the laboratory.

Tined surfaces. Tining a concrete surface greatly increases the effective surface area. Information needs to be developed on how this affects application rates of curing compound. A section of the guide will be developed that provides the user with a way to calculate adjustments to application rate of curing compound required to compensate for this increased surface area.

Length of curing. More information needs to be gathered on length of curing, particularly when pozzolans or other non-portland cement items are included in the cementitious materials. There is substantial literature on this and existing practice. This needs to be reviewed again in more detail to arrive at reasonable guidance for pavements.

Test methods—verifying curing compound application. Plausible test methods for verifying curing compound application need to be developed. The preliminary report listed several plausible ones, but no details on how they might be executed were included. These will be developed and then evaluated in that section of the report.

Test method—verifying curing. Plausible test methods for evaluating the quality of curing of the near-surface concrete need to be developed. Several candidate procedures were mentioned in the preliminary report, but no details were included. Methods will be evaluated in that section of the report.

Emphasis on curing compound methods. It was emphasized during the review of the draft guide with the TAP and in comments from the contracting officer's technical representative (COTR) that the emphasis of the guide should be on concrete paving and that water-curing and sheet-curing methods would generally not be practical. These methods will be de-emphasized in the revised guide, although information will be presented in the section on technical notes on these topics.

CHAPTER 4: INFORMATION GATHERED TO COMPLETE THE GUIDELINES

This chapter describes the work that was done to add information to the guide or to revise information already in the guide. The rationale for this needed work is in the last part of chapter 3. Information in this chapter is taken from available literature and/or guidance. Additional information obtained from laboratory work or from original analysis is contained in chapter 5.

GUIDELINES FOR SELECTING CONCRETE MATERIALS AND MIXTURE DESIGNS

Choice of materials and mixture proportions can have a significant effect on curing requirements, although choices of materials and mixture proportions are normally based on the expected properties of the hardened concrete and not on curing considerations. However, there are some details to be brought to the designer's attention, as discussed in chapter 2. The information that follows is an expanded discussion.

Hydraulic Cement

The major curing issue in choosing cements is the rate of strength gain and hence the length of curing time required to attain adequate physical properties. However, there are several other pertinent properties, as discussed below. Hydraulic cement is covered by five ASTM specifications and three AASHTO specifications.

The diversity in ASTM specifications reflects trends within the cement industry. ASTM C 150 is the first standard cement specification (1940) still in use.(44) ASTM C 595 was first published in 1967 to meet the needs of the emerging blended cement industry.(61) This specification has not been widely used, mostly because of user preference and not because of any negative quality issues. ASTM C 1157 was first introduced in 1992 as a performance-based specification for blended cements in an effort to overcome some of the user preference problems.(53) The scope has since been broadened to include all hydraulic cements, including portland cement (now specified also under C 150).(44) There is considerable interest in the cement manufacturing industry to move all cement specifications to this standard. The performance-based format of C 1157 allows for more freedom to use innovative materials and processes.(53) A major factor driving this trend is pressure to reduce carbon dioxide (CO_2) emissions.

Partially for economic reasons, it is popular to purchase pozzolan separately and replace part of the cement with it. This is only common practice, however, when using portland cement as the primary cementitious material. There is concern that cements furnished under other specifications (e.g., C 595(61) and C 1157(53)) may perform badly when blended with pozzolan because most of them already contain a fraction of pozzolan or slag and the effects of adding a third cementitious material are largely unknown. It is plausible that this kind of three-way cementitious mixture could be successfully used, but there is currently little or no guidance on this practice.

ASTM C 150[44]*/AASHTO M 85*.[62] Some ACI guidance (e.g., ACI 308[31]) makes a significant distinction about the length of moist curing required when using the various cements covered by ASTM C 150:[44]

- Type I–7 days.
- Type II–14 days.
- Type III–3 days.
- Type IV–no recommendation.
- Type V–no recommendation.

These recommendations assume a curing temperature of ≥ 10 °C.

The shorter curing times recommended for Type III cements is probably still valid. The distinction between Type I and Type II cement is, for all practical purposes, no longer valid. Until about 1980, Type II cements were commonly made with lower tricalcium silicate (C_3S) contents than Type I cements, hence were slower to reach required strengths and needed extra curing time. With changes in some details of C 150 requirements, the Type II cements now can be manufactured to gain strength at the same rate as Type I cements.[44] Most are now formulated for this higher early strength property. An exception would be a Type II cement meeting the optional C 150[44] heat of hydration (HH) requirement. Cements meeting this requirement are rare except as a special purchase item. Type IV cement is more rare than a Type II HH cement and normally used only in mass concrete. Type V cement is specified in high sulfate environments. Early strength gain of these cements is typically a little slower than Type I and II cements, but faster than the Type II HH cement. A prescriptive curing time of 10 days would be a reasonable interpolation of the above recommendations.

AASHTO M 85[61] is identical to ASTM C 150[44] except for the requirement of ≤55 percent C_3S for Type II cements. Most ASTM Type I and II cements meet this requirement, but it does exclude a few cements with unusually high level of C_3S. This difference does not make a significant change in length of curing requirements developed around the ASTM types.

ASTM C 1157[53] *(no AASHTO equivalent)*. No guidance was found that makes recommendations about curing times required for cements meeting this specification. The following equivalency in strength gain rate with C 150[44] cements is reasonably valid:

- Type GU = Type I.
- Type MH = Type II HH—not normally used with pavements.
- Type HE = Type III.
- Type MS = Type II without the HH requirement.
- Type LH = Type IV—not normally used with pavements.
- Type HS = Type V.

ASTM C 595[60]*/AASHTO M 240*.[63] This is the original specification for blended cements. The ASTM and AASHTO specifications are identical except for some requirements on sulfate resistance and MgO levels. The differences are irrelevant to curing. These specifications contain a relatively complicated system of classification based on composition. The types designated as I(SM), IS, I(PM), IP is the close approximation to a Type I with respect to strength-gain properties and is most likely to be used for paving.

ASTM C 845[64] *(no AASHTO equivalent)*. This specification covers expansive cement. The only product currently marketed is Type K. Cements meeting this specification were marketed aggressively for many years in the late 1980s and early 1990s. Availability has been greatly reduced in recent years. This cement is rarely used for large paving projects because of cost, but has been used in smaller paving and flat work because the expansive property helps avoid shrinkage. The chemical mechanism that causes the expansive property requires quite a lot of water, so that the maximum benefit of this property of the cement is obtained if wet curing is applied.

ASTM C 989[65]*/AASHTO M 302*.[66] Ground granulated blast-furnace slag is actually a hydraulic cement, but it is often referenced as a supplemental cementing material (SCM). Its specification and test methods (C 989)[65] are managed by ASTM Committee C 9 (on concrete and concrete aggregates), along with pozzolans and other admixtures. This is a result of past internal politics in ASTM and not based on technical considerations. ASTM recognizes the term “ground granulated blast furnace slag” as representing the 100 percent slag product (C 989)[65], and the term "slag cement" as representing a portland cement-slag blend (C 595).[61] Some 100 percent slag products are marketed and labeled as “Slag Cement.” The confusion in this terminology is currently unresolved. However, the user can recognize the 100 percent slag product by the “C 989” designation and the blended cement product by the “C 595” designation.

Slag is sold under three designations based on strength development potential: Grade 80, Grade 100, and Grade 120. The grade designations are based on the approximate expected strengths of portland cement-slag mixtures, expressed as a percentage of controls at 28 days. Grades 100 and 120 would be suitable for paving. Grade 80 is more suitable for mass concrete applications and is less commonly available than grades 100 and 120.

Pozzolans

Pozzolans are specified by AASHTO M 295[67] and ASTM C 618[68]. These two specifications have the same requirements except for the limits on loss on ignition and sulfate resistance. Neither of these has curing implications. Three classes are described:

- Class N—natural pozzolan, little marketed in recent years.
- Class F—fly ash from bituminous and anthracite coals, widely available.
- Class C—fly ash from subbituminous and lignite coals, widely available.

Pozzolans typically have two major effects on concrete that pertain to curing. These are time of setting and strength development.

Most fly ashes retard time of setting of cement pozzolan blends. This retardation varies from less than an hour to as much as several hours. There is no requirement in C 618[68]/M 295[67] for effect on time of setting and, in practice, there is no selection that is normally made on the basis of this property. In paving this retardation affects timing of the texturing operation and application of final curing. Delay of these operations means that there is a longer period of time when the concrete may need to be protected from evaporation to prevent plastic shrinkage cracking.

Most pozzolans also retard the rate of strength gain in concrete, affecting the length of time they must be cured to get the desired physical properties. An exception to this generalization is when pozzolans are interground with portland cement during manufacture of blended cements. The grinding operation tends to effectively increase the surface area of the pozzolan so that there is essentially no strength-gain penalty.

Strength-gain retardation is particularly acute with Class F fly ash. Some research has recommended 10 to 14 days curing to get desired strength properties, while 7 days is recommended for portland cement. Class C fly ash tends give better early strength gain. This is because these materials are only partially pozzolanic and usually contain a significant fraction as cementitious compounds. Under proper circumstances, some Class C fly ashes can be used as the basis for hydraulic cement, although these cements are currently used only for patching.

The hydraulically active nature of Class C fly ash sometimes has a negative effect on early workability. Some materials cause the concrete to lose workability rapidly. This property is not covered by requirements in C 618[(68)]/M 295.[(67)] The reactions that cause this tend to consume a considerable amount of water and cause the concrete to take on the appearance of early setting. This is not, however, the traditional setting reaction in concrete that involves the hydration of C_3S in the cement. This reaction is usually retarded by Class C fly ash, so the common manifestation of this effect is that the concrete loses workability within a few minutes, but then the time of setting is delayed. It has not been demonstrated, but this pattern of behavior may contribute to susceptibility to plastic shrinkage cracking.

Other Considerations on Cements and Pozzolans

Heat of Hydration. The HH requirements in C 150[(44)], C 1157[(53)], and C 595[(61)] are intended principally to meet the needs of mass concrete construction. However, at least one State (Florida) now specifies a HH limit on cement used in summer paving. The limit is for 335 kilojoules per kilogram (kJ/kg) at 7 days for concrete containing no pozzolan and 375 kJ/kg (88 cal/g) for concrete containing pozzolan. These limits do not conform to any standard ASTM requirements. Heat of hydration for Type I/II cements at 7 days is commonly near 335 kJ/kg, and most sources would probably meet this limit, but some companies make Type I and II cements that evolve as much as 395 kJ/kg (95 cal/g) at 7 days. The AASHTO M 85[(62)] limit of 55 percent on C_3S would probably effectively exclude these.

Fineness of Cement and Pozzolan. Very finely divided cements and pozzolans are noted for contributing to increased susceptibility to plastic shrinkage. Typical values of fineness for cements are 350 to 400 m^2/Mg (ASTM C 204), and for pozzolans are 10–30 percent retained on a 45 µm sieve.[(53)] Values much finer than this may contribute to plastic shrinkage cracking. Type III portland cements typically have a fineness of 500 m^2/kg or more. Silica fume is approximately an order of magnitude higher still. Fineness of slag is usually not measured, but typically it is ground somewhat finer than ordinary Type I/II cements. Grade 120 may reach 500 m^2/Mg.

Admixtures

Water-reducing and air-entraining admixtures are commonly used in pavement concrete. There are some implications on curing with the water-reducing admixtures (WRAs). Some WRAs tend to retard the time of setting of cementitious materials significantly. This retardation is typically in addition to the retardation caused by use of fly ash. Unless the retardation is truly needed to overcome the accelerating effects of high concrete temperatures then, as discussed above under the section on pozzolan retardation, this retardation can cause an extension of the time when excessive evaporation must be avoided and possibly the timing of the texturing operation.

Mixture Proportions

Three mixture proportion properties have relevance to curing: water-cementitious materials ratio, cement content, and percentage of pozzolan.

Water-Cement Ratio. Paving mixtures are typically proportioned to a low w/c, but curing related problems may develop if water-cement ratios are too low. Sometimes water-cement ratios less than 0.40 are used to get high early strength development and to get desired cohesiveness for slip-form paving. A negative side to this practice is that low water-cement ratio concrete may have little or no bleed water. In moderation, bleed water is useful for buffering against the effects of high evaporation rates. If evaporation rates exceed bleeding rates, then conditions easily develop that favor plastic shrinkage cracking. Another negative feature of low water-cement ratios is internal desiccation. At water-cement ratios less than about 0.40, essentially all of the mixing water is consumed by cement hydration and gel water adsorption. This leaves the capillary pores in a condition exactly analogous to evaporative drying. This results in drying shrinkage and the potential for cracking unless water is added to the concrete during curing operations.

Cement Content. Some agency specifications set minimum levels of cement content to around 325–355 kg/m^3. Other specifications are based around a minimum flexural strength limit. It is common practice to use higher cement contents if there is difficulty in getting the minimum strength or if there is uncertainty with respect to acceptance testing issues surrounding flexural strength testing. The precision of this test method is so poor that owner-contractor disputes over strength results are common. A negative side to using more rather than less cement, other than cost, is that it results in a concrete with a high paste content. It is the paste content that dominates the long-term drying shrinkage behavior of the concrete, particularly if the cement in the paste is largely hydrated. Ideally, cement contents should be just high enough to obtain the necessary strength (with enough extra to protect against testing uncertainty), but not higher than that.

Percent of Pozzolan. As noted above, portland-pozzolan mixtures hydrate slower than portland cement, so strength gain is slower and setting times are often extended. The hydration rate affects the length of the curing period required to get adequate strength. In USACE airfield construction, strength development problems normally limit pozzolan contents to about

20 percent for Class F and 25 percent for Class C fly ashes. In this type of construction, common practice is to slip form alternate lanes. Then, when there is sufficient strength to support the paving machine on the slip-formed concrete, the alternate lanes can be paved using conventional paving techniques. It is the rate of strength development of the slip-formed lanes that limits pozzolan contents in this type of construction.

GUIDELINES FOR PROTECTION BETWEEN PLACING AND CURING

The time between placing concrete and application of curing has been termed the "Initial Curing Period" (ICP) in ACI 308R.[6] This is a critical time for pavements under severe drying conditions because of the relatively large areas of unprotected concrete that are often left exposed and because of the relatively large effects of loss of water on plastic concrete. This condition cannot always be effectively remedied by early application of final curing measures because of the possibility of either damage to the concrete surface or poor membrane formation (in the case of use of curing compounds).

The conventional guidance (ACI 308[31], caption to figure 1) on curing practices during the ICP is that evaporation rates exceeding 1.0 $kg/m^2/h$ are severe enough that protection of concrete surfaces from evaporative water loss should be required, and it cautions that evaporation rates more than 0.5 $kg/m^2/h$ may also result in damaging shrinkage.

These drying rate limits are apparently derived from typical bleeding rates of concrete (Al-Fadhala and Hover, 2001).[32] If evaporation rates of bleed water exceed bleeding rates, then the near-surface zone of the concrete will start to dry and shrink, potentially resulting in plastic shrinkage cracking. Paving mixtures, particularly those used with slip-form paving, tend to have low water contents and high content of fine materials, which tend to reduce the amount of bleeding. It is commonly believed that slip-form paving mixtures do not bleed at all. Therefore, for paving mixtures, it becomes important to know what the bleeding rates are for a particular placement so that critical evaporation conditions can be determined.

ASTM C 232 describes a test method for measuring bleeding in concrete.[69] The conditions of the test are tightly prescribed, which is necessary for comparing mixtures and materials, but this tends to make the method insensitive to details of actual placements. The rate and duration of bleeding depend on the thickness of the placement and to some degree on the nature of the base on which the concrete is placed (some bleed water will drain into a porous base).

A useful field test is a modification of C 232 in which the depth of the specimen is adjusted to simulate the depth of the actual placement.[69] A standard 150 mm by 300-mm mold is useful for this. If the concrete is to be placed on a drainable base, a layer of sand can be placed in the bottom. A more detailed protocol is described in the revised guide (Poole 2005).[5] A time-dependent bleeding pattern can be determined for a concrete mixture.

An approximation of evaporation rates can be anticipated from the weather forecast. From this, an approximation can be made of whether or not a critical situation will develop. Then during placing, the ACI evaporation rates can be estimated with simple testing equipment. Temperature-humidity measuring devices and wind meters can be obtained for modest cost, so that onsite conditions can be determined periodically. Alternatively, evaporation rate can be determined directly by measuring mass loss from an open container of water located near the construction site. If this kind of testing shows that evaporation rates are likely to exceed bleeding rates, then protection measures can be implemented. Use of evaporation reducers is becoming a common practice in paving.

In reviewing State DOT practices, it was found that several States have a maximum time limit of 30 min during the initial curing period that the concrete can be left in an unprotected condition. This limit was discussed with a paving engineer who has had some experience with plastic shrinkage cracking in a California desert situation. The engineer thought such a limit might have been adequate to prevent the cracking he had observed.

There is not much information on which to base the length of such a limit, other than perhaps such practical experience. Plastic shrinkage cracking is such a multivariable problem that it is very difficult to develop simple guidance on length of exposure. However, some hypothetical calculations can provide at least an approximate frame of reference.

Holt (2000) published a water-loss versus shrinkage curve and a tensile strain capacity versus time curve that suggests that a water loss of about 1 kg/m^2 during the initial curing period might be sufficient to cause cracking in the concrete under investigation.(70) Thus at evaporation rates of 1 to 2 kg/m^2/h, which is relatively high, evaporation would exceed the 1 kg/m^2 limit in 30 to 60 min. However, as shown above, paving mixtures are likely to have a low bleed rate, perhaps averaging considerably less than these values. A laboratory investigation of bleed rates of paving mixtures is reported in chapter 5.

NOMOGRAPH

The "estimated evaporation rate" used in much guidance is usually a calculation based on the ACI nomograph found in ACI 308.(31) The nomograph only represents the evaporation rate of a free-water surface, such as exists with bleed water on the surface of concrete, and does not represent evaporation of water from fresh or hardened concrete when the free-water surface disappears below the exposed surface of the concrete. Representing this process in form of an equation allows development of practical software tools for translating site conditions to evaporation rates. The nomograph was translated into a calculation formula using Menzel's equation, which is the basis of the nomograph. The equation was found in the literature in non-SI (International System) units and the conversion to SI units is not obvious, therefore it is presented here in non-SI units (the final form of the equation later in this section is in SI units).

$$\mathrm{ER} = 0.0415(\mathrm{e_o} - \mathrm{e_a})(0.253 + 0.215\mathrm{V}) \qquad (1)$$

where,

ER is the estimated evaporation rate (lb/ft^2/h),
e_o is the vapor pressure of water at the evaporating surface (psi),
e_a is the vapor pressure of water is air (psi), and
V is the wind velocity (mph).

Vapor pressure of water in air varies with temperature, so that these components of the equation can be replaced by the vapor pressure/temperature relationship, which was determined by fitting an exponential curve to handbook data. The resulting equation is as follows:

$$ER = 4.88\{0.1113 + 0.04224(WS/0.447)\}(0.0443)(e^{0.0302(CT \cdot 1.8)+32}) - (RH/100)(e^{0.0302(AT \cdot 1.8)+32}) \quad (2)$$

where,

ER is evaporation rate ($kg/m^2/h$)
WS is the windspeed meters per second (m/s),
CT is concrete temperature (^oC),
AT is air temperature (^oC), and
RH is relative humidity (%).

This calculation assumes that the concrete temperature represents the temperature at the evaporating surface. Since this is not strictly true because of the surface cooling that occurs during evaporation, it seems that a direct measurement of the concrete surface temperature would be the best value to use in the calculation.

EFFECT OF TEMPERATURE ON TIME OF SETTING

Exponential functions have been found to well represent the effect of temperature on chemical reactions. The well-known Arrhenius equation, which forms the basis for the maturity method, is an example. The effect of temperature on time of setting should also be approximated by such a relationship. The following function has a form similar to the Arrhenius equation and will be inserted into the guide.

$$TOS = TOS_{Labtemp} \cdot e^{K\left(\frac{1}{CT} - \frac{1}{LabTemp}\right)} \quad (3)$$

where,

TOS is the time of initial setting (h) under field conditions,
$TOS_{stdtemp}$ is the time of initial setting (h) under standard laboratory temperatures,
CT is the concrete temperature in the field placement (K), and
LabTemp is the temperature of the laboratory test (K).
K is a constant that varies with the cementitious materials, commonly called the activation energy.

A value of the constant *K* of 5000 Kelvins has been found to be a good default value for cementitious systems in general.

Time of setting is typically measured on concrete using ASTM C 403 at laboratory temperatures of about 23 °C, but this can actually be any temperature.[71] In field conditions, concrete temperatures are usually allowed to vary between approximately 10 and 35 °C, so in place time of setting could vary significantly from the laboratory-determined value.

This equation was evaluated using data from several publications that describe the effects of temperature on time of setting. The data were presented graphically in these publications, so numbers used in this analysis were taken off of the graphs. The data in these publications represent time of setting under three similar temperature conditions: 10–15 °C, 23–25 °C, and 35–38 °C. The time of setting at the 23–25 °C condition was taken as the standard determination, and time of setting at the colder and hotter conditions was calculated using the above equation. Table 1 summarizes the data, the observed time of setting, and the time of setting predicted using this equation. A value of K of 5000 K was first used. A value of 4500 K was found to give a better fit of the data.

Table 1. Time of setting data, predicted and observed conditions.

Source of Data	TOS, standard conditions, hours	T_{std} (°C)	T_x (°C)	Predicted TOS, hours	Observed TOS, hours	Error, predicted–observed (% relative to observation)
Pinto and Hover (2000)[72]	3.5	25	15 33	5.9 2.4	6.0 2.5	−0.1 (−1.7) −0.1 (−4.0)
Pinto and Hover (2000)[72]	2.5	25	15 33	4.2 1.7	4.5 1.6	−0.3 (−6.7) −0.3 (−19)
Pinto and Hover (2000)[72]	5.5	25	15 33	9.3 3.7	9.2 3.5	−0.1 (−1.1) −0.2 (−5.7)
Mehta and Moneiro (1993), figure 10-10A[73]	4.2	23	10	8.4	8.0	−0.4 (−5.0)
Mehta and Moneiro (1993), figure 10-10B[73]	6.0	23	33	3.7	4.2	−0.5 (−12)
ACI 305R[12], figure 2.5.2	8.7	24	38 10	4.4 18.4	4.8 19.9	−0.4 (−8.3) −1.5 (−7.5)
ACI 305R[12], figure 2.5.2	12.4	24	38 10	6.3 26.2	6.5 26.2	−0.5 (−7.6) 0 (0)
ACI 305R[12], figure 2.5.2	10.0	24	38 10	5.1 21.2	7.0 19.8	−1.9 (−27) 1.4 (7.0)

The average error is −0.1 h (−4.1 percent) for the low-temperature conditions and 0.6 h (−11 percent) for the high temperature predictions.

CURING COMPOUNDS

Product literature on curing compounds from many suppliers presents a large diversity of products. On first reading there seems to be quite a lot of overlap in properties among the various produces offered by each manufacturer. Quite naturally manufacturer's product literature lists all of the positive features of the material, so that the differences among the individual products tend to get lost in the long list of common features. The following is a reasonably complete list of properties and options. Combining the properties would result in hundreds of different products.

a. *Type 1 versus 2*. Type 1 materials are clear and used for architectural applications. Type 2 materials are white pigmented for use in hot weather or where the white pigment can assist in evaluating application quality. Type 1 may be supplied with a fugitive dye to assist in assessing application. The dye fades within a week of exposure to sunlight. Paving applications normally require Type 2.

b. *Class A versus B*. Class A is unrestricted, active ingredients often being wax-based or a linseed oil-based material because of cost. The active ingredient of Class B materials are resins. These are usually held by the manufacturer to be a somewhat higher performance class of materials and may be more expensive than Class A. There have been no implications that Class B materials do not meet the stated water retention requirements, but they may be messy to work with. Both Class A and B are normally allowed in paving.

c. *Water Retention*. Water retention (ASTM C 156) levels are set by various specifications.[18] There are two different ASTM specifications (one of which is duplicated as an AASHTO specification) each with a different water retention requirement, the USACE has a different requirement for airfield paving, and State DOTs often have individual requirements. A large part of the diversity in product offerings is attributable to the variation in user's performance requirements for this property.

d. *Drying Time*. Drying time requirements in ASTM and AASHTO specifications are constant at ≤4 h, but there is variation among agency specifications. Some agencies require 30 min or less. This property also contributes to product diversity.

e. *Compatibility With Coatings*. Many curing compounds serve as effective bond breakers with materials applied over them, such as paints and adhesives.

f. *Dissipating versus Nondissipating Curing Compounds*. For some applications, it is necessary that the curing compound be removed. Dissipating curing compounds tend to break up and flake off when exposed to sunlight for a few days. Non-dissipating curing compounds are durable to the effects of sunlight.

g. *VOC Compliance*. Recent U.S. Environmental Protection Agency regulations require that some types of construction use low VOC materials, defined as less than 350 grams per liter (g/L) of volatile compounds. This requirement is often used in specification for indoor concreting where accumulation of volatile organics can present a health hazard. Other applications are not restricted.

h. *Vertical Surfaces*. Application to vertical surfaces requires that the viscosity of the compound be high enough to prevent it from sagging when applied to vertical surfaces at the recommended dosage. This property may also be important for curing deeply textured horizontal surfaces. These materials are likely to be of a higher viscosity than those designed for application to horizontal surfaces, and may not be suitable for spray-on application with the same equipment normally used in paving.

i. *Special Properties*. Some curing compounds are advertised to possess other special properties, such as acting as sealers after the curing period is over.

Application rates and practices vary considerably among agencies. Application rates vary from about 2.5 m^2/L to about 6 m^2/L. Some agencies require application in two coats or power spray equipment—even giving details on the pressures required, type of spraying patterns, type of agitation equipment, etc. These are detailed in Volume I.[5]

TINED SURFACES

Grooving and tining have the effect of increasing the surface area of the concrete beyond the simple surface area calculated from the length and width measurements of the structure. The amount of the increase depends on the grooving pattern. On simple analysis, it would appear that the application rate of curing compounds to ungrooved pavements should be increased in proportion to the increase in surface area caused by the grooving, as represented by the following equation:

$$\text{Appl Rate (grooved pavements)} = \text{Appl Rate (nongrooved)} \times \frac{\text{simple surface area}}{\text{grooved surface area}} \tag{4}$$

The grooved surface area is calculated from the distance between grooves and the width and depth of the grooves. This equation was put into the guide as a planning tool. It was evaluated using data from Shariat and Pant (1984).[74]

Shariat and Pant[74] showed that moisture loss for a grooved specimen tested according to ASTM C 156[18] increased in proportion to the extra surface area created by the grooving. In their tests, surface area of the grooved to the nongrooved surface increased by a factor ranging from 128 to 145 percent. In another part of the study, they investigated the relationship between curing compound application rate and water retention of grooved specimens in which the grooved surface to nongrooved surface-area ratio was 1.35 (0.74 inverted, as expressed in the above equation). There was a fairly large scatter in these data, but on the average, the amount of curing compound needed to achieve the water retention of the grooved mortar was 3.9 m^2/L. The application rate to the non-grooved mortar was 5.0 m^2/L. The above calculation would result in a calculated application rate of 3.7 m^2/L, indicating that the calculation correctly accounts for the increased surface area.

EVAPORATION REDUCERS

Little information was found on evaporation reducers (now the preferred terminology—also sometimes called evaporation retarders) except for manufacturer's information sheets. There are currently no specifications for these products.

Holt (2000) included one such product in an investigation of plastic shrinkage cracking and showed significant benefit.[70] At least one manufacturer claims an 80 percent reduction in evaporation rates. Laboratory work performed in conjunction with this investigation showed about a 50 percent reduction.

The action principle of these products is that they form an oil-like film on the surface of the concrete or bleed water, which then physically retards the rate that water molecules can evaporate. The active ingredient is polyvinyl alcohol.

Application rates are about 5 m^2/L, the same as for curing compound. Given that most of the carrier is water, this liquid provides something of a buffer from evaporation for a few minutes to an hour or more, depending on the drying conditions, independently of the action of the alcohol film.

EFFECTIVENESS OF WATER-ADDED CURING IN LOW WATER-CEMENT RATIO CONCRETE

It is recognized that low water-cement ratio concrete can consume all of its mixing water in hydration, creating the potential for autogenous shrinkage cracking and that added water during curing should be an effective tool for preventing this. However, the caution often expressed is that water does not effectively penetrate low water-cement ratio concrete. Some additional literature was found on this subject that can be used as at least a partial evaluation of this subject.

The continuity among pores and with the surface of concrete tends to decrease rapidly in low water-cement ratio concretes, so that introducing appreciable water into the concrete may be difficult (Meeks and Carino, 1999[(4)]; Cather, 1994[(75)]). The onset of capillary discontinuity varies with water-cement ratio. Table 2 gives times to capillary discontinuity from three different references. The numbers are similar but not in exact agreement.

Table 2. Curing time to capillary discontinuity.

Water-Cement Ratio	Powers and Brownyard (1946–47)[(76)]	Van der Molen (1979)[(77)]	Mindess and Young (1981)[(78)]
0.40	3 days	2 days	3 days
0.45	7 days	3 days	7 days
0.50	14 days	7 days	28 days
0.60	6 months	3 months	6 months
0.70	1 year	9 months	1 year
0.80	Never	>1 year	Never
>0.80		Never	

For purposes of curing concrete pavements, the important point is that capillary discontinuity of 0.40 water-cement ratio concrete develops in 2 to 3 days and that any attempt to introduce water into the concrete through wet curing methods will decrease sharply in efficiency after this time. It is not uncommon in modern slip form concrete mixtures (and bridge deck concretes) for water cement ratio to be below 0.40 and as low as about 0.35. The information cited above was apparently assembled before such concretes were as common in practice.

TEST METHODS FOR DETERMINING AMOUNT OF CURING COMPOUND APPLICATION

Several methods for estimating the application rate of in place curing compound, after the fact, were mentioned in the interim report. These included indirect methods based on flow rates through the spray nozzles along with rate of movement of the curing machine, infrared images of the pavement, direct measurement with sampling coupons, and visual estimation. Another potential method is reflectance.

The Minnesota DOT wrote a rather extensive report on curing compound application along with the method of estimation based on flow rates.(79) This has been extracted in parts and put into the guide. Some data on the infrared approach was developed and that method rejected as being too sensitive to a number of variables to be of practical use. These data are presented in chapter 5. Methods for direct measurement with sampling coupons for use of visual estimation and for use of reflectance have been developed and put into the guide.

LENGTH OF CURING

Fixed time interval curing specifications tend to oversimplify the problem. Development rates of the physical properties of concrete vary widely, depending on materials, proportions, and temperature. The advantage of fixed time interval requirements is that interpretation and enforcement are relatively simple. Because specifications tend to oversimplify the problem, they are somewhat conservative. Project specifications should allow more complicated, performance-based requirements as an option.

The prescriptive approach to specifying length of required curing has been largely based on strength-gain rates of the cements used to make the concrete. AASHTO guidance is that curing should be at least 3 days at temperatures 10 °C and above. No mention is made of the effects of pozzolan or slag. ACI guidance varies, but approximately converges on 7 days for concrete containing Type I (or equivalent, presumably), and 14 days for Type II, also at temperatures ≥10 °C. The latter guidance was developed in a time when Type II cement actually gained strength slower than Type I cement. In general, this is no longer true. The ACI guidance is also silent on pozzolans and slag. Most of States surveyed reported prescriptive curing times of 3 days. A smaller number reported 7 days, and a few reported 4 days.

The AASHTO guidance may be based on development of flexural strength and on the nature of paving concrete mixtures. Paving mixtures are typically proportioned with relatively high cement contents and relatively low water-cement ratios. As a result, 3-day strengths are relatively higher than at the same age when using leaner, higher water-cement ratio concretes. Also, one set of USACE data showed that flexural strength in airfield paving mixtures developed even faster than compressive strength. A discussion of these data is presented in chapter 5.

Three days is probably adequate time for most paving mixtures to develop strength sufficient for service when temperatures are around 20 °C or higher. However, rates at 10 ^{o}C may be only about half this rate and it appears that additional time would be of benefit. Perhaps an approach similar to that used in the UK(7) would be appropriate. This guidance bases lengths of curing required on maturity concepts, resulting in a set of curing times that graduate upwards as temperatures drop. Such an approach will be developed for this project.

On the question of rate of development of durability properties in the near-surface zone of the concrete, examination of the literature suggests that these properties develop at about the same rate as compressive strength development. The length of curing for mixtures containing pozzolan or slag seems to converge on 7–10 days at about 20 °C.

TEST METHODS FOR DETERMINING EFFICIENCY OF CURING OF THE NEAR-SURFACE ZONE

As mentioned in the preliminary report, strength is a good measure of the overall state of curing of concrete, but does not represent well the effects of moisture loss in the near-surface zone, usually thought to be about 50 mm thick. A wide variety of test methods have been developed for determining the degree of physical property development in the near-surface zone as a result of curing. Many of these require specialized equipment and are not easily applied in the field due to lack of control of moisture content of the concrete. Several were thought to be plausible and some work was done to check this plausibility.

Ultrasonic Pulse Velocity (UPV). UPV has been reported to be useful as a field tool for measuring strength development. One drawback is that the measurement path does not appear to be necessarily confined to the near-surface zone of the concrete, which is the zone of interest. A simple evaluation of this concept is described in chapter 5.

Rebound Hammer. The rebound hammer (ASTM C 805) is often criticized as an unreliable method for measuring strength development in concrete because of its sensitivity to surface irregularities.[79] However, some preliminary work suggested that rebound numbers could possibly reflect differences in curing. An evaluation of this method is described in chapter 5.

Water Absorption. Water absorption has been demonstrated as a good method for distinguishing degree of curing in mortars. It was the basis of ASTM C 1151 for evaluating curing compounds.[27] It has since been withdrawn for lack of use in the curing compound industry, but in principle it may still be a useful method, although there is some uncertainty about its use in concrete. It is one of the methods sensitive to the moisture content of the concrete; hence, it is difficult to apply in the field. However, it can be easily applied to cores without elaborate gear and since coring is such a common way to obtain samples to evaluate field concrete. An evaluation of this approach is described in chapter 5.

Abrasion Resistance. Abrasion resistance is the basis for another test method basis that is often mentioned in the literature as being heavily dependent on degree of curing. The effect of poor curing on the abrasion resistance of lab specimens is fairly obvious when simple nonquantitative approaches like scratching or grinding the surface are employed. Past experience in USACE has shown that putting this on a quantitative basis reproducible among laboratories would not be straightforward. Therefore, this method was not pursued further.

Chemically Combined Water. Measuring the amount of chemically combined water is one of the oldest methods for measuring the amount of hydration in cement pastes. It is not field applicable, but like water absorption, it can be executed on cores. Preliminary work suggested that the method might be more sensitive to details when applied to concrete, given the relatively small amount of cement in concrete and the relatively small amount of water consumed in early hydration reactions. Consequently, this method was not pursued further.

CRITICALITY OF THERMAL GRADIENT (SHORT-TERM THERMAL SHOCK)

Guidance exists and is cited in the guide on limits to temperature gradients that can develop between the surface of concrete and the interior due to rapid cooling of the surface, either by evaporation or by application of cold curing water. Additional guidance will be developed on the level of evaporation expected to result in sufficient cooling that these limits might exceed.

CHAPTER 5: ADDITIONAL INVESTIGATIONS

A number of places in the draft guide present information for which there seems to be some uncertainty as to the applicability or sensitivity to concrete pavements. The following sections identify several of these and present information derived either from literature sources and/or from laboratory work that provide additional information.

BLEEDING RATE—EVAPORATION RATE RELATIONSHIP.

The relationship between bleeding rate of freshly placed concrete and the evaporation of water from concrete during the first few hours after placing is critical in the initial curing period to avoid early-aged cracking. The conventional understanding is that when the evaporation rate exceeds the bleeding rate in fresh concrete, a dangerous condition exists that could lead to plastic shrinkage cracking. The most commonly used guidance for general concreting is that when evaporation rates exceed 1.0 kg/m^2/h, as determined from the nomograph in figure 1 of ACI 308(31) (and in many other places), definite action to retard evaporation is necessary. An evaporation condition of 0.5 kg/m^2/h warrants caution. There appears to be uncertainty in how this same guidance applies to pavement concrete.

Two things need to be evaluated in this section. One is to evaluate how well the ACI nomograph predicts the evaporation rates of bleed water from concrete. The other is to evaluate the bleeding rate of pavement concretes to determine whether the current guidance is still reasonable.

The approach is to use some recent literature that has been developed on the evaporation rate calculation, along with some laboratory work that measures evaporation rates of water from concrete at various stages of maturation from initial casting to some hours after time of setting. This will allow definition of the limits of the nomograph calculation. Bleeding rates of pavement concrete are investigated with laboratory specimens.

Evaluation of the ACI Nomograph

Al-Fadhala and Hover (2001) present a comprehensive review of the origin of the ACI nomograph and conducted a rather involved investigation of the accuracy with which it represents evaporation rates from concrete.(32) The calculation is intended only to represent the evaporation rate of water from a free-water surface, so would only be expected to apply to the bleed water of concrete, and not to represent evaporation of water from within the mass of the concrete.

In Al-Fadhala and Hover's(32) investigation, the nomograph was found to accurately represent the evaporation rate from a free-water surface for evaporation rates up to about 0.5 kg/m^2/h. Above this point, the nomograph tended to overestimate the rates of evaporation. For example, at observed evaporation rates of about 1.8 kg/m^2/h, which was the upper extreme of their investigation, the nomograph overpredicted evaporation by about 50 percent. The authors offered a revised equation to represent the phenomenon, based on an empirical fit of the data.

$$ER = 0.0565(e_o - e_a) + 0.0485V - 0.305 \tag{5}$$

Variables are defined as in the description of Menzel's equation in chapter 4. The authors comment that neither calculation is particularly reliable when windspeeds drop below 5 m/s.

Analysis of Menzel's equation by calculating and comparing evaporation rates for some trial conditions shows that two variables dominate: wind velocity and concrete temperature. The calculated evaporation rates are relatively less sensitive to changes in air temperature and relative humidity. This would suggest that control of plastic shrinkage cracking should focus around control of concrete placing temperatures and avoiding or protecting against the effects of wind.

An effort was also made to verify the nomograph in this project. Evaporation of pure water and of bleed water from concrete and mortar were measured under variable conditions.

Evaporation rates of pure water were measured from two different container types. One was an evaporation cup specified in ASTM C 156.(18) These are aluminum cups covered with a disc of filter paper and secured by a threaded ring, similar to the configuration of a Mason jar. The cup is filled with cotton balls and partially filled with water. The cotton balls provide a wicking action that keeps the filter paper wet. Evaporation actually occurs from the wet filter paper surface. The surface area of the cup is relatively small, 0.0045 m^2. The other device was a somewhat larger (surface area of 0.014 m^2) plastic dish half full of water. In this configuration, water was evaporated directly from the water surface.

Experimental conditions were either room temperature (22 °C, 50 percent RH) or a walk-in environmental room (38 °C, 30 percent RH). The windspeed was varied from 0 to 3 m/s. Surface temperature measurements were determined with an infrared thermometer.

Work was done with the C 156(18) evaporation cups in the 38 °C room only. The measured rate of mass loss when air was directed onto the surface at 3 m/s was 2.2 kg/m^2/h. The calculated evaporation rate using the nomograph was 0.41 kg/m^2/h. The surface temperature was constant at 26 °C. There has been some commentary on the nomograph that the surface temperature should not be used in the calculation because of the evaporative cooling effect, but instead the temperature of the mass of the container (or the concrete) should be used. The temperature of the interior of the evaporation cup was not measured, but the verification ran about 4 h, so there was ample time for this small device to equilibrate with the ambient temperature. If temperature of the interior the cup was assumed to be 38 °C, then the calculated evaporation rate would have been 1.4 kg/m^2/h, still considerably lower than the observed value.

When the air was directed 355 mm above the evaporating surface at 3 m/s, the observed mass loss was 0.79 kg/m^2/h. Using measured surface temperatures (29 °C), the calculated evaporation rate was 0.62 kg/m^2/h. This wind condition approximates the conditions described in ACI 308R(5) for collecting appropriate data for calculating evaporation rates.

The verification was repeated using the plastic dishes. Determinations were made at both the 22 °C and 38 °C conditions with varying windspeed. The comparison of the observed mass loss and the calculated evaporation rate is shown in figure 10.

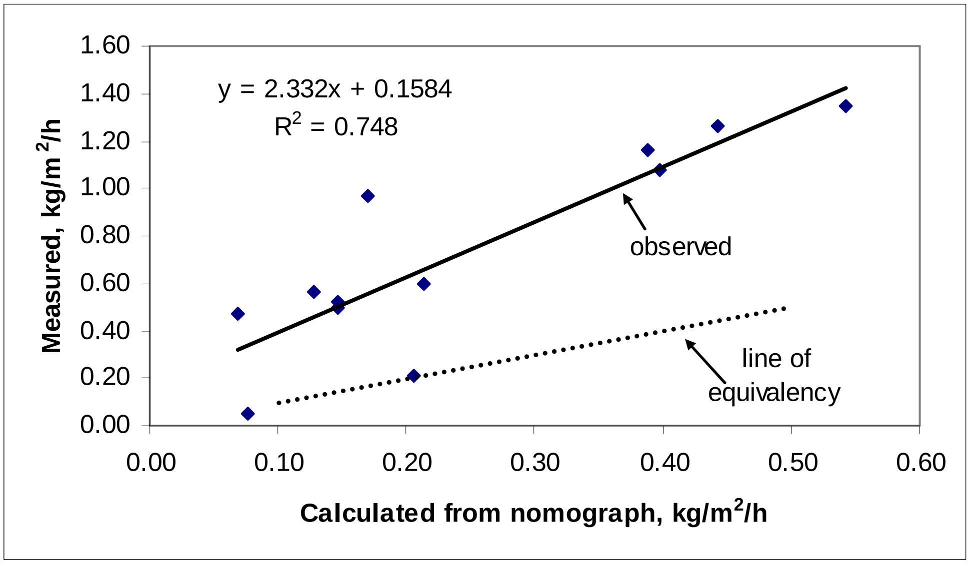


Figure 10. Calculated versus measured evaporation rates.
Wind directly on the free-water surface.

In this experimental setup, temperatures of the water below the surface could be determined and were found to average about 2 °C higher than the surface temperature. Using this value causes the calculated evaporation rate to increase slightly and is the basis for the data shown in figure 10.

The results of this investigation suggest that the actual mass loss of water from a surface may be strongly dependent on the details of the wind flow patterns. Perhaps more than simple evaporation is involved when the wind is blowing directly onto the surface. Aerosol formation potentially becomes a significant mechanism for transport of water away from the surface. In the case of the C 156 evaporation cups, the filter paper surface potentially creates a much higher effective surface area than does a simple free-water interface.(18) This same condition might be analogous to a mortar surface as the bleed water just starts to recede below the surface.

To further investigate this problem, water losses from concrete specimens of known bleed rate were measured. Specimens were made at 23 °C, then immediately put into a 38 °C walk-in room at 30 percent RH, with windspeed 3 m/s blowing directly on the specimen surface. Both surface temperature and concrete temperature at a depth of 25 mm were measured using an embedded thermocouple. The 25-mm temperature ramped up slightly during the course of the test (4–6 h), so calculated evaporation rates using this value varied from 0.34 kg/m^2/h at the start to 0.75 kg/m^2/h at the end. Test specimens were cast either in a 240 by 140 by 75-mm Nalgene® pan or in a 150 mm by 100 mm cylinder mold (150 mm by 300 mm standard strength mold cut down).

Concrete was made with 25 mm nominal maximum sized crushed limestone coarse aggregate (816 kg/m^3), natural sand (544 kg/m^3), Type I portland cement (350 kg/m^3), and a water-cement ratio of 0.37 to 0.45. Air content was about 6 percent and slump about 40 mm (1.5 inch).

Figure 11 shows the mass loss, bleeding rate, and calculated evaporation rates for one of the specimens cast in the Nalgene pan made with a water-cement ratio of 0.45. Note that the bleeding rate and the calculated evaporation rate (using the temperature of the concrete at

25 mm) were very close to the same and averaged 0.5 kg/m^2/h (bleeding rate is not really constant, as will be shown in a later section). Mass loss from the concrete averaged about 4 kg/m^2/h. This indicates that all of the bleed water and then some of the water from the mass of the concrete were being lost.

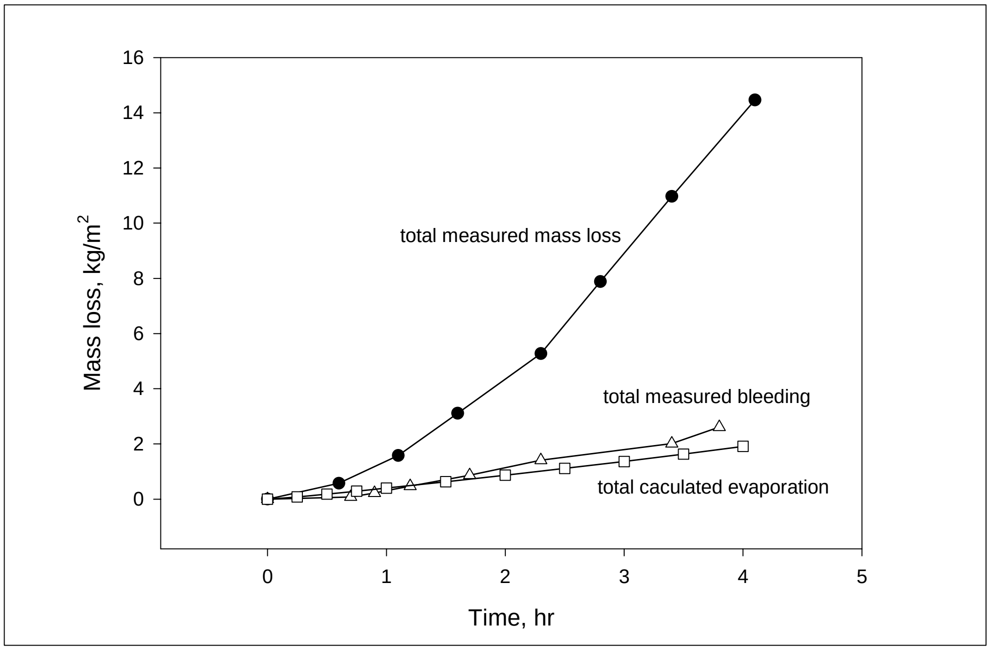


Figure 11. Comparison of total water lost, expected from the ACI 308 nomograph and bleed rate of a 0.45 water-cement concrete.

Figure 12 shows results of another set of determinations on a 0.37 water-cement ratio specimen cast into the 150 by 100 mm molds. Bleeding rate was not measured. The total evaporation rate in this case was less than in the previous one, but still higher than the rate expected from the nomograph.

The measured mass loss on these specimens was lower than in the previous example, but still higher than the calculated evaporation rates from the nomograph. The lower water-cement ratio specimens lost somewhat less water, presumably because of the lower bleeding rate and somewhat tighter microstructure of the fresh paste.

The conclusion to be drawn from this work is that wind blowing directly onto the surface of fresh concrete causes loss of water considerably higher than expected from the nomograph. This condition is not implausible during construction. Under such conditions, water losses of about twice as much as under laminar flow conditions might be expected.

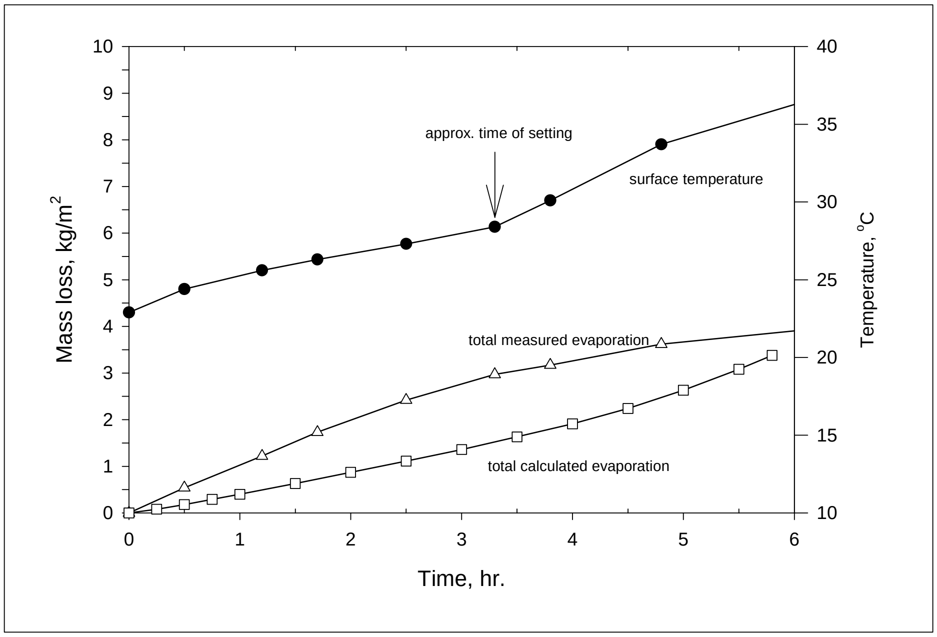


Figure 12. Evaporation of water from a 0.37 water-cement specimen compared with the rate expected from the ACI 308 nomograph. Surface temperature changes approximately track evaporation rates.

Bleeding

It is a common belief that the levels of evaporation that serve as limits in table 1 of ACI 308 are based on past history of typical bleeding rates of concrete.[(31)] Al-Fadhala and Hover (2001)[(32)] have verified this in their review of the literature. Apparently the National Ready Mixed Concrete Association report (NRMCA, 1960) typified bleeding in concrete as ranging from 0.5 to 1.5 kg/m^2/h.[(81)] Paving mixtures tend to be of a lower water-cement ratio than is often used for general concrete construction. Some practitioners have commented that concrete for slip-form paving has little or no bleeding, which would appear make it more vulnerable to evaporative effects.

Figure 13 shows bleeding rate for a typical concrete paving mixture, containing 350 kg/m^3 cement and a water-cement ratio of 0.43. The test specimen was 28-centimeters (cm) thick. Bleeding stopped between 4.5 and 5.0 h. This corresponds approximately to the time of initial setting of this concrete. Average bleeding rate was 0.19 kg/m^2/h, with a peak of 0.33 kg/m^2/h at about 2.5 h after mixing.

Two features are significant about this pattern. First, the average bleeding rate is considerably below the most conservative limit in the ACI guidance of 0.5 kg/m^2/h. Even for a thicker pavement, in which the total bleeding would be expected to be higher, the standard guidance is probably not sufficient. For example, scaling this bleeding rate by simple proportion up to a 45-cm thickness would result in an estimated average bleeding rate of 0.31 kg/m^2/h.

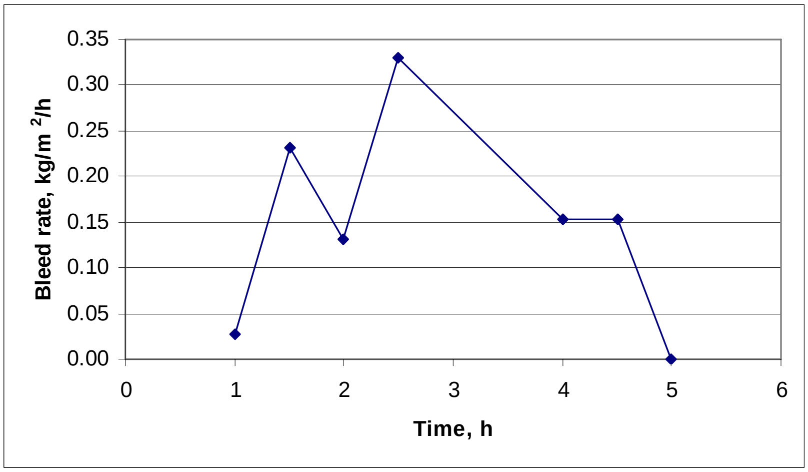


Figure 13. Bleeding pattern of a 0.45 water-cement ratio concrete.

The second significant feature is the extremely low bleeding rates during the first and last part of the bleeding period. During the first hour, the bleeding rate was only 0.025 kg/m^2/h. Bleeding similarly approaches a very low rate as time of setting is approached.

While bleeding rate varies as a result of changes of several concrete mixture properties and properties of concrete materials, water-cement ratio is likely to be a major variable influencing bleeding rate. The effect of this variable was investigated among mixtures ranging from a water-cement ratio of 0.35 to 0.50. Test specimens varied in thickness, so the rates are standardized in terms of a unit thickness of concrete, in centimeters, i.e., kg/m^2/h/cm. Results are shown in figure 14.

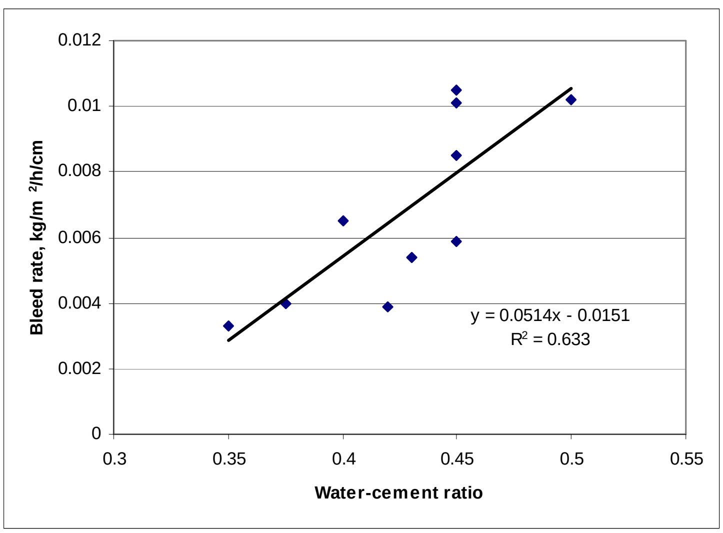


Figure 14. Bleeding rate per unit thickness of concrete (cm) versus water-cement ratio.

The equation in figure 14 is then useful for approximating the average bleeding rate of a given concrete. This number can then be compared to the estimated evaporation rate and a determination made as to the likely danger of cracking due to excessive drying of the concrete. For example, for a 30-cm thick pavement made at a water-cement ratio of 0.45, the estimated average bleeding rate is 0.24 kg/m^2/h. Evaporation rates higher than this will constitute a drying hazard.

The conclusion from these determinations is that bleeding rates of paving mixtures, even at their peak rates, may be less than the warning level of 0.5 $kg/m^2/h$. This, together with the apparent tendency of the nomograph to underestimate rates of water loss under some windy conditions, suggests that the current guidance on deleterious drying conditions may be insufficiently conservative for paving. The results of this limited investigation suggest that water losses from the concrete of as much as two times the calculated evaporation rate could occur, depending on conditions. Evaporation rates of as little as 0.3 $kg/m^2/h$ may cause critical losses from some concrete if not protected, particularly during the few minutes immediately after placing and the time immediately before time of setting when bleeding rates are considerably lower than average.

Whether cracking actually develops during these periods when evaporation exceeds bleeding depends on the tensile strain capacity of the concrete. Freshly placed concrete of a modest water-cement ratio has a very high tensile strain capacity, so that its reaction to shrinkage strains is largely to settle into a thinner placement. Slip form concrete is a stiffer mixture and may present a much lower tensile strain capacity, so that shrinkage cracks may be more likely to develop soon after placement than in more plastic concrete. However this is conjecture at this point. Just before time of initial setting, concrete has a much lower tensile strain capacity and is quite sensitive to shrinkage-strain cracking.

A reasonable practical approach would be to determine the bleeding rate of the concrete on a particular project. This can be done relatively simply on site as part of preplacing activity. Then use that data to determine deleterious evaporation rates from nomograph calculations. If windspeeds are over about 2 m/s, then an extra level of caution is required. During placing, if surface sheen disappears within the first hour, or before final curing is applied, then that would be taken as evidence that water losses are excessively high. The preplacing determinations and estimation of potential evaporation rates using the nomograph are useful in cautioning the field crews as to the likelihood of a deleterious condition developing.

Evaporation from Hardened Mortar

Time of setting was found to have a significant effect on losses of water from concrete. Presetting loss rates were measured as high as 2–4 $kg/m^2/h$ even though very little of this is bleed water, apparently even some of the pore water is still reasonably evaporable. Evaporation rates from specimens covered for various periods then exposed to evaporative conditions showed that evaporation rates dropped dramatically after time of setting. Some results are shown in table 3, in which different evaporation conditions were created by windspeed, air temperature, and relative humidity. The evaporations rates from these specimens were always higher immediately after uncovering the specimen surface than after 1 to 2 h of drying. Evaporation at just 1 hour after time of setting was still strongly affected by wind. This effect was reduced as the mortar aged, which would be expected by the continued consumption of mixing water by hydration reactions.

Table 3. Evaporation rates (kg/m2/h) from hardened mortar (C 109).[82]

Mortar 5 h old (time of setting ~ 4 h)			
Initial exposure to drying		**> 1 hour drying**	
Nomograph	Measured	Nomograph	Measured
0.12 0.50 0.30	0.13 1.10* 0.70*	0.12 0.39 0.35	0.13 0.74* 0.60*
Mortar 24 h old			
Initial exposure to drying		**>2 h drying**	
Nomograph	Measured	Nomograph	Measured
0.10 0.65 0.46	0.12 0.28* 0.16*	0.10 0.65 0.46	0.05 0.10* 0.06*
Mortar 4 days old			
Initial exposure to drying		**>2.5 h drying**	
Nomograph	Measured	Nomograph	Measured
0.19 0.90 0.61	0.05 0.08* 0.05*	0.19 1.25 0.61	0.02 0.05* 0.03*
*windspeed 2–3.5 m/s directed onto the specimen surface.			

The sharp reduction in water loss after time of initial setting can be understood by observing time of setting specimens (ASTM C 403).[71] If specimens are formed and covered to prevent evaporation, then the time of setting apparatus leaves a hole in the concrete after it has stiffened enough to hold its shape. Before time of setting, the hole will fill with bleed water. The water level will remain relatively stable leading up to time of setting if no evaporation is allowed. As the concrete starts to show the higher penetration resistance typical of incipient setting, the water level drops rapidly, and the holes are found to be essentially empty soon after setting. This also corresponds to a rapid loss of sheen on the surface of the concrete.

Measurements of the heat of hydration show that this time corresponds with the onset of rapid hydration of the C_3S in the cement. As a result, there is considerably less free mixing water in the concrete that can move to the surface of the concrete and evaporate.

Concrete continues to be susceptible to shrinkage cracks (now called drying shrinkage cracks as opposed to plastic shrinkage cracks that form in plastic concrete) after time of setting, so it is important to start final curing measures as soon as possible after initial time of setting.

EFFECTIVENESS OF EVAPORATION REDUCERS

Evaporation reducers are marketed as a product that can be of substantial benefit to reducing evaporation from fresh concrete when evaporation rates are high enough to cause concern that plastic shrinkage cracking could develop. On informal inquiry of some users, there seems to be some concern about whether or not these products are useful. There is currently no specification or test method for evaluating them, and no literature could be found on their evaluation. Other users were quite confident of their value, though no data were available.

Three evaporation reducers were investigated in a limited testing program. These are represented by serial numbers 010147, 010149, and 030019. Mortars were prepared according to ASTM C 156.[18] Evaporation reducers were applied at the manufacturer's recommended rate (5 m^2/L) immediately after molding, and the specimens were put into a walk-in environmental room at 38 ^{o}C, 30 percent relative humidity, with a fan directed on the surface at a speed of 3 m/s. Specimens were weighed periodically and evaporation rates calculated. Control specimens had no evaporation reducer applied. The test was run for 2.5 h. Table 4 presents the results.

Table 4. Effect of evaporation reducers on evaporation of bleed water from mortar specimens.

Evaporation Reducer	Mass loss, kg/m^2/h		% Reduction
	With Evaporation Reducer	Control	
010147	0.58	0.75	23
010149	0.49	0.88	44
030019	0.42	1.19	65

From this limited investigation, it appears as though protecting concrete during the period between placing and applying final curing using evaporation reducers might require repeated applications, depending on conditions. This would particularly apply if the time of initial setting was several hours after placement. A plausible practice would be to use evaporation reducers as a protection against excessive drying, but to repeat applications whenever sheen disappears prior to time of initial setting.

Test methods and a specification for evaporation reducers need to be developed. The limited test results presented above suggest wide variation in performance among products. These products are in common use and potentially have an important role to play in preventing early drying problems.

TIME OF CURING COMPOUND APPLICATION

Existing guidance on time of application of curing compounds cautions against several scenarios that negatively impact the performance of curing compounds. It is not clear that these cautions are relevant to paving concrete or to the newly developed low-VOC curing compounds that are the new standard material used in highway paving. The approach to investigating this issue will be to review current practices in highway paving, then to execute lab work in which curing compounds are applied at different times and under different conditions to test specimens of laboratory concrete.

Manufacturer's guidance and standard guidance all direct that curing compounds be applied to a concrete surface when sheen has disappeared. Most State DOT guidance reflects this, although a few DOTs direct that curing compound be added while there is still some sheen present. ACI 308 distinguishes between disappearance of sheen that results when bleeding stops and the bleed water evaporates, and the apparent loss of sheen that occurs before bleeding stops under conditions in which evaporation rate exceeds bleeding rate.[31]

ACI 308 describes the consequences of applying curing compound at first point of apparent loss of sheen due to high evaporation rates.[31] The curing compound is described as forming a bond with the surface of the specimen, then when additional bleed water rises to the surface, it causes a delamination of a thin layer of surface mortar.

During this investigation, a USACE pavement was investigated that may have represented a case of delamination from early application of curing compound. The pavement was placed during strong drying conditions (not measured, but quite windy). Curing compound was applied within about 15 min of placing due to concern for development of plastic shrinkage cracks. A solvent based (not VOC compliant) curing compound was used. About 3 months later, the pavement had developed some small areas of delamination of a thin layer of surface mortar. Spalled areas were about 15–25 mm across. Petrographic examination showed the damage to be larger than the spalled areas, apparently caused by cracks that had developed parallel to the surface at a depth of about 1–2 mm (See figure 15).

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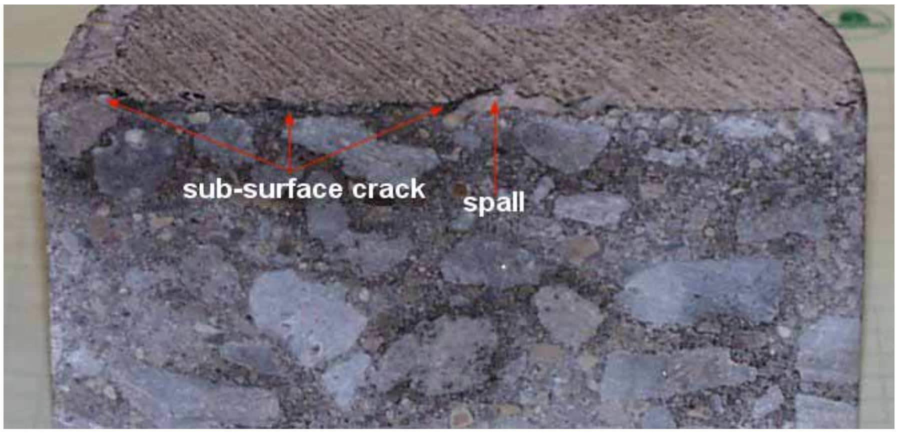

Figure 15. Development of spall as a result of early application of curing compound.

As discussed above, bleeding starts within a few minutes to an hour after concrete is placed and is terminated by the time of setting. Depending on the materials and mixture proportions, some concrete may cease bleeding before this. But, being at least approximately tied to time of setting, loss of sheen may not occur for 2–4 h or more. Therefore, strict adherence to the standard guidance could result in considerable delay to work schedules and decreased productivity. In interviews with paving engineers it was found that it is common practice to apply curing compound sooner than the probable time of setting. In some cases it is common practice under strong drying conditions to apply curing compound as soon as is practical after the paving machine passes.

The work involved six low-VOC curing compounds. One was a wax-based, one was a polyalphamethyl styrene based material, and four were described in product literature as being resins based. Some additional information is summarized in table 5.

Table 5. Curing compound information.

Curing Compound (USACE ID No.)	Description	Moisture loss (ASTM C 156[18]) kg/m^2 at 72 h
CMB 000134	low VOC, wax, 12% solids	0.50
CMB 000135	low VOC, resin, 12% solids	0.49
CMB 000182	low VOC, resin, 28% solids	0.34
CMB 010021	low VOC, resin, 16% solids	0.09
CMB 010150	low VOC, polyalpha methylstyrene, 40% solids	0.63

The test conditions varied some as the work progressed and new things were learned about this process, but test protocols fell into five categories, as described below. Details are annotated with the test results (tables 11–16).

1. Half of the curing compound was applied immediately after forming the specimen, then the other half applied 1.5 to 3 h later. The specimen was left in a 38 °C, 30 percent RH room with a windspeed of 4 m/s during this time and for the subsequent curing time (to 7 days).

2. The entire curing compound dose applied was after 1.5–2.0 h of exposure to the above conditions. This was before the time of setting, but at a time when other experiments showed that almost all of the potential bleed water had been evaporated. In these experiments, there was no obvious appearance of bleed water after application of curing compound, suggesting this assumption was valid.

3. Specimens were covered for most or all of the period before time of setting. In some, bleed water was poured off periodically during this period. In others, bleed water was allowed to re-absorb. Following this, curing compound was applied.

4. In a number of experiments curing compound was not applied at all or was applied after 24 h exposure.

5. Some tests were also run in which the top surface was cured by closing the specimen to water losses with a tight-fitting plastic sheet.

Evaporation conditions, as calculated from the ACI nomograph ranged from about 0.34–0.56 $kg/m^2/h$ during the first 4 h after placing in the 38 °C environmental chamber. Measured specimen surface temperatures were used in the evaporation rate calculation. During this time, concrete surface temperatures increased slowly from the temperature at fabrication due to the cooling effects of evaporation (25 °C at fabrication to about 30 °C at time of setting). After time of setting, concrete temperatures quickly rose to approximately equal to air temperatures, which resulted in a calculated evaporation rate of 1.24 $kg/m^2/h$.

Three properties were measured to determine the effects of application protocols. One was water loss as indicated by mass change. The second property was water absorption. The water absorption test was patterned after ASTM C 1151 (now withdrawn).[27] The rationale was that if membrane formation was negatively impacted, then the effects of a higher water loss rate in the period after time of setting would appear as a poorly hydrated zone of paste in the top several millimeters of the concrete. The third test was the rebound number (ASTM C 805).[80] The results of this test were found to reflect the development of surface hardness.

Test specimens were cast in 240 by 40 mm by 75-mm Nalgene pans. A paving-type concrete containing 350 kg/m^3 of portland cement and a water-cement ratio of 0.45 was used. Time of setting was determined to be 3.9 h at 23 °C. Sheen disappeared from this concrete within about 10 min of the time of setting of a covered specimen. Mass change was measured approximately every 30 min until time of setting, then at a greater intervals with increasing time.

The surfaces were prepared for measuring water absorption and rebound number by brushing with a wire brush to remove any curing compound and any loose material. Both the top and bottom of the specimen were brushed, even though the bottom contained no curing compound. Specimens that were obviously poorly cured tended to lose some surface paste in this process, which probably made the surface absorption appear to be a little better than would have been observed if this could have been prevented. The bottom surface of the specimen was used to indicate the quality of a well-cured surface (this assumed that water losses at the 75-mm depth were minimal).

No delamination of surface mortar was observed. The effect of bleed water developing under the curing compound that was applied before bleeding stopped was (1) to cause a poorly formed membrane containing tears and (2) cracking that appeared to result from shrinkage.

Figure 16. Cracked curing membrane resulting from application before cessation of bleeding.

Plausibly, formation of bleed water under a freshly applied coat of low-VOC curing compound acts as a diluent. Manufacturers commonly caution against diluting curing compound because it might interfere with proper membrane formation. Figure 16 shows development of cracks in a curing membrane that has been applied before bleeding had stopped.

Other details resulting from applying curing compound very early seemed to vary among curing compounds. One curing compound was observed to form a relatively strong membrane that floated on the surface of the bleed water and cracked only when the specimen finally dried. Another effect of early application is that a substantial amount of liquid accumulates on the surface of the concrete. Application of curing compound at a rate of 5 m^2/L results in addition of liquid to the surface of concrete of 0.2 kg/m^2. If bleed water then appears at a rate of 0.3 kg/m^2 in a relatively short interval, which is plausible, then the sum of these two volumes of liquid makes for a substantial amount of liquid on the surface of the concrete, which will be of low viscosity and subject to running or blowing around by the wind.

Water-loss data, water absorption data and rebound number data for the top and bottom surfaces of test specimens treated at various times with the various curing compounds are summarized in tables 6–11. Water-loss data were divided into loss before final curing treatments were completed and water loss between the time of final curing treatments and 7 days. These data are a little confusing, but some patterns do emerge on careful examination.

Water lost before curing treatments were complete would impact the possibility of plastic shrinkage cracking developing. Shrinkage was not measured in these experiments because it was not believed that it could be practically done. Holt (2000) designed and built a relatively sophisticated test apparatus for measuring shrinkage of fresh concrete and related that property to water losses.[(70)] It can be deduced from her data that for the concrete she was studying, plastic shrinkage cracking could reasonably be expected when water loss before time of setting exceeded about 1 kg/m^2. Plastic shrinkage cracking is far too complicated a phenomenon to be reduced to such a simple criterion, but in the absence of a better approach to analyzing the data in this work, hopefully it provides a useful point of reference.

Another reference point for this work is the amount of water expected to be lost during the initial curing period if no action is taken to prevent it. For the specimens and conditions in this work, a water loss of 3.0 kg/m^2 can be expected if no curing or protection is applied during the 4-hour period between placing and time of setting. This value is taken from the average losses in experiments 17-2 and 17-4 (table 9). This value includes approximately 0.6 kg/m^2 bleed water and that can reasonably be considered expendable.

Table 6. Summary of Experimental Series 9 with CC 010150, polyalphamethyl styrene.

Exp. No.	Conditions before application of final curing treatment	Application rate, m^2/L	Mass loss before final curing applied, kg/m^2	Mass loss start of final cure to 7d, kg/m^2	Water absorption, kg/m^2 T=top B=bottom	Rebound number, kg/m^2 T=top B=bottom
9-1	Half curing compound (CC) early, half applied 1.5 h (h), exposed to wind, 38 °C, 30% RH.	5.8	2.09*	0.93	T=0.18 B=0.18	T=19 B=27
9-2	Exposed to wind, 38 °C, 30% RH for 1.5 h, then add CC.	5.8	1.65*	0.98	T=0.18 B=0.18	T=23 B=23
9-3	Covered at 38 °C until TOS, sheen gone.	4.9	0.0	1.16	T=0.36 B=0.21	T=11 B=21
9-4	Covered at 38 °C for 3.5 h, blotted off remaining bleed water.	5.6	0.18**	1.31	T=0.29 B=0.21	T=17 B=21

*This value includes bleed water lost, estimated to be 0.60 kg/m^2 from exp. 12-3.
**Amount of residual bleed water. No evaporative losses, some bleed water was reabsorbed. Surface still had sheen when curing compound applied.

Table 7. Summary of Experimental Series 12 with CC 000182, resin.

Exp. No.	Conditions before application of final curing treatment	Application rate, m^2/L	Mass loss before final curing applied, kg/m^2	Mass loss start of final cure to 7d, kg/m^2	Water absorption kg/m^2, T=top B=bottom	Rebound number kg/m^2, T=top B=bottom
12-1	Half CC early, half applied 1.5 h, exposed to wind, 38 °C, 30% RH.	4.7	1.54*	0.93	T=0.21 B=0.15	T=18 B=22
12-2	Exposed to wind, 38 °C, 30% RH for 1.5 h, then add CC.	5.2	0.97*	0.81	T=0.20 B=0.15	T=24 B=25
12-3	Covered 3.5 h, 23 °C, bleed water poured off at intervals.	5.6	0.60**	0.64	T=0.27 B=0.18	T=21 B=29
12-4	Covered 3.5 h, 23 °C, small residual bleed water poured off.	4.5	0.32***	1.06	T=0.35 B=0.21	T=17 B=26
12-5	Bleed water evap for 2.5 h at 38 °C, 30% RH, no wind.	3.5	0.55*	0.67	T=0.18 B=0.19	T=25 B=24
12-6	Covered for 2.5 h at 38 °C, residual bleed water blotted off.	4.0	0.13***	1.22	T=0.28 B=0.16	T=22 B=25

*This value includes bleed water lost, estimated to be 0.60 kg/m^2 from exp. 12-3.
**Bleed water only, no evaporative losses.
***Amount of residual bleed water. No evaporative losses, some bleed water was re-absorbed. Surface still had sheen when curing compound applied.

Table 8. Summary of Experimental Series 13 with several curing compounds.

Exp. No.	Conditions before application of final curing treatment	Application rate, m^2/L	Mass loss before final curing applied, kg/m^2	Mass loss start of final cure to 7d, kg/m^2	Water absorption kg/m^2, T=top B=bottom	Rebound number kg/m^2, T=top B=bottom
13-1 000134 wax	Half CC early, half applied 1.5 h, exposed to wind, 38 °C, 30% RH.	3.5	0.77*	1.58	T=0.40 B=0.19	T=17 B=26
13-2 000134 wax	Exposed to wind, 38 °C, 30% RH for 1.5 h, then add CC.	3.3	1.22*	1.04	T=0.31 B=0.19	T=20 B=26
13-3 010021 resin	Half CC early, half applied 1.5 h, exposed to wind, 38 °C, 30% RH.	5.8	0.41*	1.57	T=0.44 B=0.19	T=17 B=27
13-4 010021 resin	Exposed to wind, 38 °C, 30% RH for 1.5 h, then add CC.	6.2	1.02*	1.61	T=0.32 B=0.19	T=21 B=25
13-5 000135 resin	Half CC early, half applied 1.5 h, exposed to wind, 38 °C, 30% RH.	4.8	1.33*	1.15	T=0.34 B=0.11	T=20 B=26
13-6 000135 resin	Exposed to wind, 38 °C, 30% RH for 1.5 h, then add CC.	5.1	1.66*	1.26	T=0.37 B=0.12	T=21 B=25

*This value includes bleed water lost, estimated to be 0.60 kg/m^2 from exp. 12-3.

Table 9. Summary of Experimental Series 17 with no curing compound.

Exp No.	Conditions before application of final curing treatment	Application rate, m^2/L	Mass loss 0–4 h, kg/m^2	Mass loss start of final cure to 7d, kg/m^2	Water absorption kg/m^2, T=top B=bottom	Rebound number kg/m^2, T=top B=bottom
17-2	Exposed to 3 m/s wind, 38 °C, 30% RH for 7 days.	–	3.48	2.82	T=0.47 B=0.26	T=12 B=24
17-4	Exposed to 3 m/s wind, 38 °C, 30% RH for 7 days.	–	2.56	2.17	T=0.44 B=not determined	T=12 B=20

Experiments 12-3 (table 7), 23-1, and 24-2 (table 10) represent near ideal conditions in that all bleed water was lost before curing compound was applied, but there was no evaporation loss of any additional water. In 12-3, bleed water was drained off periodically, then curing compound applied when the sheen was nearly gone. In 23-1 and 24-2, enough time was allowed for most or all of the bleed water to drain into a layer of sand on the bottom of the specimen. Evaporative losses during the remainder of the 7 days exposure ranged from 0.64 to 1.2 kg/m^2. An unexpected result in these data was that the water absorption data for specimens that had been allowed to set with bleed water reserved showed higher values, which indicates less density in the surface concrete.

Experiments 9-3, 9-4 (table 6) and 12-4 represent conditions when most or all of the bleed water was allowed to re-absorb before curing compound was applied. Evaporative losses ranged from 1.1 to 1.3 kg/m^2 after application of curing compound.

Table 10. Summary of Experimental Series 23 with CC 000182, resin. These specimens were cast onto a bed of sand to simulate effects of bleed water draining off.

Exp. No.	Conditions before application of final curing treatment	Application rate, m^2/L	Mass loss before final curing applied, kg/m^2	Mass loss start of final cure to 7d, kg/m^2	Water absorption kg/m^2, T=top B=bottom	Rebound number kg/m^2, T=top B=bottom
23-1	Covered at 38 °C for 3 h.	4.8	0	0.72	T=0.21 B=N/A*	N/A*
23-2	Half CC immediately, half applied 1.5 h, exposed to wind, 38 °C, 30% RH.	5.2	0.89	1.57	T=0.21 B=N/A	N/A
23-3	All CC applied immediately.	4.6	1.4 (lost in 3 h)	1.86	T=0.20 B= N/A	N/A
23-4	No CC.	–	3.30 (lost in 3 h)	0.96 (3 hour–7d)	T=0.46 B= N/A	N/A

*Effect of casting on sand made the bottom of the specimen unsuitable for determining water absorption or rebound number.

Table 11. Summary of Experimental Series 24 with CC 010150, resin. These specimens were cast onto a bed of sand to simulate effects of bleed water draining off.

Exp. No.	Conditions before application of final curing treatment	Application rate, m^2/L	Mass loss before final curing applied, kg/m^2	Mass loss start of final cure to 7d, kg/m^2	Water absorption kg/m^2 T=top B=bottom	Rebound number kg/m^2 T=top B=bottom
24-1	Covered at 38 °C for 3 hour.	4.7	0	1.26	Not determined	Not determined
24-2	Covered at 38 °C for 4 hour.	5.3	0	1.16	Not determined	Not determined
24-3	All CC applied immediately.	4.0	Not determined	2.56	Not determined	Not determined
24-4	Half CC immediately, half >3 h at 38 °C, 30% RH, wind 3 m/s.	6.3	Not determined	2.93	Not determined	Not determined

A couple of things can be deduced from the water loss data during the early hours after placing. One is that even though early application of curing compound seems to have negative effects on the quality of the membrane formation, the presence of the curing compound before the time of setting seems to have some effect of retarding water losses during this period. Experiments 13-1 and 13-3 (table 8) show this effect particularly well. In 13-3, even some of the bleed water was retained. The poor membrane quality shows up as somewhat higher evaporative losses between time of setting and 7 days. This is discussed below in the section on water retention.

The water absorption and rebound number shows the condition of the concrete surface. Surface density is inversely related to water absorption. Results are somewhat complicated. In general, when heavy drying occurs, large water absorption and low rebound numbers result. When moderate water losses occur, lower water absorption and high rebound numbers result. However, an unexpected result occurs when no water losses are allowed through the time of setting, so that all bleed water is reabsorbed prior to application of curing compound. In these cases, water absorption values were typically a little higher and rebound numbers were typically a little lower. The conclusion is that some water loss during the initial curing period results in some compacting of the solids of the concrete's surface zone. If this occurs without plastic shrinkage cracks, then there may be some benefit to the phenomenon. However, the balance point between too much evaporation and resulting cracking and a small amount of evaporation and a useful densification of the concrete may be a little too sensitive to warrant engineering this condition into a pavement placement.

In conclusion, the following guidance appears to be appropriate.

- For maximum water retention, protect the concrete if evaporation rates are higher than bleed rates until the time of setting, then let the sheen disappear and apply curing compound.

- A small amount of evaporation of mixing water beyond the amount of bleed water may have some beneficial effect on surface density; however, when evaporation rates are higher than bleed rates, particularly if this is driven by wind directed onto the surface of the concrete, evaporation can easily get out of control and result in cracking.

- If curing compound must be applied before the natural disappearance of sheen due to cessation of bleeding, it is best to get past the major bleeding event, then apply one half of the curing compound, let dry, and apply the second half.

WATER-RETENTION REQUIREMENTS FOR CURING COMPOUNDS

The purpose of using curing compounds to cure concrete is to retain sufficient water in the concrete that physical properties develop adequately in the time required. Whether a curing compound application retains sufficient water under a given set of climatic conditions is strongly affected by two properties: the basic impermeability of the material making up the compound and the amount of application (basically the thickness of the membrane). Guidance on both of these is somewhat varied. The importance of these properties will be evaluated by using some literature that has been found since the interim report was written, by comparing practices used by State DOTs and other agencies, and by evaluating some laboratory tests on concrete specimens. The test method for determining the inherent water retention properties of curing compound is quite variable among laboratories, to the point that serious buyer-seller disputes sometimes develop. The test method is investigated with laboratory work, with the intention of recommending improvements that might reduce this variation.

When curing materials fail to perform adequately in a drying environment, the drying only affects the near-surface zone of the concrete and is usually thought to be confined to the upper 50 mm of concrete. The conventional understanding of the problem is that hydration ceases when the relative humidity of the concrete drops below 80 percent. The effect is to inhibit development of physical properties because of inadequate hydration of cement. Cracking can also occur.

Physical properties affected are strength and abrasion resistance. There is some indication that they can be recovered with water derived from rainfall subsequent to completion of the structure, if such water is available. The position held by T. C. Powers is that water retention is necessary to develop properties only to the point of meeting immediate needs, then additional curing can be derived from natural sources.[83] Aside from strength and abrasion resistance is the issue of drying shrinkage cracking. The amount of drying shrinkage in concrete has been shown not to be strongly related to extent of curing. In fact there is some thought that excessive hydration contributes to increased drying shrinkage. But, the effects of drying very early may not exactly follow the same rules. The consequences of drying shrinkage are potentially related, at least in part, to the rate of drying (creep effects). As shown above, concrete loses water by evaporation very rapidly before time of setting, but slows down substantially after time of setting. Even this slower evaporation rate has a time dependency to it. Concrete dries faster immediately after setting than it does several days after setting. This was demonstrated above under the discussion of evaporation of water from concrete. Thus, if absence of adequate water retention occurs early, then the consequences are likely to be greater than if it occurs later.

There is not much information or research on the subject of exactly how much water retention is required during the final curing period. The current requirements for curing compounds vary from a high value of 0.55 kg/m^2 at 3 days (ASTM C 309[23]) to low values of about 0.25 kg/m^2 at 3 days (some State DOTs) and 0.31 kg/m^2 at 7 days (USACE CRD-C 300)[84]. It is difficult to determine how these limits were developed. During the period when much of the research that focused on developing curing compounds occurred, the approach to evaluating various products was to cast 150 mm by 300 mm cylinders and after being stripped from molds, coat them with curing compound. Strength relative to specimens cured in water or fog was the evaluation criterion. Abrasion resistance and water absorption are mentioned in the literature as relevant properties, but most of the results presented emphasized strength. No single value was reported as critical, but if one averages across several of the results in the major publications, a value of around 0.6 kg/m^2 emerges.

No data or discussions were found in the literature supporting the lower numbers used by some agencies. It seems likely that these were developed as a response to the commonly held belief that curing operations are mostly inadequately performed, both in the performance of the curing compound and the attention to detail with which it is used. The lack of confidence in the curing compounds may stem from the huge uncertainty in the testing of products for water retention. ASTM C 156 is the recognized standard, but some State DOTs have developed variants of the method. Information on this will be presented below.[18]

Some information on the effects of water losses on near-surface properties can be derived from concrete experiments done in this project. The experimental protocol was described in the "Time of Application of Curing Compounds" section. Some test results are from those data, but some additional data were also generated separately and reported in this section of the report.

As above, water absorption and rebound number are metrics for near-surface condition. Water loss during the period after application of final curing is the principal independent variable, but losses during the period before application of final curing varied widely (0–3.9 kg/m^2) and were included in the analysis. Multiple linear regression was the statistical tool used to evaluate the effects of losses during these two curing periods on the surface properties of water absorption and rebound number. Loss during the initial curing period was found not to be a significant variable in the analysis of either water absorption data or rebound numbers. This indicates that losses during the initial curing period do not have a major effect on the measured near-surface properties developed during the final curing period, at least for the small laboratory specimens used in this work. Plausibly, large concrete placements would have developed some plastic shrinkage cracks that would increase the water absorption. The effects of water losses after curing compound application on surface properties appear to be linear with moderate scatter. Figures 17 and 18 illustrate the effects.

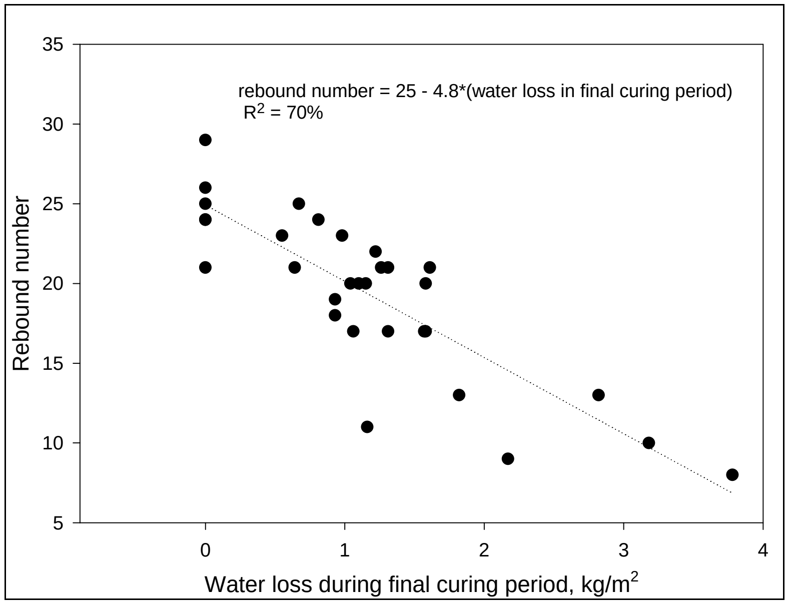

Figure 17. Rebound number of concrete surface versus water loss in final curing period (7 days).

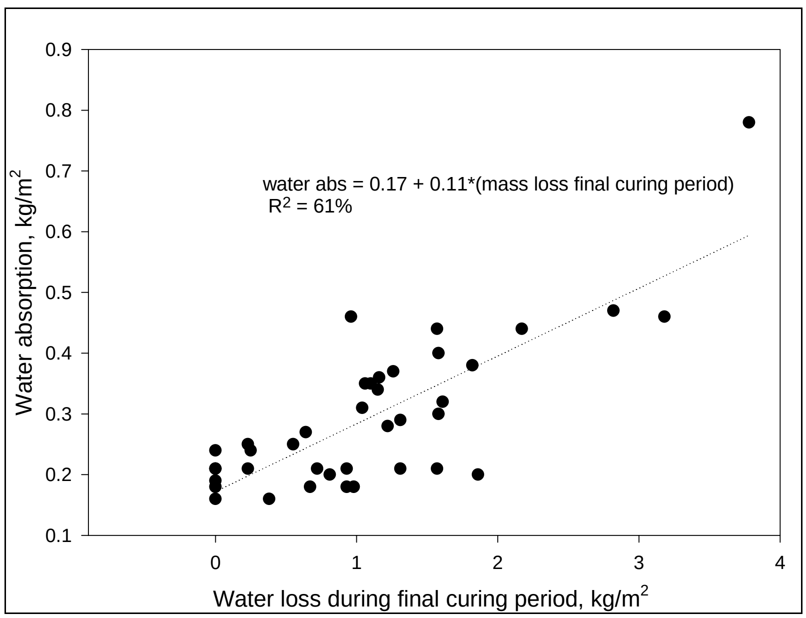

Figure 18. Surface water absorption versus water loss during the final curing period (7 days).

These results show that water retention appears to have a perceptible effect on near-surface properties, even down to very low values of water loss. However, scatter in the data makes it very difficult to resolve the effects, as measured by these two properties, at values of water loss of less than 1 kg/m^2 at 7 days. In other words, even though the effects appear to be linear and continuous throughout the range, it would difficult to reliably distinguish a concrete that lost 0.3 kg/m^2 from one that lost 1.0 kg/m^2 of water using these methods. Predicted water absorption at a water loss of 0.3 kg/m^2 would be 0.20 kg/m^2 and rebound number would be 23. For water losses of 0.55 kg/m^2, water absorption would be predicted to be 0.23 kg/m^2 and the rebound number would be 22. These effects are difficult to resolve experimentally and may not be perceptible in practice.

White and Husbands (1990)[85] used ASTM C 1151[27] to study the effects of different water-loss properties of curing compounds on the near-surface zone of mortars. Their objective was to determine whether the USACE's more restrictive requirement of 0.31 kg/m^2 at 7 days actually resulted in a measurable improvement in performance over the requirement in ASTM C 309 of 0.55 kg/m^2 at 3 days.[23] In their study, they used both curing compounds as supplied by the manufacturer and curing compounds they engineered to give target water-loss properties by dilution. This dilution was executed with manufacturer-supplied solvent thus avoiding potential interactions. Water-loss values ranged from 0.28 to 1.40 at 3 days. Specimens were cured as in USACE test method CRD-C 300 (38 °C, 30 percent RH, 4 m/s wind).[84]

White and Husbands[85] were unable to detect any deterioration in performance until losses exceeded 1 kg/m^2 at 3 days. They concluded that there was no evidence in the test results to support the continued requirement of 0.31 kg/m^2 at 7 days and recommended that the USACE should adopt the less restrictive requirement in ASTM C 309 for curing compounds.[23] This has been done for most USACE construction except for airfield pavements. The change has not been made there because the proponents of the guidance for airfield pavements are of the belief that pavements are under more stress for water losses than most concrete and that a more restrictive than average requirement was in order.

The results reported in this work showing effects of water losses in the final curing period on water absorption and rebound number show a more general, apparently linear, trend over a wider range of water-loss values than reported by White and Husbands.[84] The slope of this relationship suggests that the differences expected for a hypothetical decrease in water loss from 0.5 to 0.25 kg/m^2 would be about 1.2 on the rebound number and 0.025 kg/m^2 on water absorption. These are small effects, probably undetectable above experimental error and probably not perceptible in field concrete, given all of the other variables.

The conclusion is that water losses do appear to have an effect on the near-surface zone, as measured by at least two procedures, but that the practical effect of relatively small changes in performance, as is represented by differences in various curing compound specifications, is difficult to see. In the opinion of one technical representative of a curing compound manufacturer interviewed during the information gathering phase of this work, the time of application of a curing compound is far more important in determining performance of curing compound than is performance in the water-retention test.

The selection of a limit on the water-retention property of curing compounds may be influenced more by philosophical considerations than by empirical evidence. The approach seems to be that problems with curing compounds (e.g., variable properties, errors in application rate) are the basis for many curing problems, so that requiring more stringent properties is a way to insure that the performance of the material is robust to these problems.

A couple of practical issues affect this. One is that imprecise water-loss test methods make it very difficult to determine exactly whether a curing compound is meeting a limit or not. If the limit is set at the highest tolerable level commensurate with good performance, then the manufacturer has some space to work with in over-designing a product so that testing errors do not threaten rejection. At least one major manufacturer commented, when interviewed on this subject, that his company does not compete in the paving market because of the intense contentiousness involved with specification-compliance issues. Another practical problem is that curing compounds that meet very low water-loss specifications may be difficult to work with. Within a given product line, water-retention performance is commonly engineered by adding or subtracting vehicle solids. Having very high solids content makes a material viscous and could make application by mechanical spraying difficult. Low VOC materials also present this problem.

VARIABILITY IN TEST METHOD FOR WATER RETENTION OF CURING COMPOUNDS—ASTM C 156[18]

During the course of this study, there was the opportunity to work with ASTM C 156 from a beginner's viewpoint.[18] During the last several years, all USACE personnel experienced in this test method were lost without opportunity to retain their capability. This required a totally new learning of the method, which may have resulted in some useful insights.

The ASTM C 156 method directs that specimens be placed in the curing cabinet after they are fabricated and left uncovered under the full evaporation conditions of the test until the sheen disappears before applying curing compound.[18] One of the most difficult things for the new user to learn is the point at which the sheen on the test specimens disappears. There are some supplemental instructions in C 156 on verifying this, but there is still quite a bit of uncertainty on this point to the novice user of the method.[18]

A small study was executed to investigate this detail of the test method involving three curing compounds. Time of application was systematically varied from about 1 h to 3 h after fabrication. The mortar used reached initial set in about 2 h. Application rate of curing compound was also varied. Test results were analyzed by multiple linear regression using water loss at 3 days as the dependent variable and application time and application rate as the independent variables. Both variables were found to be statistically significant. The following equations were developed for the three curing compounds, representing water-loss rates (kg/m^2) at 72 h.

$$WaterLoss(CuringCompound\ 1) = 0.25 - 0.34 * time + 0.18 * appl.rate \qquad R^2 = 0.85 \qquad (6)$$

$$WaterLoss(CuringCompound\ 2) = 0.60 - 0.31 * time + 0.19 * appl.rate \qquad R^2 = 0.86 \qquad (7)$$

$$WaterLoss(CuringCompound\ 3) = 0.55 - 0.24 * time + 0.06 * appl.rate \qquad R^2 = 0.43 \qquad (8)$$

Units of measure for *time* and *appl.rate* are h and m^2/L, respectively. The low R^2 of the third equation suggests a large random error. This probably is not true, given the residuals, but rather a consequence of some nonlinear effects. The data in this equation covered a much smaller range of evaporation rates. The cause of this effect was not further investigated.

The first two equations are very similar. The positive sign on the application rate coefficient is due to the convention for reporting application rates (m^2/L), so that a high number represents a small amount of curing compound. In a hypothetical situation where time of application was changed from 1.5 h to 2.0 h, the change in measured evaporation rate would be 0.17 kg/m^2 in the first equation, 0.15 kg/m^2 in the second, and 0.12 kg/m^2 in the third. This source of error could possibly be removed in a single laboratory by standardizing time of application for a given mortar recipe, but this is plausibly a significant source of between-laboratory error. It is easy to see how large between-laboratory variation could arise when each laboratory is using its own mortar recipe and may be interpreting the instructions on cessation of bleeding a little differently.

APPLICATION RATE OF CURING COMPOUNDS

A potentially better way to improve water retention is to require a higher application rate (or more applications) of a relatively weak curing compound rather than insist on extremely conservative acceptance limits.

A demonstration of this concept was executed in the laboratory using a curing compound with a relatively low solids content and a water retention (C 156[18]) that, at 0.49 kg/m^2, was close to the 0.55 kg/m^2 limit in C 309.[23] Application rates were 2.6, 5.4, and 9.7 m^2/L and no curing compound. The test specimens were same as used in the work on curing compounds described above. Water-loss values in concrete are not expected to be exactly the same as in mortar, but they should be correlated with the results from mortar tests (C 156[18]). Results are shown in figures 19–21.

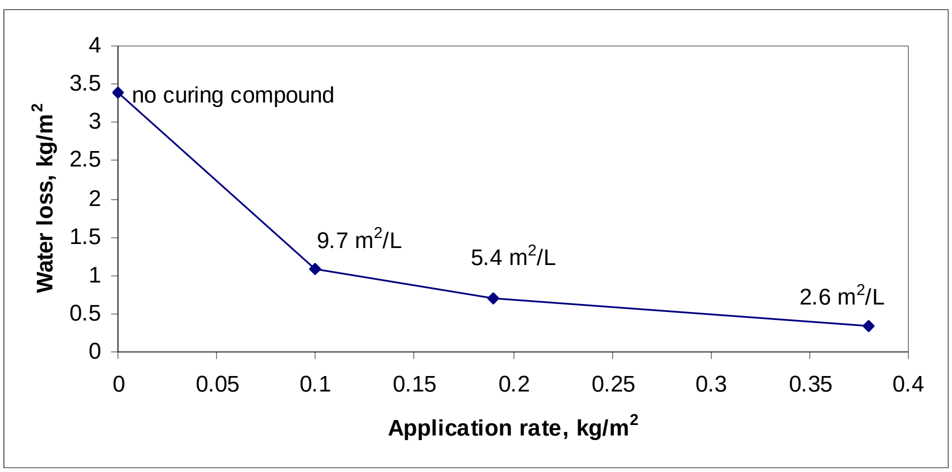

Figure 19. Water loss at 72 h versus application rate of curing compound. The more conventional representation of application rate (m^2/L) is annotated by each point.

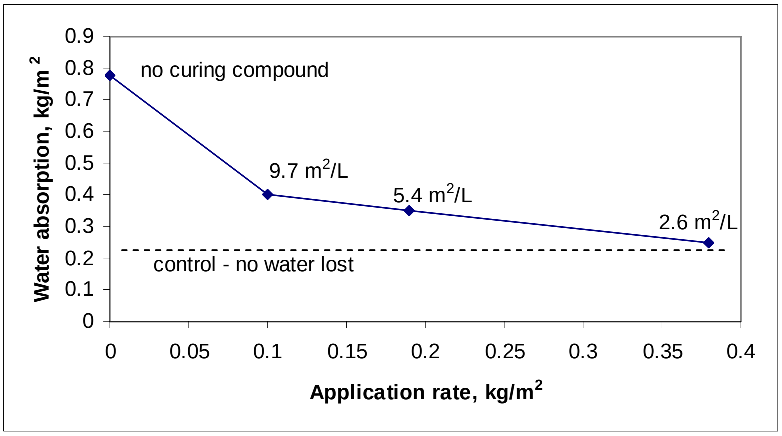

Figure 20. Surface water absorption versus application rate of curing compound.

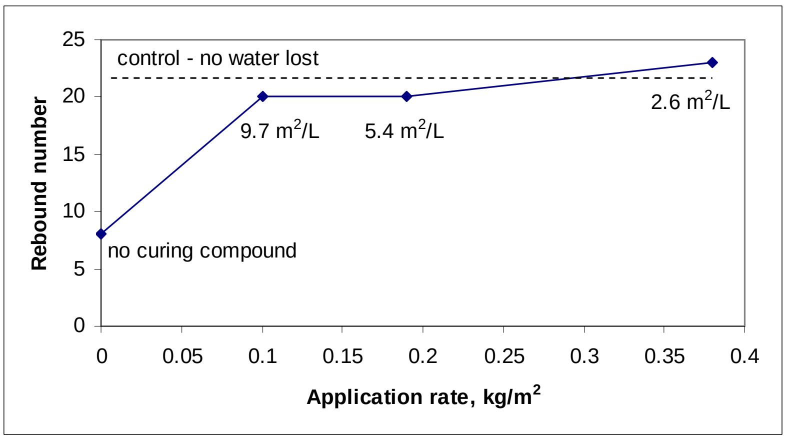

Figure 21. Rebound number versus application rate of curing compound.

These results show that a relatively high level of performance can be attained by increasing the application rate of a relatively weak curing compound. In this case, the curing compound had to be applied in two coats to prevent too much liquid from collecting on the surface at one time.

RECOVERY FROM POOR OR LATE APPLICATION OF CURING COMPOUND

Losses of too much water during the final curing period have been shown to negatively impact the quality of the near-surface zone of the concrete, as measured by water absorption and rebound number. Some guidance on water-added and sheet curing methods contains provisions for correcting for drying events during the final curing period. The practice is that if dry concrete is discovered during the final curing period, the problem is to be fixed and curing extended. The question is whether surface properties are recoverable upon reapplication of water. This could also be an important question for concretes cured with too light a curing compound application.

Four tests were run to examine this question. All were performed using the 0.45 water-cement ratio concretes as described above (see subheading of “Time of Curing Compound Application”).

1. A test specimen was exposed to 38 °C, 30 percent RH, 3 m/s wind from immediately after casting until 7 days. Mass loss was 4.44 kg/m^2. The water absorption was 0.44 kg/m^2, which is a relatively high number and to be expected under these conditions. The rebound number for the top surface was 12. The rebound number of the bottom was 19, possibly indicating that the effects of the drying extended some to the full depth of the specimen (75 mm). The rebound number of the bottom surface of a well-cured specimen was nominally about 25. After 7 days, the specimen was put into a moist cabinet for 13 days. Mass gain was 3.68 kg/m^2 (presumably water), and the rebound numbers increased to 23 on the top and 24 on the bottom. Surface water absorption was not determined.

2. This specimen was a companion specimen to the one described above, but to which a light coating (14 m^2/L) of curing compound was applied after 3 h. The manufacturer's recommended application rate is 5 m^2/L. Water loss was 4.71 kg/m^2 after 7 days, which indicates that the curing compound at this level of application did essentially nothing to retain water. The water absorption was 0.46 kg/m^2, and the top and bottom rebound numbers were 14 and 21 respectively. After 13 days in the moist cabinet, mass gain was 3.97 kg/m^2, and the rebound numbers increased to 20 for the top and 24 for the bottom.

3. A test specimen was allowed to dry for the first 24 h after fabrication in the 38 °C, 30 percent RH, 3 m/s condition, then water was ponded on the surface for 1 hour and curing compound applied at 5 m^2/L. Water lost in the 24-hour drying period was 3.94 kg/m^2, and 2.71 kg/m^2 was recovered in the 1-hour ponding. During the subsequent 11 days under curing compound, 0.60 kg/m^2 was lost. The surface absorption was 0.18 kg/m^2, which is very low, and the rebound numbers were 22 for the top and bottom, which is comparable to a specimen that has been relatively well-cured.

4. The last determination was conducted as in paragraph 3 above, but the initial drying period was 48 h. Water loss was 4.30 kg/m^2, but 3.05 kg/m^2 was recovered in the one-hour ponding. Rebound numbers after 10 days under curing compound were 24 for the top and 19 for the bottom. The bottom number was a little low. Water absorption was 0.17 kg/m^2 (low) for the top and 0.24 kg/m^2 for the bottom. The apparently poor quality of the bottom of the specimen may have been due to poor consolidation. There were no notes on this from the experiment, but this was found to be true in other cases.

In conclusion, it appears that there is substantial capacity for concrete that has dried out early in its hydration history to recover, at least as indicated by surface density-type measures. Drying shrinkage, on the other hand, is known to be only partially recoverable (as discussed in Mindess and Young (1981)[78], and other concrete texts). The same may be true for surface density, but it does not appear to be true within the limits of the experiments done in this work.

EFFECT OF CLIMATIC CONDITIONS ON CURING COMPOUND DRYING TIME

Drying time of curing compounds can be a practical problem in the field, particularly when environmental drying conditions are not favorable. The current specification limit for drying time is 4 h under the moderately high evaporation rates defined in test method C 309.[23] The problem can be particularly acute with use of low-VOC curing compounds. The effect of drying conditions on drying time of some low-VOC curing compounds was investigated with laboratory specimens. The purpose of this analysis is to determine whether a simple calculation based on the evaporation-rate nomograph can be developed for estimating drying times under poor evaporation conditions. Six low-VOC curing compounds were included. Drying conditions varied from 0.02 $kg/m^2/h$ (cold, high humidity, no wind) to 1.0 $kg/m^2/h$ (38 ^oC, 30 percent RH, 2.5 m/s wind). The following equation reasonably represented the drying times over this range.

$$Drying\ Time = 1.04 * (evaporation\ rate)^{-0.67} \tag{9}$$

where the evaporation rate is as calculated by the ACI 308 nomograph, assuming the surface temperature is equal to the air temperature.[31] Figure 22 shows the relationship between predicted and observed drying times.

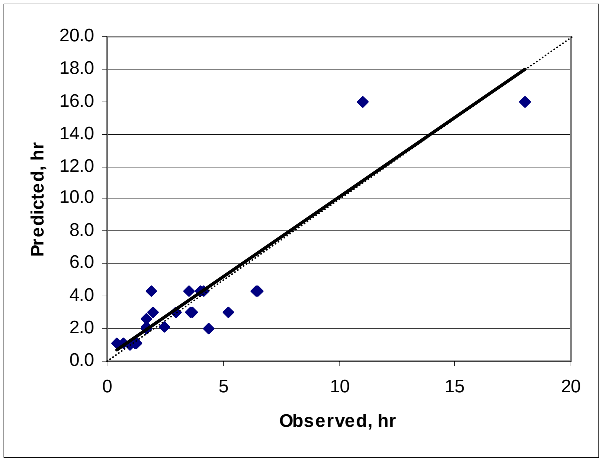

Figure 22. Comparison of calculated versus measured drying times for six curing compounds under a range of drying conditions.

This is not a highly accurate calculation and cannot resolve drying time effects of 1–2 h or less. But the calculation does appear to have some value in helping to anticipate approximate effects of poor drying conditions on a specific construction site or for determining whether seemingly excessive drying times on a project are out of the ordinary and possibly due to a defective product or are attributable to poor drying conditions.

APPLICATION OF CURING COMPOUND TO TINED SURFACES—EFFECT OF SAGGING

Tined and grooved surfaces contain a considerable amount of vertical or near-vertical surfaces. Curing compounds that tend to sag when applied to vertical surfaces will likely perform poorly because the compound will tend to run into the low spots of the tined pattern. To investigate this, three curing compounds were evaluated for their tendency to sag. No standard test method for this property was known to exist, so an *ad hoc* method was constructed.

The test was performed on 140 by 120 mm hardened concrete specimens. Specimens were soaked in water for 1 hour, then surface-dried with a towel and in air for about 10 min. Four specimens were turned on edge so that the surface to which application was to be made was in a vertical position. Curing compound was sprayed onto the specimens at four different application rates, ranging from about 15 m^2/L to about 5 m^2/L. Specimens were left for about 5 min to detect any delayed sagging. Curing compounds were chosen for this evaluation for their apparent viscosity: one appeared to have the approximate viscosity of water, another was of intermediate viscosity, and a third was of very high viscosity.

The low-viscosity material sagged at an application rate of 16.8 m^2/L, the intermediate-viscosity material sagged at between 4.6 and 6.7 m^2/L, and the high viscosity material did not sag at 5.0 m^2/L (no higher application was attempted).

The interpretation of this result is that the low viscosity material should be applied in three or four coats, the intermediate viscosity material in two coats, and the high viscosity material in a single coat.

After this work was done, it was discovered that the Texas DOT (TxDOT, 1998) has viscosity and sagging requirements for curing compounds to be used on grooved pavements.[86] They appear to be using proprietary testing equipment, procedures, and guidance based around this to set their requirements.

TEST METHODS FOR MEASURING CURING COMPOUND APPLICATION

Existing methods for estimating curing compound applications involve indirect measurements. One involves bookkeeping on the amount of materials used and the surface area covered. Another involves measuring flow rates through delivery nozzles and rate of movement of the application equipment and then calculating the average application rate. Both of these procedures should give good estimates of average coverage, but neither is probably strong in detecting localized irregularities in application.

Three methods were investigated that should be more sensitive to local irregularities in curing compound application: direct measurement of mass of application, infrared measurements, and visible light reflectance. A report of these results was published during the execution of this project (Poole, 2001).[87]

Direct measurement of curing compound application by weighing sampling devices placed in the path of the curing compound application equipment is plausible. A typical application rate for curing compounds is 5 m^2/L. At this rate, a 10- by 10-cm coupon would then receive 2.0 grams of curing compound. To verify curing compound application to within 10 percent accuracy, one would need to measure the mass of application to within 0.2 grams (g) of wet curing compound. These limits are reasonably attainable, even with field usable balances. However, a significant source of error is in the loss of solvent due to evaporation between the time when the curing compound is applied and the sampling coupon retrieved for weighing. Under relatively severe drying conditions (e.g., 1 $kg/m^2/h$) 0.8 g would evaporate in 5 min, assuming the evaporation rate follows Menzel's formula for evaporation of water from a free-water surface. Even under less intense evaporation rates, sizable measurement error could occur unless considerable attention is paid to collecting the sample and protecting it from evaporation relatively quickly.

One solution to the evaporation problem is to measure dry mass. However, since curing compound contains 70 to 85 percent solvent, a somewhat larger sample would be required to collect enough material to give a precise measurement on the dried material. A 10 by 10 cm sampling device would contain from 0.3 to 0.6 g of dry material at the above described application rate and solvent content. This procedure would be easily done in a laboratory setting, but probably would be awkward in a field setting because of the necessity to dry the material to constant weight, need for a constant temperature oven, and the need for a relatively precise balance to weigh the relatively smaller amounts of material. This is basically a plausible method, but considerable care would be required to eliminate sources of error. It is the only method that would appear to work on nonpigmented curing compounds.

The concept behind this technique is that concrete that has a poorly formed or thin coat of curing compound will allow more water to evaporate that concrete on which a well formed and adequately thick curing compound has been applied. This difference in evaporation would then result in a surface temperature difference that could be detected by an infrared thermometer or an infrared camera. The plausibility of this approach was examined using laboratory specimens. Three mortar specimens were prepared according the ASTM C 156.(18) No curing compound was applied to one, and curing compound was applied to the other two at a rate of 5 m^2/L at different application times. If useful temperature differences could be demonstrated under these conditions, then the concept could be further investigated for its ability to detect more subtle variations in treatment. The specimens were exposed to C 156 conditions (evaporation rate of 0.6 to 1.1 $kg/m^2/h$) and surface temperatures measured with an infrared surface temperature thermometer.(18) Results are shown in figure 23.

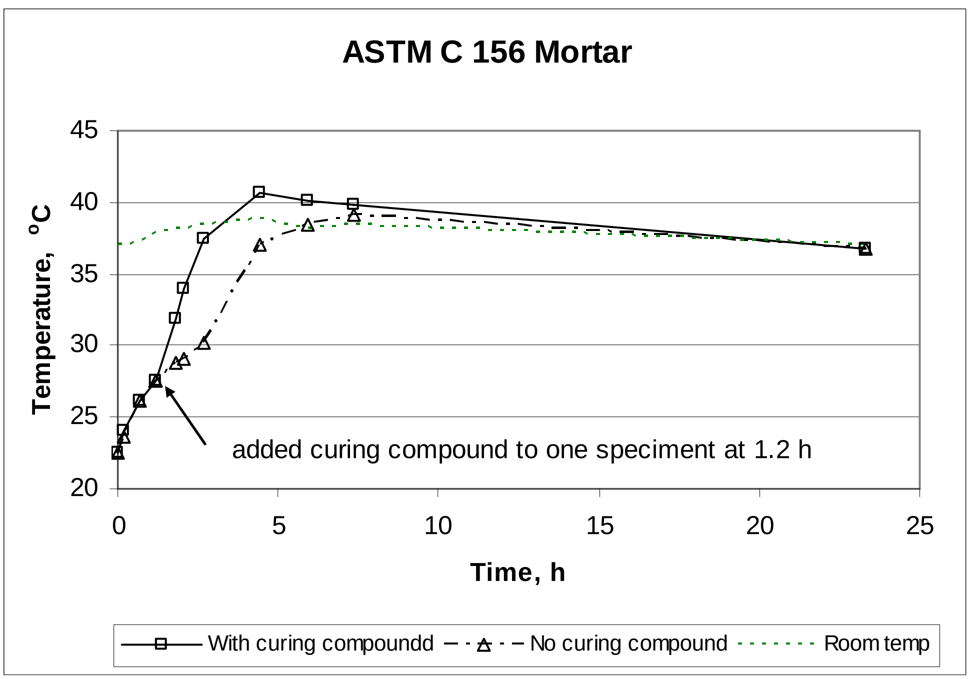

Figure 23. Effect of curing compound application on concrete surface temperature.

A measurable temperature difference was observed. The temperature of coated specimens rose above the temperature of uncoated specimen almost as soon as the curing compound had dried (about 2 h after specimen fabrication), reaching a maximum of 4 °C after 5 h. However, this temperature difference persisted only for a short while, becoming indistinguishable by about 7 h.

The conditions of this experiment were relatively simple and did not include the effect of sunlight. Incident radiation might tend to obscure the observed temperature effect, particularly with white pigmented curing compounds. The high level of reflectance of these materials would tend to have the opposite effect on surface temperature relative to the evaporative effects. This same effect would not appear to apply to clear curing compounds.

Given the relatively small temperature and transient difference that was observable under relatively high levels of evaporation, this technique does not appear to have promise for general field use, given the complicating effects of sunlight, and variable evaporation conditions that might exist there.

As discussed above, visual examination is a common method for verifying application of white pigmented curing compound. The purpose of this investigation was to give this practice some quantitative basis. The investigation was conducted on fresh mortar specimens and on black paper specimens coated with different levels of a white pigmented curing compound (resin based).

The mortar specimens were 10.2 cm in diameter and 5 mm thick. The mortar was proportioned as in ASTM C 156.[18] Curing compound was applied using a paint sprayer to four specimens at variable application rates that gave a visual effect varying from relatively grey to relatively white. Actual application rates were then determined by weighing the specimens. Application rates were 3.2, 5.4, 7.9, and 15.2 m^2/L. An application rate of 5 m^2/L is commonly cited by manufacturers as being appropriate. These four specimens were used to develop a visual standard curve. Three more specimens were coated with variable amounts of curing compound and treated as unknowns. An estimate of the actual amount of the application was made by visual comparison with the standard curve. The person making the comparison did not know the actual application rate.

Figure 24. shows photographs of the specimens. Table 12 shows the comparison of the actual and estimated application rates. The visual estimation was within about 2 m^2/L of the actual application rate.

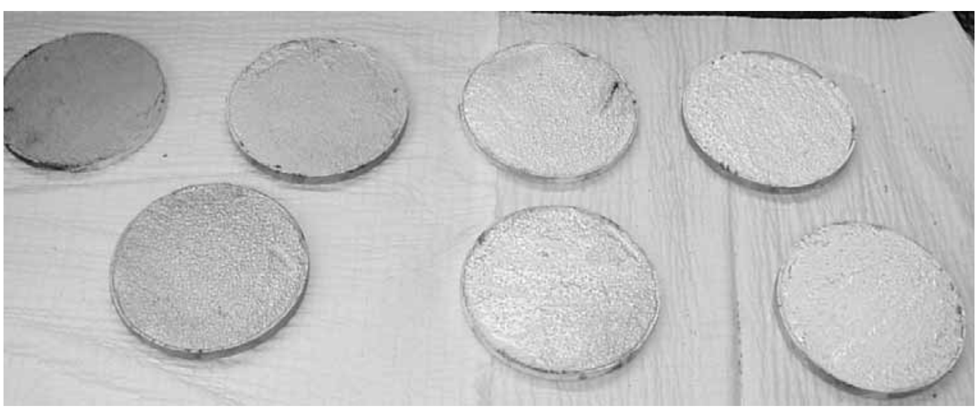

Figure 24. Fresh mortar specimens with variable applications of white pigmented curing compound. The top four specimens contained 15.2, 7.9, 5.4, and 3.2 m^2/L (L to R). The bottom 3 specimens were treated as unknowns (see table 12).

Table 12. Comparison of actual and visually estimated curing compound application on fresh mortar specimens.

Actual application rate (m^2/L)	Visually estimated (m^2/L)
12.5	9
6.5	5
3.8	3

The experiment was repeated using black construction paper glued to a stiff cardboard as the sampling device. The rationale for this variation was that the black background might provide a better contrast for visual estimation. If this is true, then a test method based on examination of paper coupons might reasonably be developed involving dispersing the coupons on a concrete surface before application of curing compound, and then collecting them for analysis.

Figure 25 is a photograph of the specimens. Table 13 shows the comparison of the actual and estimated curing compound application.

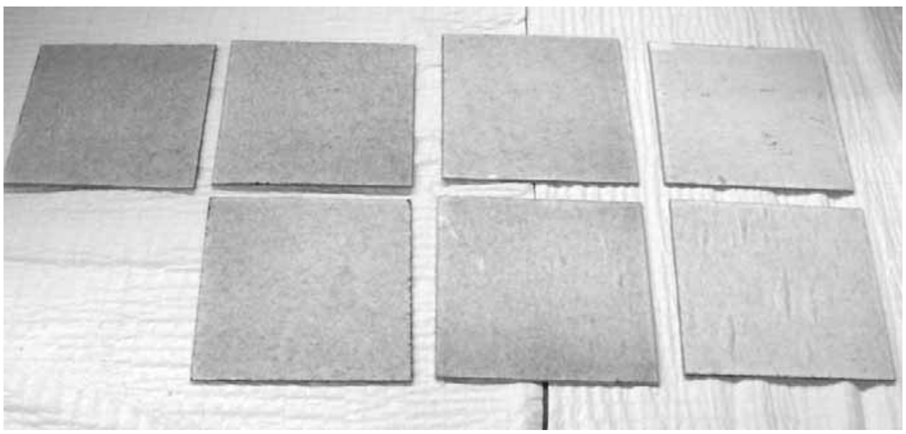

Figure 25. Black construction-paper specimens with variable applications of white pigmented curing compound. The top four specimens contained 10.1, 7.5, 5.9, 4.5 m^2/L (L to R). The bottom 3 specimens were treated as unknowns (see table 13).

Table 13. Comparison of actual and visually estimated curing compound application on black construction paper.

Actual application rate (m^2/L)	Visually estimated (m^2/L)
4.2	4
6.1	7
9.2	6

The enhanced contrast of the black paper specimens relative to the mortar specimens was not conspicuous when the mortar specimens were fresh, since they were also very dark. However, the mortar specimens containing light applications of curing compound tended to show an increase in whiteness when the surface dried, which tended to reduce the contrast on these specimens.

Reflectance is a measurement commonly used in the paint industry to measure degree of whiteness (ASTM E 1347).[88] It is also a specification-requirement test in ASTM C 309.[23] A portable reflectometer was used to measure the reflectance of the specimens made in the experiment described above. Figure 26 shows the graphical representation of the reflectance versus curing compound application of the "standard" specimens. A nonlinear curve was fitted to the data and used to calculate the curing compound application of the unknown specimens. Table 14 shows the results of the comparison. The average accuracy of the three determinations is within 15 percent.

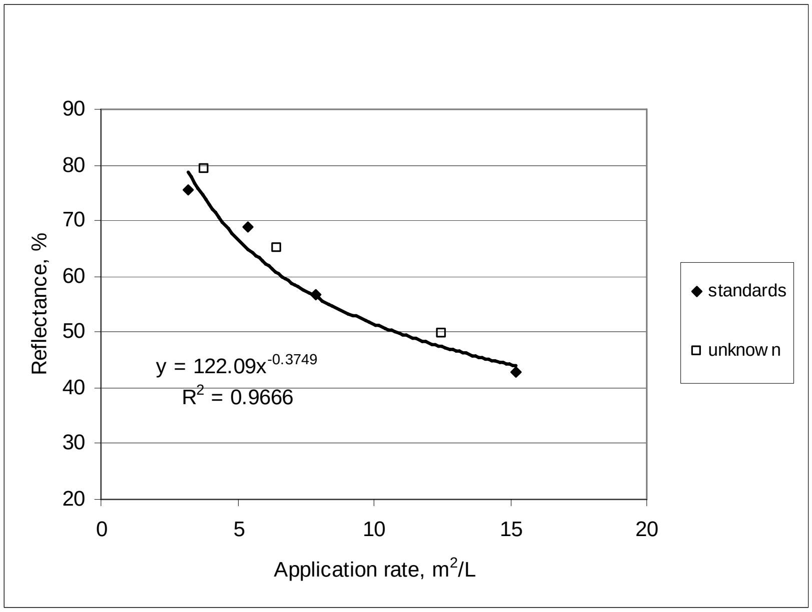

Figure 26. Reflectance versus application rate for white pigmented curing compound applied to fresh mortar at different rates. Data points represented by open symbols were treated as unknowns.

Table 14. Comparison of actual and reflectance-estimated curing compound application on fresh mortar, using the power equation in figure 26.

Actual application rate (m^2/L)	Estimated from Reflectance (m^2/L)
12.5	11.0
6.5	5.3
3.8	3.2

Figure 27 and table 15 show results obtained using the black-paper specimens. Two of the three unknown determinations were accurate to better than 10 percent of the true value. The other was off by 33 percent. This may be a statistical outlier, but there is insufficient replication to conclude this definitively.

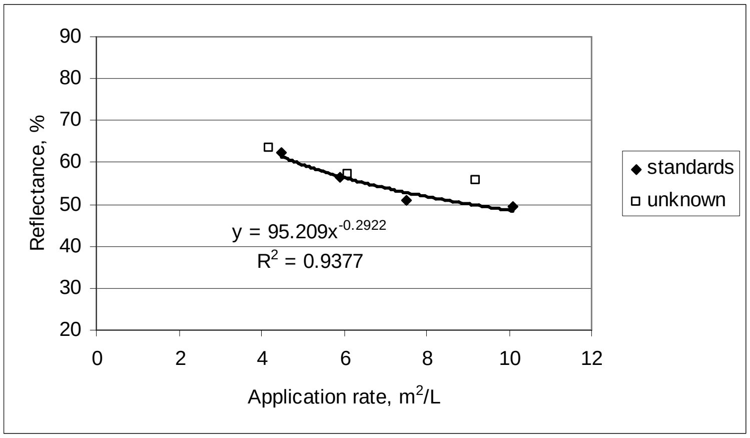

Figure 27. Reflectance versus application rate for white pigmented curing compound applied to black-paper specimens at different rates. Data points represented by open symbols were treated as unknowns.

Table 15. Comparison of actual and reflectance-estimated curing compound application on black paper, using the power equation in figure 27.

Actual application rate (m^2/L)	Estimated from Reflectance (m^2/L)
4.2	4.0
6.1	5.7
9.2	6.2

Of the methods investigated, only the direct weighing appeared to be reasonably suited for non-pigmented curing compounds.

The visual estimation of white pigmented curing compound appears to give reasonable results when a standard set of specimens is available for comparison. The visual detection limit (difference detectable in a side-by-side comparison) appears to be about 2 m^2/L. The sensitivity of this estimation probably would be substantially reduced if this frame of reference were not available, particularly if spatial variation in application rate was gradual. However, it is clear from this work that a concrete that is noticeably grey on visual examination is probably substantially undercoated, perhaps containing only half of the specified application rate.

The portable reflectometer appears to be a good tool for use in a method for quantitatively measuring curing compound application. The field portability of this instrument allows spot checking with minimal setup requirements. The instrument is battery operated and measures 10 by 15 by 5 cm. It measures reflectance on a spot approximately 2 cm in diameter. One approach to field quality assurance would be to develop a standard curve using job materials and then determine a reflectance value that corresponds with the desired application rate. Then that reflectance could be used as a criterion for evaluating the quality of application of curing compound in a field situation.

In conclusion, visual estimation of the application rate of white pigmented curing compound can be useful where a suitable reference comparison is available. Visual estimation is probably also reliable to detect areas of very low application rate in close proximity to areas of proper application rate. However, visual estimation is not a strong method for detection of low application rates when the under-application is slight or the low-application membrane is uniform. Measuring reflectance with a field reflectometer provides a useful tool for objectively determining subtle variations in application rates.

LENGTH OF CURING

Specification on the length of the final curing period has traditionally been prescriptive in format, and the more recent trend is toward performance-based specifications. Requiring curing for a fixed time interval is the usual prescriptive specification. This type of specification is still quite common with State DOTs. The advantage of fixed time interval requirements is that interpretation and enforcement are relatively simple. But, because of the simplicity of this type of specification, the requirements must be somewhat conservative and therefore may not be representative of actual onsite conditions. Rates of development of the physical properties of concrete vary widely, depending on materials, proportions, and temperature. Performance specifications typically take the form of requiring curing until a certain state of development of one or more physical properties is reached. Strength is the most common physical property used, but at least one agency has been reported to use surface water absorption as its criterion for some concrete.

None of the standard guidance mentions the effect of using pozzolan, even though it is common knowledge now that such concretes typically gain strength more slowly. A number of papers from the research literature cite a minimum of 7–10 days when pozzolan is used, although strength gain with Class C pozzolan is typically much faster than with Class F pozzolan, and there is a strong effect of amount of pozzolan used.

Table 16 summarizes various prescriptive curing requirements.

Source of Guidance	Guidance
ACI 318[3]	≥7 days at T ≥50 ^{o}C
ACI 301[43]	7 days, silent on temperature, pozzolans
ACI 308[31]	7 days when using Type I cement, 14 for Type II
ACI 308R[6]	No prescriptive recommendation
ACI 325[21]	7 days at T≥4 ^{o}C
AASHTO[33]	3 days, silent on temperature, pozzolans
USACE (CEGS 03300)[19]	7 days when using Type I cement, 14 for Type II
State DOTs	Most require 3 days, some 4 and 7 days.

Comparisons of strength gains among eight mixtures, four containing 20 percent (mass) Class F fly ash as replacement for cement, proportioned as part of USACE planning for an airfield pavement showed that about 7 days was required for the fly ash concretes to gain the same strength as gained in 3 days in concretes without fly ash. This suggests that an approximate doubling of curing time is required when Class F fly ash is used at this replacement rate, a relatively common level in pavements.

The AASHTO guidance may be based on development of flexural strength and on the typical behavior of paving concrete mixtures. Paving mixtures are typically proportioned with relatively high cement contents and relatively low water-cement ratios. As a result, 3-day strengths are often relatively high.

Three days is probably adequate time for most paving mixtures to develop strength sufficient for service when temperatures are around 20 ^{o}C or higher. However, rates of strength development at 10 ^{o}C may be only about half this rate, and it appears that allowing additional curing time would be of benefit. Perhaps an approach similar to that used in the UK (see appendix A, table 19) would be appropriate. This guidance bases lengths of curing required on maturity concepts, resulting in a set of curing times that graduate upwards as temperatures drop. Such an approach will be developed for this project.

Although strength development is the criterion on which prescriptive performance limits are based, properties of the concrete surface and near-surface zone are also very important in the long-term performance of pavements. No information was found to indicate that near-surface properties develop at a different rate than strength, but it is plausible that near-surface concrete may experience a significantly different temperature history than the concrete at greater depths. Thus, in cold placements, the most conservative curing guidance would need to be used. Also, concrete away from the surface will continue to hydrate after deliberate curing is terminated; concrete in the near-surface zone may or may not, depending on the climatic conditions. Conservative guidance may need to be followed in dry climates.

As is common knowledge for concrete systems, the time required to attain a given set of properties that depend on the extent of cement hydration is affected by a large number of variables, including properties of the cement, presence of pozzolan or slag, properties of the pozzolan or slag, temperature history, water-cement ratio, cement-aggregate ratio, and effect of admixtures. The cumulative effect of these creates such a variation in strength gain that no single prescriptive curing time can reasonably capture them all. Consequently, general prescriptive guidance should be relatively conservative, relying on performance tests or more sophisticated development of prescriptive times based on specific project conditions as an optional approach.

Given the tendency for concretes to be proportioned so that strength development will be substantially faster than the minimum requirements, it seems likely that the designer would want to include optional approaches that would allow for shorter curing times when justifiable. Temperature is likely to be the most common cause for variation from the prescriptive guidance if concrete materials and mixture proportions are held constant. A common rule of thumb developed from the Arrhenius relationship, which is the basis for some maturity calculations, is that time required to reach a given strength approximately doubles for each 10 °C increase in temperature, or conversely halves for each 10 °C decline. This suggests that a 7 day requirement at 10 °C would become a 3.5 day requirement at 20 °C, and a 1.75 day requirement at 30 °C.

Darter (1988) published a table of minimum opening times for pavements that corrects for temperature.(89) Results are similar to the Arrhenius approximation given above. The guidance also accounts for pavement thickness, with thinner pavements needing more time than thicker ones. The table covers pavements 180–250 mm thick. For the 180-mm pavement, the guidance is for 4.5 days at 10 °C, 2.5 days at 20 °C, and 1.5 days at 30 °C.

It is becoming increasingly common to use the maturity method as an in place estimator of strength gain based on real-time monitoring of concrete temperatures. To make best use of this technology some experience and thought must be given to the location of temperature sensors because of the relatively wide variations in temperature history among the various types of locations in a pavement (e.g., edges, top surface, center, etc.). Typically a number of locations will be instrumented so that the engineer can develop at least a partial mapping of strength development over the pavement. Hardware and software are commercially available to set up such a program, and there are consulting firms that provide this service.

Other performance methods are used to account for the variation in strength gain. One of the oldest is the use of field-cured cylinders. With this technique, cylinders are placed in locations near the placement that will give the best simulation of the temperature history of the in place concrete. This method is very simple to execute, but is commonly criticized for often representing a poor approximation of the in place condition.

A technique commonly used in precast concrete is temperature-matched curing. In this method, a thermocouple in the concrete structure feeds back to a temperature controller on a curing chamber containing standard strength cylinders. The temperature of the curing chamber then tracks the temperature in the placement, so that the cylinder strengths reasonably represent in place strengths. Use of this method would require judgment in determining the location in the concrete structure from which to take this “guide” temperature.

TEST METHODS FOR MEASURING CURING EFFECTIVENESS

As mentioned in the preliminary report, a wide variety of test methods have been developed for determining the degree of physical property development in the near-surface zone of concrete as a result of curing. Many of these require specialized equipment and are not easily applied in the field. Lack of control of moisture content of the field concrete is often fatal to the field application of a test method. Several methods were thought to be plausible and some work was done to verify this.

Ultrasonic Pulse Velocity

Ultrasonic pulse velocity (UPV) is related to the modulus of elasticity of the concrete. Given that the modulus tends to increase with degree of hydration of the cement, UPV would appear to be a good tool for monitoring effectiveness of curing. Literature on the technique indicates that such a method should be workable, although the specialized nature of the equipment and the sophistication of the data analysis reported in this literature suggest the technique may be more complicated than is suitable for easy field application, at least without some development. A relatively simple analysis was done in this project to verify the plausibility of application for analysis of curing.

Concrete specimens made at a water-cement ratio of 0.42, 244 kg/m^3 cement, 81 kg/m^3 Class F fly ash, 926 kg/m^3 coarse aggregate, and 870 kg/m^3 of sand, 25-mm slump were cast into 150 by 150 mm cylindrical molds (cut down from 150 by 300 mm standard strength molds) and exposed to 38 °C, 30 percent RH, 3.3 m/s wind for 6 days. Four curing treatments were applied: no curing, curing under plastic sheet, a light coating of curing compound, and a heavy coating of curing compound (about 9 and 4 m^2/L, respectively, estimated from reflectance). Specimens were demolded and UPV measurements taken by placing the transmitter on one margin of the top surface and the receiver on the far margin. The distance between the centers of the two was 120 mm. Four measurements were taken for each specimen. Table 17 summarizes the averages and standard deviations.

The pooled standard deviation among readings is 21 m/s (standard error among means = 11 m/s). The bottom of the specimens should have all been cured to approximately the same degree, so the standard deviation among the means (mean = 2720 m/s, s = 64 m/s) should give some estimate of variation to be expected among sampling sites on a single placement.

Table 17. Comparison of Ultrasonic Pulse Velocity (m/s) among curing conditions.

	No Curing	**Plastic Sheet**	**Curing Compound, 4 m^2/L**	**Curing Compound, 9 m^2/L**
Mean (n=4) of top surfaces	2660	2750	2710	2730
Standard deviation among determinations	44	7	4	9
Mean (n=4) of bottom surfaces	2740	2790	2640	2710
Standard deviation among determinations	14	37	4	6

The difference between the completely uncured surface and the plastic covered surface was large enough that the difference would be detected with reasonable certainty by averaging about four sampling sites. However, the method, as executed here, was not sensitive to detecting degradation in curing due to under application of curing compound. It would then appear that the method would not be particularly good at detecting other relatively subtle variations in curing, at least as demonstrated with this equipment.

This result should not be taken as a total invalidation of the method, but as an example that simple application of the technology might not be sufficient to detect curing effects. More sophisticated hardware and data analysis procedures exist and these might be able to detect such differences.

Rebound Hammer

The rebound hammer (ASTM C 805)[(80)] is intended, as described in the scope of the test method, to provide an in situ method for estimating strength. C 805[(80)] requires calibration by actually measuring strength on companion cylinders or cores taken from the concrete, therefore, the rebound number is only a relative indicator of strength. The method is often disparaged because it is most sensitive to near-surface properties of the concrete and may not represent the properties of the concrete as a whole very well. Though this may be a weakness for estimating gross strength, it was thought to potentially represent a strength for evaluating curing of near-surface concrete. A major outstanding question about use of the method for evaluating curing is whether the rebound numbers of very weak near-surface concrete are within the operating range of the instrument.

The approach to evaluating this method was to fabricate concrete specimens that had deliberately been given poor curing, then to determine whether this was detectable by C 805.[80]

In one experiment, 100 by 200 by 75 (w-l-d) mm concrete specimens were fabricated at a water-cement ratio of 0.45, 350 kg/m^3 of portland cement formed into Nalgene pans. Specimen edges were sealed so that only the 100 by 200 mm surface was exposed to drying. Specimens were placed in an environmental chamber at 38 °C, 30 percent RH, and 3.3 m/s wind, directed onto the surface of the specimens. At several ages, the specimens were demolded and rebound number determined on both the top and bottom of the specimen.

Rebound numbers on relatively small specimens is strongly affected by the surface supporting the test specimen. Even well cured specimens will give very low rebound numbers if tested while sitting on a soft, flexible, or uneven surface. To give a rigid surface, a concrete cylinder (330 mm diameter by 700 mm high) was used as a base for the test specimens during testing. The average of ten relatively evenly spaced determinations was taken as a test result for each specimen. The top of the specimen (exposed surface) was expected to show significant impact of the poor curing, and the bottom of the specimen was considered to be at least relatively well cured given the common belief that the effects of poor curing do not penetrate much beyond 50 mm. Figure 28 shows the results.

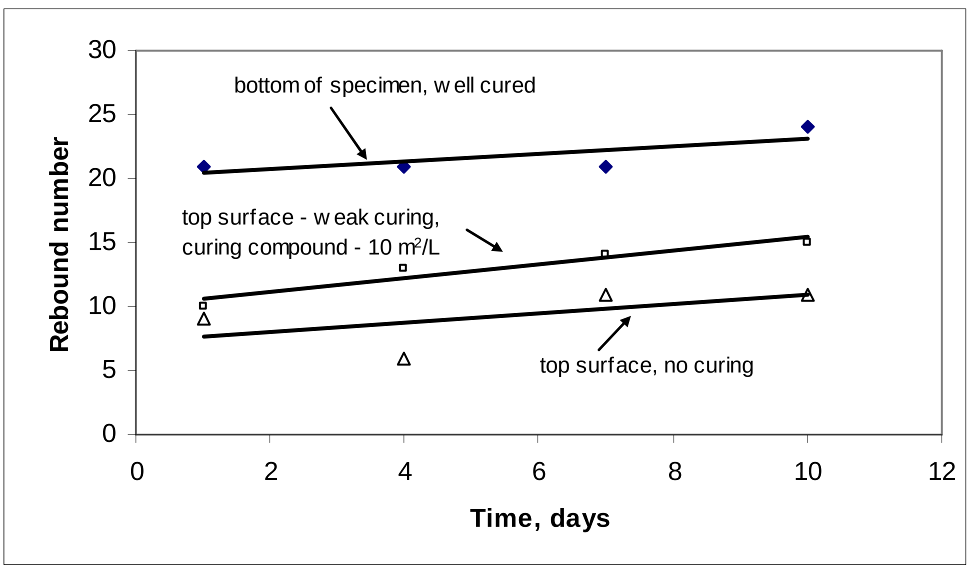

Figure 28. Effect of curing quality on development of rebound number at early ages. Specimens cured at 38 °C.

In a similar experiment involving only measurement of top or exposed surfaces, conditions of no curing, light curing compound, heavy curing compound, and plastic sheeting were compared, as shown in figure 29.

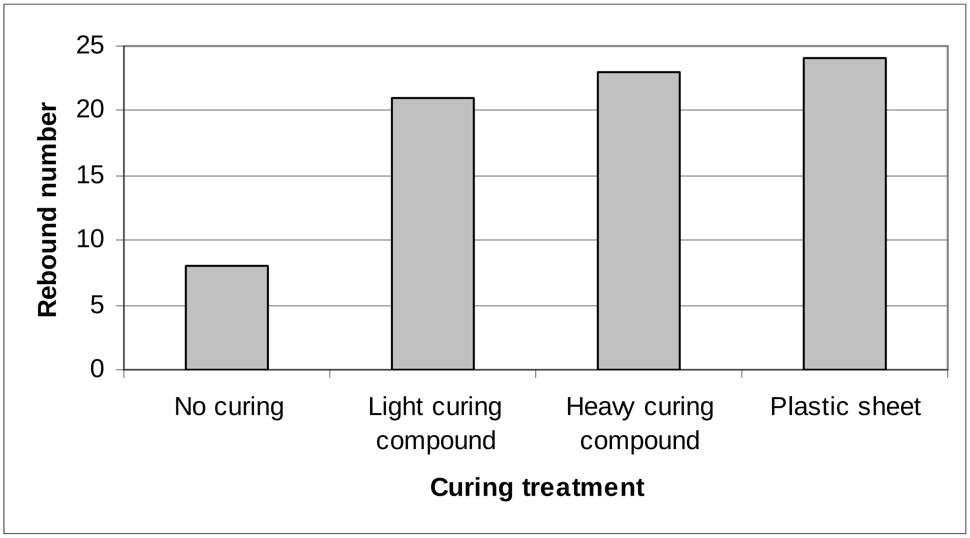

Figure 29. Effect of curing condition on rebound number of top surface of specimens at 7 days.

Rebound number was also used as one of the measures of curing effectiveness during many of the experiments in other parts of this work, along with surface water absorption and measures of water-loss from specimens. There was a relatively strong correlation between water absorption and rebound number in these data, as shown in figure 30, as well as between rebound number and water lost in the final curing period (figure 17, above).

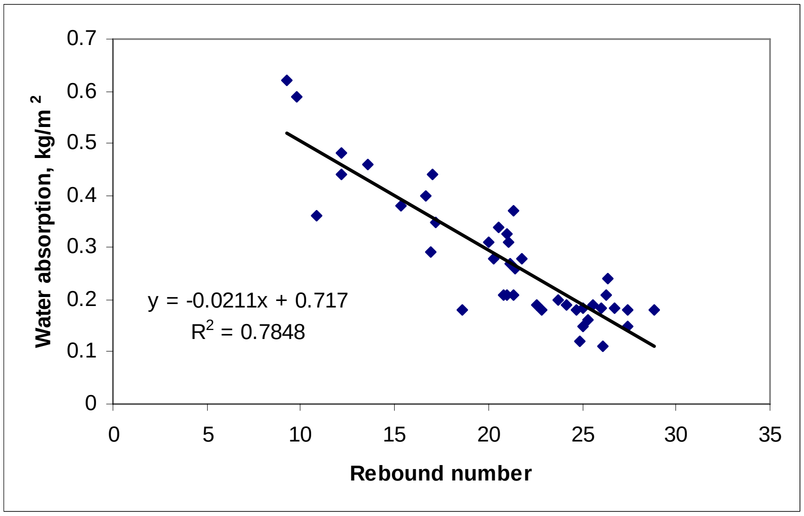

Figure 30. Correlation between rebound number and surface water absorption.

In field application, it would probably be best to select a section of pavement to serve as a standard condition, in which good curing could be assured, e.g., cured with water, or covered with plastic sheeting, or treated with curing compound under well controlled conditions. Then the rebound numbers determined on this control area could be used as a standard of comparison for the remainder of the pavement.

Surface Water Absorption

As found in the literature review, abundant evidence shows that surface water absorption is a useful tool for measuring the quality of concrete curing. Surface water absorption was the basis of ASTM C 1151 (test method for evaluating curing compounds).[27] This method has since been withdrawn for lack of use in testing curing compounds, but in principle it may still be the basis of a useful method for evaluating the quality of curing. The objective in this investigation is to develop some information on the sensitivity of the method to variations in curing. It is one of the methods that is sensitive to the moisture content of the concrete; hence, it is difficult to apply in the field. However, it can be easily applied to cores without elaborate equipment, and since coring is such a common way to obtain samples to evaluate field concrete, it should be evaluated further and is included in the revised guide.

Concrete specimens identical to those used in the ultrasonic pulse velocity evaluation were used. Four specimens were cast in and stored at 38 °C, 30 percent RH with no wind until bleed water had stopped appearing and surface sheen had disappeared (4 h). One specimen was then left unprotected, another was covered with a plastic sheet secured around the edges with a rubber band, another was treated with curing compound at 4 m^2/L, and the last one was treated with curing compound at 9 m^2/L. Specimens were exposed to 38 °C, 30 percent RH, 3.3 m/s wind for 11 days. The specimens were demolded and sawed into slices parallel to the exposed surface at approximately 15–25 mm thickness, creating surfaces that could be tested at several distances away from the exposed surface.

To standardize the finished surface of the concrete specimens to the sawed surface of the pieces cut from deeper into the specimen, a small amount of material was also sawed from the exposed surface of the specimen. More material was removed from the poorly cured specimens than from the well-cured ones because of some difficulty with sawing weak material. This is shown in the results. Specimens were dried at 60 °C, cooled, and weighed. A shallow dish was partially filled with water and paper towels folded and placed so that the concrete specimen surface would be wet, but the sides would be minimally wet when set onto the paper towels. The specimen was left for 60 seconds, excess water blotted off, and then weighed. The water absorption was calculated as the mass of water absorbed divided by the surface area, in units of kg/m^2.

This method appears to clearly distinguish among the curing treatments. Results are summarized in figure 31. The concrete that was not cured showed a strong relationship between water absorption and depth down to at least 75 mm below the surface. The effect was also discernable on the lightly cured specimen, but it was not as strong and truncated at about 50 mm. The specimen that received the heavy coat of curing compound showed a slightly higher absorption near the surface, but this could not be reliably distinguished from the pattern of the specimen covered in plastic sheeting.

The data representing the specimen covered in plastic showed a slight negative slope, suggesting that the near-surface concrete was actually either slightly better cured or slightly more dense. The latter seems more plausible.

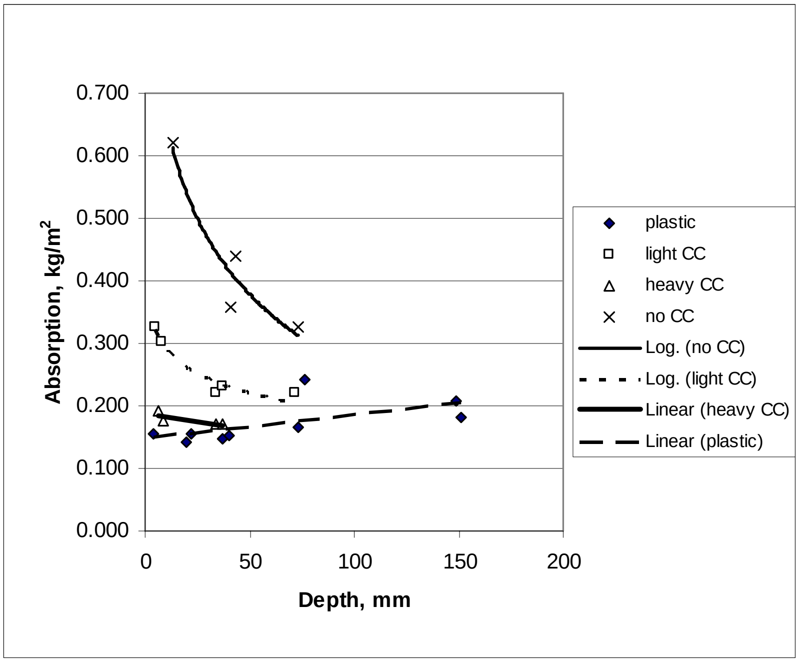

Figure 31. Surface water absorption versus depth for concrete cured with different methods.

An estimate of testing error can be derived from these data. Assuming that the degree of curing is about the same for all specimens below approximately 35 mm (except the one with no curing), then the variation among specimens is an indicator of the expected error in the method among sampling sites within a concrete placement. The coefficient of variation among these values was 16 percent. Therefore, for improved sensitivity in detecting effects, best results would be obtained if several sites were sampled and results averaged. Averaging over 4 would reduce the coefficient of variation to 8 percent. This would result in a method that would be reasonably sensitive to a 20 percent difference in water absorption.

Taking the water absorption on both sides of the saw cut as a replicate of the test method on the same concrete, the CV was found to be 11 percent.

This method was used as one of the tools for evaluating the effects of water losses in the section on evaporation of water from concrete. Figure 18 (p. 69) shows the relationship between water loss in the final curing period and water absorption of the concrete surfaces. This also supports the plausibility of the method.

To further develop the implications of the water absorption test, 75 by 75 by 250 mm prisms were cast and given the same treatments as the cylinders. Brass measuring pins were embedded in the surface and length change measured with a Whittamore gauge. The pins penetrate to about 15 mm into the concrete. Figure 32 shows the relationship between shrinkage and surface water absorption.

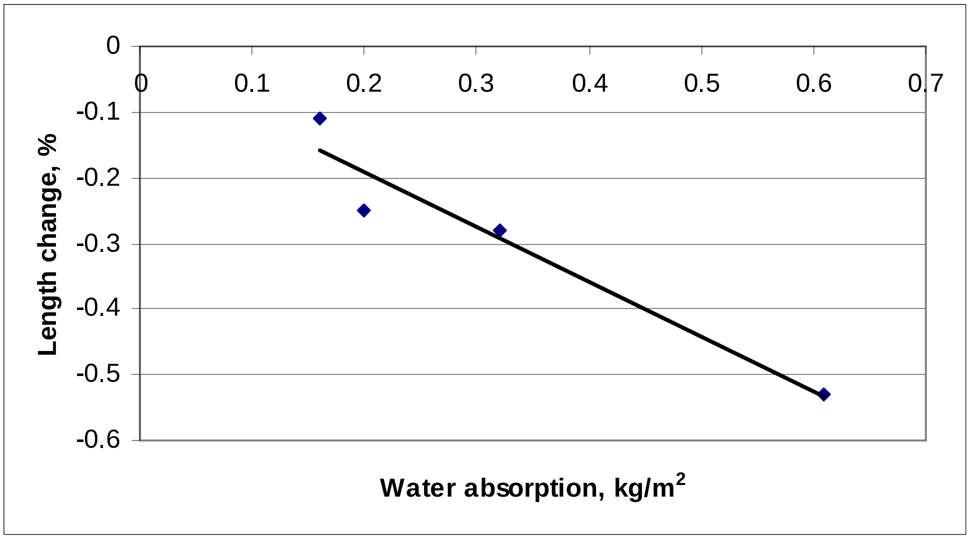

Figure 32. Relationship between shrinkage of near-surface zone of concrete and water absorption after 11 days of exposure to drying conditions.

The most serious drawback to the water-absorption method is that it requires that cores be taken so the effects of concrete moisture condition can be removed by drying. Doug Hooton of the University of Toronto has developed a variation of this test that allows in situ measurements and is purported to have a method for correcting for the water in the concrete (personal communication).[90]

Abrasion Resistance

As covered in the literature review (appendix B), abrasion resistance is considered to be one of the major properties affected by curing, and it appears be a useful basis for a field applicable test method. Work by White and Husbands (1990) also showed this method to have promise.[85] Part of the procedure for the water absorption test was to scour the surface of the specimen with a powered wire brush or a horizontal polishing wheel using coarse grit. It became evident from this experience that the mortar fraction of poorly cured specimens had poor abrasion resistance. The mortar was easily removed from between the coarse aggregate particles. Care had to be taken not to remove too much mortar, thus negatively impacting the water absorption test. However, it also became apparent that the abrasion resistance of the coarse aggregate would dominate an abrasion test that was based on grinding the surface with a cutting wheel or other abrasive device that acted on a relatively large surface. Therefore, efforts ceased on developing and evaluating an abrasion resistance method for concrete. Some kind of method-based use of a powered wire brush under controlled pressure could probably be developed and might be field applicable, but this was not pursued.

Chemically Combined Water

Measuring the amount of chemically combined water is one of the oldest methods for measuring the amount of hydration in cement pastes. It is not field applicable, but like water absorption, it can be executed on cores.

Hydration products of portland cement decompose at about 550 °C, releasing the water to evaporation, which is detectable by mass change. Therefore, mass-loss differences between 110 °C (which removes free water) and 550 °C give an indication of the amount of hydrated cement paste.

White and Husbands (1990) performed an evaluation of this method for detecting differences in curing quality of mortars and found the anticipated effect, but the differences were small enough that they concluded the method to lack adequate sensitivity for this purpose.(85) The sensitivity would be made considerably worse if applied to concrete because of the relatively low mass percentage of cement in concrete, even relative to mortars. This method was not pursued further.

THERMAL STRESS DUE TO EVAPORATIVE COOLING

ACI hot weather guidance (ACI 305R) cautions about creating situations in which the surface of the concrete is cooled to more than approximately 10 °C cooler than the interior of the concrete.(12) USACE guidance is to allow no more than a 13 °C gradient between the surface and a depth of 50 mm into the concrete (CEGS 03300, paragraph 3.15.6).(19) Gradients sufficient to cause cracking have been reported on structures that were water cured in windy conditions. This seems unlikely in a PCC pavement, but an examination of the necessary evaporation conditions required to create this temperature difference is evaluated in this section.

A set of five laboratory experiments was conducted in which a 50 mm (thick) by 150 mm (diameter) piece of concrete was warmed to plausible pavement temperatures, surface wetted, and exposed to various evaporation conditions. Temperature differences between the evaporation surface and the bottom were measured. Initial evaporation rates (at the start of the experiment) were calculated from the ACI nomograph using measured concrete temperature, wind velocity, RH, and air temperature.

Figure 33 illustrates temperature differences between the concrete surface and the 50 mm surface in such an experiment. The concrete temperature started at 44 °C, wind velocity was 4.6 m/s, air temperature was 22 °C, and RH was 29 percent.

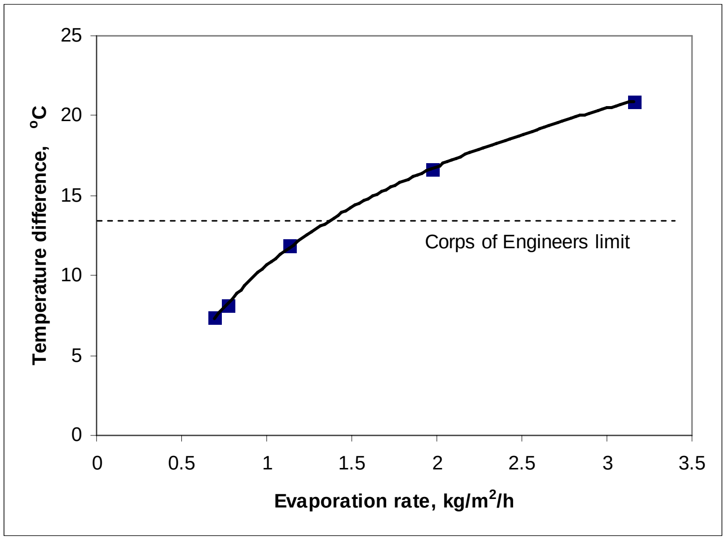

Figure 33. Relationship between maximum temperature gradient between concrete surface and 50 mm depth versus initial evaporation rate calculated from the ACI nomograph.

In general, the 50 mm surface gradient was reasonably predictable from estimates of initial evaporation rates from the wet surface. Figure 34 shows this relationship. The evaporation rate required to achieve a 13 °C gradient is about 1.4 kg/m^2/h. In these experiments, the air flow was directed immediately at the surface of the specimen. As shown above in the previous discussion on the evaluation of the accuracy of the nomograph, such conditions were found to give actual mass losses of water about twice that calculated from the nomograph.

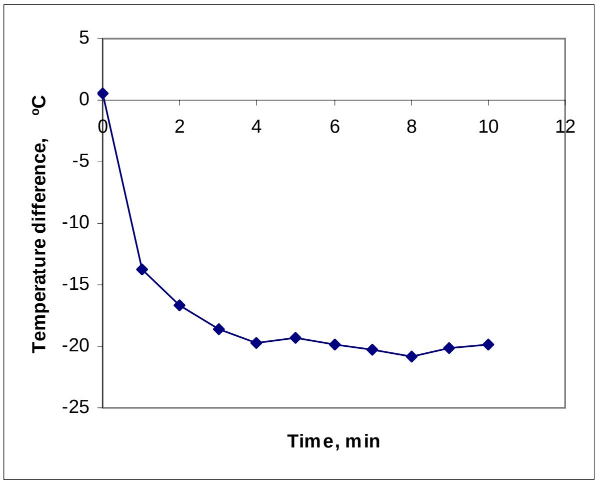

Figure 34. Temperature gradient in a 50-mm thick specimen starting at 44 °C, air temperature of 22 °C, RH of 29 percent, and windspeed of 4.6 m/s.

This does not appear likely to be a major source of problems with portland cement concrete pavements, given that most are cured with curing compound, but it could be a problem with some fast-track paving in which high curing temperatures and water are used under insulation blankets. Sudden removal of the coverings could present a warm, wet surface which, if windspeeds were high enough, cause sufficient gradient to result in cracking.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

No major inconsistencies in the theoretical aspects of curing portland cement concrete were found as a result of this work, but the results did illuminate several important details in curing practice that need particular attention in the construction of portland cement concrete pavements that may not be adequately emphasized in current standard guidance These are described below.

Pavement engineers need to be more aware of the conditions that favor development of plastic shrinkage cracking and to be cognizant of when they become critical during a particular construction project. Most current guidance focuses on evaporation conditions as the only relevant variable. Bleeding behavior and time of setting of the concrete are also important variables in determining how and when evaporative water loss affects the development of early cracking. It is well known that the balance between bleeding and evaporation is the critical variable in the development of early-age cracking, but most guidance seems to assume the bleeding rate is approximately constant, so that evaporation condition is considered the only important operational condition. Slip form paving mixtures typically have low bleeding rates, so that conventional guidance on evaporation rates may not be correct in many instances.

Bleeding behavior and time of setting should be determined during mixture verification work. Also as part of preconstruction planning, engineers need to develop a forecast of probable drying conditions based on plausible conditions for a job site, then using direct measurement of evaporation rate, or calculations from on-site conditions, to make adjustments to the evaluation during construction. It is relatively common practice to use intuition rather than measurement to estimate drying conditions—hot, dry, windy conditions being associated with severe drying. Another extremely important variable is concrete temperature, which is often not considered at all. Given the relatively low bleeding rates of slip form pavement mixtures, seemingly modest drying conditions can be critical.

Guidance on the timing of the start of final curing needs to be revised. Most guidance directs that curing be applied after final finishing and disappearance of sheen. Applying this guidance to modern paving mixtures being used with slip form paving technology would often result in application of final curing within a few minutes of placing. This could result either in damage to the concrete surface or in poor curing. The optimal time for application of final curing is after time of initial setting and then when the sheen has disappeared.

Delaying application of final curing until after time of setting may require considerable attention to detail on managing evaporative losses in the time interval between placing and time of setting. Evaporation reducers show considerable promise for being effective in dealing with high evaporation rates from fresh concrete during this initial curing period. However, a serious impediment to their widespread acceptance is the absence of standard test methods and specifications with which users can evaluate materials and to give the user an accurate picture of the limits on performance that can be expected in field application.

Reducing concrete placing temperature below the maximum allowed by most guidance would have a major effect on reducing rate of evaporative water loss. However, it is unlikely that contractors will voluntarily do this for economical reasons. Revised prescriptive specifications on maximum placing temperature would help control incidents of surface cracking. Prescriptive specifications are declining in popularity in favor of performance specifications. A performance specification could plausibly limit development of surface cracking, however development of such a specification might be difficult. Accelerating the time of setting during particularly strong evaporative conditions should, in theory, be another effective way to reduce evaporative water losses and surface cracking, but the practical side of this has not been investigated.

Testing of curing compounds continues to be a contentious process, due principally to the large between-laboratory variation in the test method. As a partial result of this lack of precision, many agency specifications for water-retention may be more restrictive than theoretically needed. In this work, it was determined that time of application of the curing compound to the test specimen is probably at least one major source of between-laboratory error, but considerable additional work needs to be done on this method to make it suitable for acceptance testing.

Measuring application rates of white pigmented curing compound lends itself to optical methods. Visual verification of white pigmented curing compound application is probably a legitimate quality assurance technique for estimating uniformity. The human eye seems to be sensitive to relatively minor changes in shades of gray that result when insufficient application of curing compound occurs. But, to verify actual applications rates for specification compliance purposes, the observer needs to develop a visual concept as to what degree of whiteness constitutes an adequate application for a given curing compound. Using a portable paint reflectometer was shown to be a practical way to improve accuracy for curing compound application estimates.

The rebound hammer was found to be a simple and useful device for estimating effectiveness of curing. This instrument is often criticized as being overly sensitive to surface conditions, which makes it particularly suitable for evaluating curing.

Another research and development need for concrete paving technology is the development of a curing compound that can be applied to concrete relatively soon after placing concrete. The material would act as an evaporation reducer before time of setting, and then function as an effect curing membrane during the final curing period.

The maturity method has been shown to be effective in estimating early-age strength. Lack of experience by users appears to be the major obstacle to its more widespread use. Use of the maturity method should be pursued as an alternative to the common prescriptive curing time requirements. In many cases, this would probably shorten curing times. The method also gives a rational way to deal with the effects of cold weather on strength development.

Guidance developed for curing pavements as a result of this study is contained in Volume I entitled *Guide for Curing of Portland Cement Concrete Pavements* (FHWA RD 02-099).[5]

APPENDIX A: ANNOTATED LIST OF PERTINENT STANDARDS AND COMMITTEE REPORTS

AMERICAN CONCRETE INSTITUTE (ACI)

The American Concrete Institute (ACI) *Manual of Concrete Practice*(91) contains the major general purpose concrete standards and state-of-the-art committee reports on concrete in the United States. Several of these standards and reports address curing. The highest level standard, in a regulatory context, is the Building Code Requirements for Structural Concrete (ACI 318-95(3)). Curing is one topic in this general standard for concrete. The Standard Specification for Structural Concrete (ACI 301-96(43)) is also a general concrete standard, but it does not have the regulatory authority of the Building Code. This standard is used to develop contract agreements on execution of concrete construction. Recommendations in ACI 301(43) should not exceed the guidance in ACI 318-95(3).

ACI standards specific to curing are ACI 308-92, Standard Practice for Curing Concrete(31), and ACI 308.1-98(45), Standard Specification for Curing Concrete. As with ACI 301(43), ACI 308.1(45) is used to develop contract agreements, the requirements of which should also fall within the limits of the ACI 318-95.(3) A new standard, Guide for Curing Concrete, has been written by ACI Committee 308.(92) The eventual result is probably that ACI 308R(6) and ACI 308.1(45) together will replace ACI 308.(31) Other official documents that contain guidance on curing are ACI 305R(12) on Hot Weather Concreting, ACI 306R(14) on Cold Weather Concreting, ACI 325.9R(21) on Construction of Concrete Pavements and Concrete Bases, ACI 330R(45) on Design and Construction of Concrete Parking Lots, ACI 330(93) on Specification for Concrete Parking Lots, and ACI 228.1R(49) on In-Place Methods to Estimate Concrete Strength.

Generally, ACI standards and committee reports focus primarily on prescribed curing times or on some fraction of specified strength as quantitative criteria. Durability criteria allowances are discussed but have not been developed. There is little consideration for the specific materials or proportions of materials used in the concrete mixture, although some ACI standards consider portland cement type and rate of strength gain. There is some mention of accounting for water-cement ratio, but this is not well developed. Considerable attention is given to details of different curing methods. Temperature is mostly considered in the context of maximum and minimum allowable concrete temperatures, protection from freezing, and thermal shocks. Time-temperature considerations are dealt with in the context of cold weather and in use of the maturity method when it is allowed for predicting the time to end curing. The following paragraphs discuss each standard in some detail.

ACI 318-95, Building Code for Structural Concrete(3)

Meeks and Carino (1999) review the history of the Building Code guidance on curing.(4) Guidance in the 1995 version is relatively simple. It directs that concrete, other than high-early strength concrete, be maintained above 10 °C and kept moist for at least 7 days. Curing for high-early strength concrete should be maintained for 3 days with temperatures also above 10 °C. Temperature-accelerated curing is allowed, but the details must be developed by the user and durability must not be worse than when the time-based prescriptive requirements are used. For details, reference is made to ACI 308[31], ACI 306R[14] (cold weather concreting) and ACI 305R (hot weather concreting).[12]

ACI 301-96, Standard Specification for Structural Concrete[42]

Curing is addressed in section 5.3.6 of the body of the specification. There is no mention of curing in the Mandatory Requirements Checklist. The general requirement is to cure for 7 days after placement (3 days for high early-strength concrete), but moisture retention measures may be terminated when: (1) field cured cylinders reach 70 percent of required strength (f_c'); or (2) the temperature is 10 °C or higher for the time required to achieve 85 percent of f_c' in laboratory cured cylinders; or (3) the concrete's strength reaches f_c' as determined by accepted nondestructive methods. A reference is given for the accepted nondestructive methods (paragraph 2.3.4.2). These methods include cast-in-place cylinders (ASTM C 873[94]), penetration resistance (ASTM C 803[95]), pullout strength (ASTM C 900[96]), and maturity (ASTM C 1074[39]).

Methods allowed for moisture preservation include:

- Ponding, continuous fogging, or continuous sprinkling.
- Keeping mats or fabric wet.
- Applying steam (<150 °C) continuously.
- Using of sheet material (ASTM C 171).[17]
- Using of curing compounds (ASTM C 309).[23]
- Other accepted moisture-retaining methods (unspecified).

A proposed revision of ACI 301[43] was published in the July 1999 issue of *Concrete International* (v. 21 n. 7). The new guidance allows that curing compounds be specified by ASTM C 1315[24], as an alternative to C 309[23] and that concretes containing silica fume be cured with added-water methods.

Additional information on the use of curing compounds is given in ACI 301-96.[43] Curing compound should be applied according to the manufacturer's instructions after the water sheen has disappeared from the concrete surface and finishing operations are complete. The rate of application should not exceed 5 m^2/L. For rough surfaces, two coats are required, applied at right angles, at an application rate not to exceed 5 m^2/L. ACI 301-96[43] also cautions that curing compounds act as bond breakers.

Section 4.2.2.7 sets minimum concrete temperatures, varying from 10 °C to 13 °C, depending on the cross-sectional area. Maximum allowable concrete temperature is 32 °C.

ACI 308-92, Standard Practice for Curing Concrete[31]

Chapter 1 of ACI 308[31] discusses general curing needs and presents the well known nomograph relating evaporation from a free-water surface to temperature, wind velocity, and relative humidity. A value of evaporation of 1.0 kg/m^2/h or more requires measures to prevent excessive moisture loss from the surface of the concrete. An evaporation rate greater than 0.5 $kg/m^2/h$ may also require some measures to control evaporation. Chapter 1 also defines the temperature limits for placing concrete. The practical lower limit is 10 °C, although hydration has been shown to continue down to –10 °C. The recommended upper limit is approximately the maximum temperature anticipated during service, although temperatures over 100 °C are sometimes used for accelerated-curing purposes.

Chapter 2 describes various curing methods, materials, and evaluation procedures. Materials that allow extra water to be applied to the concrete (aside from the mixing water) via ponding, spraying, and continuously wetting include mats, earth, sand, sawdust, straw, and hay. Materials that simply retain mixing water include plastic sheets, treated paper, and liquid membrane-forming curing compound. ASTM C 156[18] is cited (section 2.8) as the general method to use to evaluate curing materials, although the most recent revision of this test method includes only liquid membrane-forming curing compounds. This method is discussed in detail below.

Section 2.3.3 describes curing compound practices. Application rates of 0.20 to 0.25 L/m^2, usually expressed as 4.0–5.0 m^2/L are recommended. There are recommendations on application practices and a caution about the damage to concrete surfaces that can result if curing compound is applied too early, while bleeding is still occurring, even though the bleeding is imperceptible due to the high evaporation rates.

Section 2.9 gives criteria for effectiveness of curing. The basic criterion is prescriptive. The document states that, if surface moisture and temperature are maintained within "desired" levels, then adequate curing will result. Procedures are described for measuring strength development and for using maturity to assess the degree of curing. Neither of these is sensitive to the degree of curing of surface or near-surface concrete, which can be essential in determining some durability properties.

Section 2.10 recommends the length of curing to be 3 days for concretes containing Type III cement and 7 days for concrete containing Type I cement. Length of curing for concretes containing Type II cement is recommended to be 14 days. There is no recommendation for concretes containing Type IV cements (which are either nonexistent or extremely rare) or Type V cement or for concretes containing pozzolans or slag.

Chapter 3 deals with specific types of construction. Section 3.1 is specific to pavements and slabs. These types of structures are particularly sensitive to curing because of the high surface-volume ratios. They are also sensitive to thermal stresses caused by environmentally related temperature cycling. Under extreme evaporation conditions (unspecified), curing may be required even before the concrete has set. At temperatures greater than 5 °C, curing should be maintained for 7 days or until concrete reaches 70 percent of its specified compressive or flexural strength.

ACI 308.1-98, Standard Specification for Curing Concrete[45]

This standard defines two new terms: initial curing and a final curing. Initial curing is defined as "deliberate action taken between placement and final finishing of concrete to reduce the loss of moisture from the surface of concrete.” Final curing is defined as “deliberate action taken between the final finishing and termination of curing.”

The initial curing period is normally neglected unless hot weather or water-cement ratios lower than 0.40 exist. The latter condition is only mentioned in a “Note to the Architect/Engineer” in the “Mandatory Specification Checklist.” There is no other mention of mixture proportions. Fogging (section 5) and entrapment of bleed water under a uniform film of evaporation retardant are the only methods allowed for curing during the initial curing period.

Length of curing is either a predetermined period of time or determined by a level of strength or durability (paragraphs 1.1.6 and 1.6.4). The default curing time is 7 days if the temperature is greater 10 °C. Curing may be terminated early if strength is at least 70 percent of f_c' or if desired levels of durability are reached. There is no additional information on the latter criterion, except in the “Notes to the Architect/Engineer,” which references ACI 308[31], ACI 201.2R, and ASTM STP 169C (Senbetta (1994)).[52] Durability criteria must be determined by the designer. Additionally, any of the following moisture-retention techniques are allowed: sheet materials, pigmented curing compounds, addition of water, water-absorbent materials.

Section 2 discusses moisture retention using sheet materials (ASTM C 171).[17] Inspection directions require that the concrete surface be verified visually as being continuously wet. If dry spots are found, then additional water must be added. It is noted in the “Optional Specification Checklist” that the Architect/Engineer may specify the frequency of inspections. It also directs that dark sheets be used when temperatures are less than 15 °C and that white sheets be used when daily high temperatures are greater than 30 °C. The optional checklist also advises that when the temperature during the first day after placing exceeds 20 °C, then white or similarly reflective sheeting is preferable.

Section 3 on liquid membrane-forming curing compounds requires that materials comply with ASTM C 309 and be white or gray pigmented to reflect light.[23] It also requires use of power spray equipment unless the surface to be covered is less than 200 m^2 or if overspray of curing compound to adjacent areas must be avoided, in which case hand pump spraying is allowed. Materials must comply with regulations on VOCs, although no information is given on these regulations. The optional checklist allows non-VOC compliant materials if they are allowed by regulations of the using agency.

For floors with high wear resistance requirements, optimum top-surface strength, and minimal crack widths, the optional checklist allows that a curing compound may be specified with lower moisture loss requirements than in ASTM C 309.[23] A maximum moisture loss of 0.3 kg/m^2 at a coverage rate of 7.4 m^2/L is recommended. Heavier application rates or multiple application rates may also be specified as optional requirements.

Section 4 on ponding requires that the temperature of curing water be no more than 10 °C cooler than the surface of the concrete. Water must meet the requirements of ASTM C 94.[14]

Section 5 on fog spraying requires that the water meet the same requirements as for ponding. During initial curing, water must be directed so that the fog drifts down onto the concrete to prevent damage to the surface. No water is allowed to accumulate until after the time of setting. During final curing, the requirement is to keep the concrete continuously wet.

Section 6 on sprinkling requires that the water meets the same requirements as for ponding. Sprinkling is allowed only for final curing to avoid erosion of the concrete surface, unless the concrete surface is protected by a form.

Section 7 on water-absorbent materials requires that water meet the same requirements as for ponding. There is a caution on staining of materials, and burlap must meet AASHTO M 182.(20) This technique must only be used for final curing and materials must be kept continuously wet.

ACI 308R-01, Guide to Curing Concrete(6)

This standard is essentially a major revision of ACI 308(31) and contains quite a bit of pertinent information. The guidance on recommended requirements is not radically different than provided in other ACI standards. The basic requirements are already published in ACI 308.1(45) described above, but the guide contains considerable supplementary information that is not currently in any of the other ACI guidance.

The guide presents a good discussion of important considerations in the first minutes and hours after placing concrete, before final finishing and application of final curing. Duration of curing and properties of the surface-affected zone are also considered in ways different from most other guidance. The guide contains a section specific to pavements and slabs and a chapter on monitoring curing and curing effectiveness.

ACI 306R-88, Cold Weather Concreting(14)

This standard is an advisory document intended as supplemental material to the contract specification. Much of it deals with practices useful in avoiding freezing concrete at early ages. Section 6 deals with the issue of slow strength development at low temperatures. An example of the use of the maturity method is given. A tabulation (table 18, below) is given for minimum length of curing at two temperatures (10 and 21 °C) needed to obtain various percentages of 28-day strength. Allowance is made for cement type (I, II, and III).

Section 7 is about insulation. Extensive tabular data are presented by which the user can select the insulating factor (R) of insulation needed to maintain concrete temperature at 10 °C for either 3 or 7 days. The tables account for thickness of the structural member, number of sides exposed to air, and ambient temperature. This procedure is based on retention of the heat of hydration of the cementitious materials in the concrete. There is no adjustment for the variable heat of hydration exhibited by different cementitious materials.

Section 8 addresses curing requirements and methods. Heated enclosures tend to create drying conditions, so attention must be paid to moisture retention. Water curing is not recommended because of the practical problems associated with freezing of leaking water.

Table 18. Reproduction of table 6.8 of ACI 306R-88[14]. Duration of recommended protection for percentage of standard-cured 28-day (d) strength.

Percentage of standard-cured 28-d strength	At 10 °C, d			At 21 °C, d		
	Type of Cement			Type of Cement		
	I	II	III	I	II	III
50	6	9	3	4	4	3
65	11	14	5	8	10	14*
85	21	28	16	16	18	12
95	29	35	26	23	24	20

*This number is in error. It was 4 d in the previous edition.

ACI 305R-91, Hot Weather Concreting[12]

This standard is also an advisory document and is intended as supplemental material to the contract specification. It defines hot weather concreting as any combination of temperature, wind velocity, relative humidity, and solar radiation that impairs the quality of fresh or hardened concrete because of effects on moisture loss or rate of cement hydration. Quantitative guidance is given on methods to calculate expected temperature of concrete from the temperature of ingredients and on techniques to reduce the temperature of fresh concrete.

Section 4 addresses the details of curing in hot weather. It references ACI 308[31] for general guidance, but it also cautions in section 4.4 that concrete should not be allowed to get too hot since ultimate strength is negatively impacted by high initial curing temperatures. It also cautions against too rapid cooling in young concrete, which may result in formation of thermal shrinkage cracks. Curing water should be near the concrete temperature, or at least the cooling rate should be no more than 3 °C /h or no more than 28 °C in 24 h.

White pigmented curing compound is recommended to reflect light and reduce solar heating. It is recommended that liquid membrane-forming curing compounds exceed the ASTM C 309[23] requirements, which indicate that some agencies require a limit on water loss, as determined by ASTM C 156[18], of 0.39 kg/m^2. The requirement in ASTM C 309[23] is 0.55 kg/m^2.

If the concrete water-cement ratio is less than 0.40, then the concrete should be water cured rather than using a water-retentive membrane. The standard cautions that pavements 30.5- to 45.7-cm thick can experience significant thermal heating due to the cement's heat of hydration. Temperature rises of 6.7 °C per 60 kg/m^3 of cement can be expected in 18 to 72 h if no heat is lost.

ACI 325.9R-91 (reapproved 1997), Construction of Concrete Pavements and Concrete Bases[21]

Chapter 2, "Materials," Section 2.5 addresses curing materials. Guidance is offered on burlap, waterproof paper, and liquid membrane-forming curing compounds. Burlap is required to comply with AASHTO M 182[20], with further provisions that nonabsorptive materials and unit weights of less than 0.24 kg/m^2 not be used. M 182[20] allows a minimum unit weight of 0.23 kg/m^2. ASTM C 171[17] is referenced for waterproof paper and ASTM C 309[23] is referenced for liquid membrane-forming curing compounds, with Type 2, white-pigmented, being preferred.

Chapter 10 on curing and protection refers to practices in ACI 308, with additional guidance that surface water must be gone, *plus* the surface of the concrete must not be sensitive to marring.[31] Curing duration is 7 days if temperatures are above 4 °C or strength is greater than or equal to 70 percent of f_c'. Section 10.1.1 on curing compound practice directs application rates follow manufacturer's recommendation or be no less than 3.7 m^2/L in the absence of manufacturer's recommendation. Section 10.1.2 cautions not to use mono-molecular coatings (evaporation retardants) for curing. Details for use of cotton mats, waterproof paper, and white- pigmented polyethylene sheets are given. Section 10.1.6 provides guidance on addressing curing problems associated with saw cuts in pavements, including the use of ropes or twisted fabric inserted into the cut or placing strips of adhesive polyethylene over the cut.

Chapter 12 on cold and hot weather concreting references ACI 306R[14] and 305R[12], respectively.

ACI 330R-92 (reapproved 1997), Design and Construction of Concrete Parking Lots[46]

Chapter 4 on construction recommends ASTM C 309[23] for curing compounds with a minimum application rate of 5 m^2/L or manufacturer's recommendations. Opening to traffic is recommended to be no less than 3 days for automobile traffic and no less than 7 days for all other traffic if temperatures are above 16 °C. More time (unspecified) is required if temperatures are cooler. A compressive strength of 21 MPa or greater can substitute for the time requirement.

ACI 330.1-94, Specification for Plain Concrete Parking Lots[93]

This standard presents the guidance in ACI 330R[46] in a format suitable for writing project specifications.

ACI 228.1R-95, In-Place Methods to Estimate Concrete Strength[49]

This standard describes a number of in-place test methods for measuring strength that might be of practical value in evaluating curing. Methods include rebound number (ASTM C 805[80]), penetration resistance (ASTM C 803[95]), pullout test (ASTM C 900[96]), break-off test (ASTM C 1150),[97]ultrasonic pulse velocity (ASTM C 597[98]), maturity method (ASTM C 1074[39]), and cast-in-place cylinders (ASTM C 873[94]). The standard also describes principles of the test methods and some practical details on limitations.

ASTM

ASTM standards cover material specifications and test methods. These are the standards primarily referenced in the ACI standards. ASTM's curing standards are described below. Other standards are useful for measuring or estimating development of properties that depend on curing. These are summarized in ACI 228.1R-95, as described above.[49]

ASTM C 309-97, Specification for Liquid Membrane-Forming Curing Compounds for Concrete[23]

This is the original and principal standard referenced for liquid membrane-forming curing compound. The standard classifies curing compounds into Types 1 and 2, and Classes A and B. Type 1 is clear or translucent (Type 1-D may contain a fugitive dye). Type 2 is white pigmented. Older versions of the specification allowed a gray-pigmented curing compound. The class defines the type of solids in the curing compound. Class A is unrestricted. Class B must be a resin.

The standard includes qualitative requirements, called "General Requirement," on sprayability, surface adhesion to concrete, shelf life, toxicity, and deleterious reactions with concrete. There are quantitative requirements on water-retention properties, reflectance properties (for Type 2), and drying times. The water-retention requirement is the principal performance requirement pertaining to the curing function. The limit is 0.55 kg/m^2 at 72 h when tested according to ASTM C 156 at an application rate of 5 m^2/L or according to the manufacturer's recommendation.[18]

ASTM C 1315-95, Specification for Liquid Membrane-Forming Compounds Having Special Properties for Curing and Sealing Concrete[24]

This standard covers some of the same scope as ASTM C 309[23], but requires higher performance in moisture retention properties at a lighter application rate and some additional properties that are independent of moisture retention that are not required in C 309[23]. Like C 309[23], materials are classified as Types and Classes. Type I is clear or translucent. Type II is white pigmented. There is no provision for fugitive dyes. Class A is nonyellowing. Class B is moderately yellowing, and Class C may undergo severe darkening.

As in C 309, there are qualitative requirements on applicability, adhesion, deleterious reactions with concrete, toxicity, and shelf life.[23] Minimum solids content is 25 percent. This requirement is intended to ensure a minimum membrane thickness of 0.025 mm. Maximum moisture loss, tested according to C 156, is 0.40 kg/m^2 in 72 h.[18] Unless otherwise specified, the application rate for acceptance testing is 7.5 m^2/L for Type I materials and 5 m^2/L for Type II materials. There are also quantitative requirements for reflectance, drying time, yellowing in ultraviolet light, acid and alkali resistance, and adhesion of tile cement placed over the curing compound.

ASTM C 156-95, Test Method for Water Retention by Concrete Curing Materials[18]

This test method measures the moisture retention properties of curing compounds and sheet materials by measuring mass loss at 72 h of a standard mortar specimen coated with the material under test. Test conditions are 37.8 °C, 32 percent RH, and airflow sufficient to cause a water evaporation rate of 2.0 to 3.4 g/h from a free-water surface. The coverage rate for curing compounds is 5 m^2/L or according to manufacturer's requirements. Application method is according to manufacturer's guidance.

This test method, or slight variants of it, is the most commonly used method for evaluating curing compounds for water retention. The test method is often criticized for lack of precision. The published within-laboratory standard deviation is 0.13 kg/m^2. A laboratory would be expected to duplicate test results to within a range of 0.36 kg/m^2. The between-laboratory standard deviation is 0.30 kg/m^2. Two laboratories would be expected to duplicate test results to within a range of 0.84 kg/m^2. Work is underway to improve the precision of the test method.

ASTM C 1151-91, Test Method for Evaluating the Effectiveness of Materials for Curing Concrete (withdrawn)[27]

This test method, like C 156, is intended to test curing compounds and sheet materials.[18] This test method is based on measurement of water absorption by a cured sample of mortar, comparing the absorption of the exterior surface with an interior surface exposed by cutting a specimen. The concept behind the method is that a poor quality curing compound will allow the surface to dry, resulting in a less compact microstructure, and hence more water absorption relative to the interior of the specimen, which is not sensitive to the quality of curing compound. Senbetta (1994) reviews the development of this test method. There is little data on its precision.[52] A within-laboratory standard deviation is reported, but this was the result of a single laboratory's effort. When expressed as a coefficient of variation, the precision is 18.6 percent, using the recommended limit of 3.7 by 10^{-6} cm^2/s as the basis for the calculation. There is no information on the between-laboratory precision. This method is not apparently widely used for acceptance testing of curing materials, although water absorption test methods are widely recommended in the literature as a test to measure the quality of curing in the near-surface zone of concrete.

ASTM C 171-97. Specification for Sheet Materials for Curing Concrete[17]

The scope of this specification is for sheet materials for use in moisture retention and in minimizing temperature rise due to solar radiation. For moisture retention, it cites the 0.55 kg/m^2 water-loss requirement at 72 h used for curing compounds, determined according to C 156.[18] There are also requirements on physical properties that address durability consideration and a reflectance requirement for white sheet materials.

AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS (AASHTO)

AASHTO has its own set of materials specifications and test methods. These include specifications M 182[20] for burlap, M 171-97[17] for sheet materials, and M 148-97[24] for curing compounds. The only test method pertinent to curing is T 155-91.[55]

M 171[17] is identical to ASTM C 171-95[99] and M 148[24] is identical to ASTM C 309-94[23], except that SI units are the preferred standard units of measure. Test method T 155[55] is identical to ASTM C 156-95[18]. Specification M 182 for burlap is a uniquely AASHTO standard.[20]

AASHTO also publishes a "Guide Specification for Highway Construction,"[33] a "Quality Assurance Guide Specification,"[100] and a "Construction Manual for Highway Construction."[101] All of these contain guidance on curing.

AASHTO M 182-91, Specification for Burlap Cloth Made from Jute or Kenaf[20]

The scope of this specification covers burlap for use in curing concrete. Four classes are defined according to the density (expressed in the non-SI units of ounces per square yards) of the material. There are quantitative requirements on the physical properties of the material (density, thread counts and on minimum widths and lengths of pieces) and qualitative requirements on defects. There are no performance requirements on burlap's suitability as a curing material.

ASHTO Guide Specification for Highway Construction[33]

Division 500 covers rigid pavements. Curing information is in Section 501.03 on Construction, paragraph M. The basic requirement is to cure the concrete for at least 3 days, starting immediately after the finishing operation. It requires avoiding exposing concrete for more than 30 min at any time during the curing operation. Fogging is required for curing until the final curing method is in place.

Placing concrete is limited to ambient temperatures between 10 and 30 °C. The concrete must be protected (presumably from freezing) for at least 10 days or until a flexural strength of 15 MPa is achieved (AASHTO T 97).[102] Protection with blankets is required if the temperature drops below 2 °C.

Four curing methods are allowed, as described below. There is no guidance for choosing among them:

1. *Impervious membrane method (curing compounds).* Curing compound may only be applied in dry weather and applied with a fully atomized spray equipped with a tank agitator and wind guard. An application rate of 3.5 m^2/l is required. Hand spraying of irregular shapes is allowed.

2. *White opaque polyethylene film.*

3. *Burlap*. Two layers are required, saturated with water before placing.

4. *Waterproof paper*.

Division 800, Section 808 is on concrete structures. Paragraph I deals with curing including guidance on bridge decks.

General guidance is to start curing immediately after free water has left the surface of the concrete and finishing is complete. Curing is to continue for 7 uninterrupted days, 10 days when more than 10 percent (by mass) pozzolan is used. Curing time can be reduced if field-cured test cylinders indicate that 70 percent of specified strength has been achieved. In hot weather, water is applied to surfaces that have been previously treated with curing compound or that are covered with forms until cooling is no longer needed.

Five curing methods are allowed, but there is no guidance on choosing among them:

1. *Forms in place*. Retain forms in place without loosening them for the cure.

2. *Water method*. Keep surface wet by ponding, spraying, or continuously wetting materials.

3. *Liquid membrane-forming curing compound*. Type 2 (white pigmented) is allowed only on bridge decks, on surfaces that will not be exposed to view, or on other specially approved locations. The minimum application rate is 14 m^2/l. Application must begin as soon as surface water has disappeared, using a power applicator in one or two coats. The second coat must be applied within 30 min of the first. Hand powered application may be used for small, irregular areas.

4. *Waterproof cover method (sheeting)*. These are allowed only when they can be secured against wind or other disturbance. There is additional guidance on minimum overlap, sealing joints, and damage.

5. *Steam or radiant heat*. This guidance applies to precast products only, where the curing is done at the manufacturing facility. Detailed requirements are given on rate of heating, use of sheeting or curing compounds to retain moisture during steam curing, and other details of the procedure. There is no guidance on maximum curing temperature.

There is special guidance on curing bridge decks. Bridge decks are to be cured with a combination of curing compound and water. Type 2 (white pigmented) curing compound is required, with application starting immediately after finishing is complete. Water curing is applied not more than 4 h after finishing. There is no additional guidance on length of cure other than the 7 to 10 days given in the general guidance, above.

AASHTO Quality Assurance Guide Specification(100)

This standard was published 1996, but has not been balloted by AASHTO, so it is not an official

AASHTO guide or standard. Section QA-501 addresses portland cement concrete pavement. Curing is not specifically addressed in the body of the document. Compressive strength, thickness, and ride are the three major items addressed in this document.

Appendix A is a "Guide for Quality Control and Acceptance Requirements for Portland Cement Concrete." It states that the contractor must have a quality control plan that describes tests and test frequencies. It also states that the plan must address all elements that affect the quality of structural concrete, listing "Finishing and Curing" as one of them. Otherwise, there is no guidance on curing issues.

AASHTO Construction Manual for Highway Construction[(101)]

This book is intended to be a guide to State highway departments in writing their own construction manuals. Section 501.03 deals with construction requirements. Paragraph O addresses curing, but only directs the reader to project specifications for guidance. Section 501.06 deals with inspection and instructs the inspector to check curing application and to keep a diary, but there is no specific guidance. Section 707 deals with sampling and testing frequency for materials. There is no mention of curing.

U.S. ARMY CORPS OF ENGINEERS (USACE)

USACE guidance is contained in the Corps of Engineers Guide Specifications (CEGS), technical manuals (TM), engineer manuals (EM), and test methods and specifications. Test method and specifications are normally ASTM standards, however, there are some standards that are unique to the USACE. These have an alphanumeric prefix of "CRD-C." In the relatively recent past, guide specifications were distinct for military and civil construction, having designations of CEGS and Civil Works Guide Specification (CWGS), respectively. There is currently an effort to consolidate these into a single set of standards (all designated CSGS), but this is not yet complete. The two guide specifications described below have yet been consolidated and their titles suggest duplication. Guidance is largely the same, with the noted exceptions.

CEGS 03300-95, Guide Specification for Cast-in-Place Structural Concrete[(19)]

Section 2.4 on curing materials, gives specifications for curing compounds and for burlap. Curing compound must meet ASTM C 309, Type 1-D (fugitive dye) or Type 2 (white pigmented).[(23)] For surfaces that are to be painted, or are to receive bituminous roofing, or waterproofing, or floors that are to receive adhesive applications of resilient flooring, only styrene acrylate or chlorinated rubber compounds meeting Class B requirements can be used. Type 1-D curing compound shall have the reflective requirements of C 309 waived.[(23)] AASHTO M 182 for burlap and cotton mat is cited.[(20)] Curing water shall be fresh, clean, potable, and free of injurious amounts of oil, acid, salt, or alkali, except that nonpotable water may be used if it meets the requirements of USACE specification CRD-C 400.[(16)] This specification calls for tests on strength development and staining.

Paragraph 3.15 describes required practice. A general caution is given that concrete shall be protected from premature drying, extremes in temperature, rapid temperature change, mechanical damage or effects of flowing water throughout the curing period. The curing period is 3 days for concrete containing Type III cement (ASTM C 150) and 7 days for other concrete.[(44)] Temperature of air and forms in contact with concrete must be above 10 °C for the first 3 days and above 0 °C for the remainder of the curing period. If the temperature is less than 0 °C, then measures must be taken to ensure that the concrete is kept at 5 °C or above for the 7-day period.

On removal of protection, temperature at 50 mm inside concrete shall not differ from ambient by more than 13 °C.

Apart from the exceptions listed in section 2.4 on compatibility with coatings (described above) moist curing shall be used on areas that are to receive hardeners, paint, or other applied coating. Concrete containing silica fume shall be cured by fog misting during finishing, followed immediately by continuous moist curing.

For moist curing, wooden forms are to be kept continuously wet. In hot weather, nonsupporting steel forms shall be loosened and the formed surface kept wet. Burlap and mats shall be completely saturated before application to the concrete surface. When ponding is used, temperature of the water shall no be more than 10 °C cooler than the concrete.

On slabs, curing compound shall be applied as soon as bleed water disappears, with tops of joints sealed to prevent curing compound from seeping in and moisture being lost. Curing compound shall be applied in a two-coat continuous operation at a minimum pressure of 500 kPa with an application rate of not more than 10 m^2/L for each coat, with the second coat applied perpendicular to the first. If it rains within 3 h, the entire application must be redone. Surfaces on which nonpigmented curing compound are used shall be shaded from direct sun for the first 3 days.

Except for plastic coated burlap, impervious sheeting alone shall not be used for curing. Such impervious sheeting shall only be used on horizontal or nearly horizontal surfaces. Additional guidance is given on details of use.

Paragraph 3.17.9 gives guidance on curing inspection. Moist curing inspection shall occur once per shift or not less than two times per day, including nonworkdays. Moisture condition is recorded. If an area is found to be dry, corrective action is taken and curing extended 1 day. When curing compound is used, the contractor verifies that it is properly mixed. At end of each operation, the contractor shall estimate the quantity of curing compound used and the surface area covered. When the calculated rate of application is below that specified (no tolerance given) or is not uniform, the entire surface must be sprayed again. Sheets are inspected once per shift and once per day on nonworkdays, noting conditions of sheets, laps, and joints. If deficiencies are found, they are repaired and curing extended by 1 day. Reports are completed in writing daily, and weekly summaries are prepared.

CEGS 03301-94, Guide Specification for Cast-in-Place Structural Concrete for Civil Works[103]

The major difference between CEGS 03300[19] and 03301[103] is in the guidance on duration of curing. CEGS 03301 gives considerably more detail with respect to differences among cementitious materials. The following is excerpted from that standard:

Type III portland cement	3 days
Portland cement when accelerator is used to achieve high early strength, except when fly ash or ground granulated blast furnace slag (GGBFS) is used	3 days
Type I portland cement	7 days
Type IS or Type IP cement	7 days
Portland cement blended with silica fume	14 days
Type II portland cement	14 days
Portland cement blended with 25 percent or less fly ash GGBFS	14 days
Portland cement blended with more than 25 percent fly ash or GGBFS	21 days

CSGS 02753 Guide Specification for Heavy Duty Pavements[104]

This guide specification covers airfield pavements as well as other heavy-duty pavements. It directs that pavement be cured for at least 7 days. Three methods are allowed: membrane curing (curing compounds), moist curing, and impervious sheet curing.

Guidance on membrane curing directs that curing compound be applied as soon as free water has disappeared from the surface after finishing. If evaporation is high and bleeding has not stopped, then fog spray shall be used to keep the surface wet until the concrete reaches time of setting and bleed has stopped. No instructions on how to determine these conditions and events are included.

Curing compound is required to meet the USACE specification CRD-C 300,[84] which is a more stringent specification that ASTM C 309[23] (see description below). Some manufacturers advertise a line of curing compounds that meet this requirement.

The concrete surface shall not be dry on application of curing compound and additional moistening may be necessary to avoid this condition. Curing compound must be applied with power equipment that spans the entire width of the pavement. Equipment must be fitted with mechanical agitation to prevent settling of solids in the storage tank. Equipment shall be well maintained. An approved quality assurance system is required to insure a continuously wet condition.

Application rate is 5.0 m^2/L (±5 percent) in either one or two coats. The dried membrane shall be free of cracks or pin holes (noncompliance requires reapplication). If heavy rainfall occurs within 3 h of application, then the curing compound must be applied again. Instructions are included for dealing with hand spraying of irregular areas, for repairing damaged areas, and for spraying after joint cutting. Contingency curing capability is required to be on site in the event of failure of curing compound application equipment.

Moist curing must start immediately after finishing. Methods include ponding, sprinkling, wet mats or burlap, and wet plastic coated burlap.

Guidance on sheet curing focuses almost exclusively on sizes of sheets and overlap of sheets, and details of covering exposed edges.

Army TM 5-822-7 (Air Force AFM 88-6, chapter 8[105]). Practice for Concrete Pavements (1987)[25]

As part of general guidance on placing, ACI 306R[14] is referenced for cold weather concreting (temperatures below 4 °C) and ACI 305R[12] is referenced for hot weather concreting (temperatures above 32 °C). Calcium chloride is allowed as an accelerator in cold weather. In hot weather, it is recommended to avoid placing when evaporation rates are in excess of 1.0 $kg/m^2/h$ as determined from the evaporation rate nomograph in ACI 308[31]. It is further suggested that an evaporation rate of 0.75 $kg/m^2/h$ would be a safer limit to avoid plastic shrinkage cracking. Concrete should not be placed when concrete temperature exceeds 32 °C or when the air temperature is less than 4 °C.

In the section on curing, it is cautioned that all equipment and supplies must be on hand before concreting begins to insure no delays in application of moisture retention and temperature control measures. In general, pigmented curing compound is required. Equipment for applying curing compound must be power driven and constructed so as to straddle the newly paved lane and to give uniform and complete coverage. Nozzles must be surrounded by a hood to prevent wind from blowing the spray. Hand-operated pressure sprayers are allowed on odd widths and shapes, and on edges exposed by form removal. Curing compound must form a continuous void-free membrane and be maintained throughout the curing period. No guidance is given on how to determine this condition. No guidance is given on the length of the curing period.

Where experience has shown that curing compound alone does not prevent shrinkage cracking, then a combination of curing compound and moist curing may be specified.

Low melting point wax-based curing compounds should be avoided if the concrete surface is to be painted.

EM 1110-2-2000, Practice for Concrete in Civil Works Structures (February 94)[8]

Curing is covered in chapter 8 on “Concrete Construction.” As part of the general guidance, it is recommended that the contractor submit a plan for curing before construction begins. It emphasizes that positive curing procedures must be used. Form curing—where no additional water is added—is not acceptable. Forms left in place must be kept continuously wet. Water cannot have staining capability and hand sprinkling is not satisfactory, except as an emergency procedure.

Membrane-forming curing compound is particularly recommended because of ease of inspection. Uneven application is easily detected visually. When nonpigmented curing compound is used because of aesthetics, an inspector must be on hand to check uniformity of application, although there is no guidance on how to do this. When using nonpigmented curing compound and temperatures are above 32 °C, concrete must be shaded for 3 days. Compressed air lines must have traps to prevent moisture or oil from contaminating the curing compound. Ordinary, hand-held garden type sprayers are not satisfactory.

In cold weather concreting, as defined in ACI 306R[14], concrete temperatures should be monitored at several locations, particularly at corners and should be protected from cycles of freezing and thawing until it reaches a strength of 24 MPa. Drying is not likely to be a problem in cold weather unless protection systems create a particularly dry or warm condition. Precautions should be taken if concrete is warmer than 15 °C and exposed to air warmer than 10 °C.

During hot weather concreting, as defined in ACI 305R[12], precautions against plastic shrinkage cracking should be taken if evaporation rates exceed 1.0 $kg/m^2/h$, as determined from the evaporation rate nomograph or as determined by direct measurement of evaporation from an open dish. Moist curing is recommended as the best way to prevent plastic shrinkage cracks in hot weather. There are no maximum limits on concrete or ambient temperatures, but general guidance on hot weather concreting is provided.

For curing high strength concrete, water curing is recommended, particularly at early ages and when water-cement ratios are below 0.4.

As part of the concrete report required after project completion, a section on curing methods, inspections, and nonconformances is recommended.

CRD-C 300-90. Specifications for Membrane-Forming Curing Compounds for Curing Concrete[84]

This specification closely resembles ASTM C 309[23] except for the water-retention requirement (actually a water-loss requirement). The specification requires no more than 0.31 kg/m^2 loss at 7 days. Curing compounds meeting this requirement are normally specified for airfield pavements. Most other USACE specifications require curing compounds that meet ASTM C 309.[23] Several manufacturers make a curing compound complying with CRD-C 300, and this is indicated in the product literature.

CRD-C 302-79. Test Method for Sprayability and Unit Moisture Loss Through the Membrane Formed by a Concrete Curing Compound[106]

This test method closely resembles ASTM C 156[18] except that the conditions in the curing cabinet require an airflow of 10 m/s (C 156[18] requires sufficient air flow to produce a target evaporation), and the test period is 7 days.

CRD-C 400-63, Requirements for Water for Use in Mixing or Curing Concrete[16]

Guidance on curing water is that it "… must be free of materials that significantly affect the hydration of reactions of portland cement or that otherwise interfere with the phenomena that are intended to occur during the curing of concrete," (p. 1). There is no test method or quantitative requirement on this interference. However, when the same statement is used in the context of specifying mixing water, the requirement is a comparison of strength development of 50.8 mm mortar cubes made with the water in question versus strength of cubes made with deionized water.

OTHER NATIONAL STANDARDS

British Standards Institution (BSI)

British Standard, BS 8110 (1997), "Structural Use of Concrete: Part 1. Code of practice for design and construction" addresses curing in Section 6 titled, "Concrete, materials, specification, and construction."[40]

Curing and protection should start immediately after the compaction of the concrete to protect it from:

- Premature drying out, particularly by solar radiation and wind.
- Leaching out by rain and flowing water.
- Rapid cooling during the first few days after placing.
- High internal thermal gradients.
- Low temperature or frost.
- Vibration and impact, which may disrupt the concrete and interfere with its bond to the reinforcement.

Minimum length of curing required depends on type of cement, ambient conditions, and temperature of concrete. The guidance is reproduced below (table 19) with annotations in italics relating cement types to the nearest ASTM equivalent. Surface temperature should not be allowed to fall below 5 °C during this time.

Table 19. Reproduction of table 6.1 of BS 8110, Part 1[40], Section 6 on minimum periods of curing and protection.

Type of cement	Ambient conditions after casting	Minimum periods of curing and protection Average surface temperature of concrete	
		5 to 10 °C	**t °C (any temperature between 10 °C and 25 °C)**
PC 42.5 or PC 52.5 to BS 12		Days	Days
	Average	4	$\frac{60}{(t+10)}$
SRPC 42.5 to BS 4027	Poor	6	$\frac{80}{(t+10)}$
All cements in table 1 of BS 5328, Part 1 (1997), except those listed above. Blended cements, ASTM C 595[60], C 1157[53]	Average	6	$\frac{80}{(t+10)}$
	Poor	10	$\frac{140}{(t+10)}$
All	Good	No special requirements	

Note 1. Abbreviations for the type of cement used are as follows:

- PC 42.5: Portland cement (class 42.5)(see BS 12)–ASTM C 150[44] Type I.
- PC 52.5: Portland cement (class 52.5)(see BS 12)–ASTM C 150[44] Type III.
- SRPC 42.5: Sulfate-resisting portland cement (class 42.5)(see BS 4027)–ASTM C 150[44] Type V.

Note 2. Ambient conditions after casting are as follows:

- Good: damp and protected (relative humidity greater than 80 percent; protected from sun and wind.
- Average: intermediate between good and poor.
- Poor: dry or unprotected (relative humidity less than 50 percent; not protected from sun and wind).

Five curing methods are allowed. There is no guidance on choosing among them:

- Maintaining formwork in place.
- Covering with sheet materials.
- Using a compound with an efficiency index of 90 percent, according to BS 7542.[28]
- Covering with damp absorbent material.
- Continuous or frequent wetting.

BS 7542 is the test method used to test curing compounds.[28] This method is very much like ASTM C 156, in that a standard mortar specimen is coated with curing compound, then exposed to a hot, dry conditions, and mass loss measured.[18] However, instead of reporting simple mass loss, as in C 156, the method reports mass loss relative to the mass loss of an uncoated control specimen, in units of percent.[18] The property is called the “curing efficiency index.” A value of 0 percent indicates that the curing compound-treated specimen lost as much water as the control.

An index result of 100 percent means that the curing compound-treated specimen lost no water. A value of 90 percent is considered acceptable. Test conditions are: temperature 38 °C, 35 percent RH, and wind velocity of 0.5 m/s. The test age is 3 days. Precision is not given in the test method, but within-laboratory standard deviations of about 4.5 percent for three materials with curing efficiencies higher than 80 percent, and 11 percent for one material with a curing efficiency of 56 percent were reported by Cabrera, Gowiripalan, and Wainwright (1989).[107]

Euro-International Committee for Concrete (CEB)-International Federation for Prestressing (FIP)

A summary of the guidance on curing in the Euro-International Committee for Concrete (CEB)-International Federation for Prestressing (FIP) Model Code (1990)[41] is taken from Meeks and Carino (1999)[4]. The title of the section in the code is "Curing and Protection." This code only considers the moisture balance aspect of curing. Time-temperature considerations are not addressed. Protection involves avoiding effects of rain or flowing water, early freezing, thermal stresses, vibration, and impact.

It is recognized that curing has only a minor effect on the strength development of concrete, with the exception of very thin sections, because the core of thick sections maintains enough water for hydration to occur even without any deliberate curing. Lack of curing has a major effect on the properties of surface or near-surface concrete.

The recognized methods of curing are:

- Keeping formwork in place.
- Covering with plastic films.
- Placing wet coverings.
- Sprinkling with water (at temperatures above freezing).
- Applying curing compounds.

The code notes that not all methods work equally well; therefore, it is important to have frequent inspections, although no specific guidance is given. It is also noted that methods that involve addition of water give a concrete with a denser pore structure than methods that only retain water. For low water-cement ratio concretes, it is recommended that a type of curing that involves adding additional water be used.

Duration of curing for concrete in normal service environments (humid, wet, seawater, frost) is prescribed according to ambient conditions during curing and rate of development of impermeability in the concrete. Ambient conditions are categorized into three levels. Condition I is defined as exposure to no direct sun and RH greater than 80 percent. Condition II is defined as exposure to medium sun, medium wind velocity, or RH between 50 and 80 percent. Condition III is defined as exposure to strong sun, high wind velocity, or RH of less than 50 percent. No quantitative values of illumination or wind velocity are given.

Rate of development of impermeability is prescribed according to type of cement and the water cement ratio of the concrete. Curing times range from 1 to 8 days depending on the combination of these factors. The tabulation of this information is reproduced in table 20. This guidance is for ambient temperatures of approximately 20 °C. The maturity method is recommended to estimate required curing time for temperatures higher or lower than this. Such calculations result in an approximate doubling of the curing time at 10 °C. For temperatures around 30 °C, maturity calculations result in an approximate halving of the curing time. For pozzolan-containing concretes, curing time is to be increased by 1 or 2 days. For severe chemical exposures, it is recommended that curing time be extended by 3 to 5 days.

European Committee for Standardization (CEN)

Information on European standards for curing was taken from Litzner and Becker (1999).[108] A table on curing requirements was presented in this reference, cited as being taken from EN 206.[42] Table 21 is a reproduction of this table. Exposure classes XO and XC1 are for dry concrete inside buildings.

Table 20. Reproduction of Table d.10 on minimum duration of curing in days for T>10 °C, exposure classes 2a; 2b; 4a and 5a, according to Table d.1 cement CE I.[108]

<table>
<tr><th colspan="2">Rate of development of impermeability of concrete</th><th>Very Rapid</th><th>Rapid</th><th>Medium</th><th>Slow</th></tr>
<tr><td rowspan="3">Exposed ambient conditions during and after curing</td><td>I
No direct sunshine, relative humidity of surrounding air >80 percent</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td>II
Exposed to medium sunshine or medium wind velocity or relative humidity 50–80 percent</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>III
Exposed to strong sunshine or high wind velocity or relative humidity less than 50 percent</td><td>3</td><td>4</td><td>6</td><td>8</td></tr>
<tr><th colspan="6">Rate of development of impermeability of concrete</th></tr>
<tr><th colspan="2">Rate of development of impermeability</th><th colspan="2">Water-cement ratio</th><th colspan="2">Class of cement*</th></tr>
<tr><td colspan="2">Very rapid</td><td colspan="2">0.5–0.6
<0.5</td><td colspan="2">RS
RS; R</td></tr>
<tr><td colspan="2">Rapid</td><td colspan="2">0.5–0.6
<0.5</td><td colspan="2">R
N</td></tr>
<tr><td colspan="2">Medium</td><td colspan="2">0.5–0.6
<0.5</td><td colspan="2">N
SL</td></tr>
<tr><td colspan="2">Slow</td><td colspan="4">All other cases</td></tr>
</table>

Table 21. Minimum curing period for EN 206 exposure classes other than XO and XC1.[42]

Surface concrete temperature (T), °C	Minimum curing period, days*, † for a concrete strength development $r = f_{cm,2}/f_{cm,28}$			
	$r \geq 0.50$ Rapid	$r \geq 0.30$ Medium	$r \geq 0.15$ Slow	$r < 0.15$ Very Slow
$T \geq 25$	1.0	1.5	2.0	3.0
$25 > T \geq 15$	1.0	2.0	3.0	5
$15 > T \geq 10$	2.0	4.0	7	10
$10 > T \geq 5$‡	3.0	6	10	15

Notes:
* Plus any period of setting exceeding 5 h.
† Linear interpolation between values in the rows is acceptable.
‡ For temperatures below 5 °C, the duration should be extended for a period equal to the time below 5 °C.

Canadian Standards Association (CSA)

The Canadian guidance on concrete curing is in CSA23.1-94,[109] as summarized by Meeks and Carino (1999).[4] The basic curing requirement is for 3 days moist curing, with temperatures greater than 10 °C, or for the time required to reach 35 percent of the specified 28-day strength. Field cured specimens or nondestructive methods may be used. For aggressive chemical or abrasive service conditions, curing time should be increased by 4 days over the basic requirement or to the time necessary to reach 75 percent of specified 28-day strength. There is no quantitative guidance for curing of concretes that develop strength slowly, but there is a general caution about the need to account for this in project specifications. Reference is made to ACI 308 for curing methods and details of practice.[31]

Norway

Norwegian Standard 3420, as reported in Meeks and Carino (1999)[4] addresses concrete curing requirements, as summarized in Meeks and Carino (1999).[4] Concrete shall be kept moist for 3 days after setting, either with water or by prevention of evaporation. If the water-cement ratio is less than 0.40, then water curing must be used. For special requirements on impermeability, absence of cracks, and resistance to chemical attack, 14 days of curing is required. No artificial drying is allowed until 70 percent of specified 28-day strength is reached. Special care is advised with use of silica fume or large amounts of fly ash to prevent early drying of the concrete surface and resultant plastic shrinkage cracks. In very aggressive environments, maximum curing temperature is 65 °C.

Australia

Australian Standard 3600 (AS 3600, 1994[48]) addresses curing, as summarized by Meeks and Carino (1999).[4] Guidance is based mostly on severity of exposure condition in service. Exposure is classified according to climate zones (temperate, tropical, and arid) and environmental aggressiveness within each of these. Curing guidance is then based on minimum curing time or, alternatively by minimum compressive strength. For relatively mild exposures, at least 3 days moist curing is required, or if accelerated curing is used, curing to a compressive strength of 15 MPa is required. Design strengths of 20 to 25 MPa, depending on details of exposure, are required. For more aggressive exposures, at least 7 days curing under ambient conditions is required, or if accelerated curing is used, curing is required to a strength of 20 MPa for a 32 MPa design strength, to 25 MPa for a 40 MPa design strength, or to 32 MPa for a 50 MPa design strength. The design strengths vary according to exposure class.

The Roads and Traffic Authority of New South Wales (RTA)[110] has established field performance criteria for curing. Water sorptivity is used to determine effectiveness of curing on site. See Chirgwin and Ho (1995)[111] for the test method and Ho and Chirgwin (1996)[112] for the performance specification. Table 22 is reproduced from the latter reference. Concretes containing large amounts of slag must be cured for an additional 7 days in moderate to severe exposures.
Silica fume concrete is required to be cured with water for 3 to 6 days. There is also a limit on crack width on bridge decks.

Table 22. Reproduction of RTA specification requirements from Ho and Chirgwin (1996).[112]

Exposure		**Minimum binder[a] content, kg/m^3**	**Maximum water-binder ratio**	**Minimum period of standard curing, d**	**Maximum sorptivity depth, mm**
Classification	Environment				
A	Dry climate, no industry, nonaggressive		0.56	7 (7)[b]	45
B1	Industrial areas, inland	320	0.56	7 (7)	35
B2	Close to coast or permanently in salt water	390	0.46	7 (15)	17
C	Tidal/splash zone	450	0.40	14 (22)	11

[a]Binder = cementitious materials
[b]Number of days in parentheses are for high slag cement

STATE (DOT) STANDARDS

A limited survey of State DOT standards showed that States differ in many of the details of curing practice. A more thorough review of these standards was done; the results are summarized in appendix B.

APPENDIX B: LITERATURE REVIEW

The best known early work on the effects of cement hydration, and hence curing, on cement microstructure was by Powers and Brownyard (1946–47).[76] Senbetta (1994)[52], Taylor (1997),[113] and Meeks and Carino (1999)[4] have written excellent summaries of this and other early work on effects of curing. In practical terms, several major themes emerge, as described by Neville (1996a).[114]

1. The relative humidity in the cement pores must remain above 80 percent for hydration to continue, although Powers (1947)[83] and Ho, Cui, and Ritchie (1989)[115] showed that hydration slows down significantly as RH drops below 100 percent.

2. At water-cement ratios less than approximately 0.40, the cement paste will self- desiccate so that additional water must be added through curing if hydration is to continue.

3. At water-cement ratios greater than 0.40, mixing water is sufficient to cure the paste if it is not lost to evaporation.

4. Concrete within approximately 30 to 50 mm of the surface is particularly sensitive to drying, while concrete deeper than 50 mm is usually relatively immune to drying.

5. Cementitious materials that develop properties slowly, such as those containing pozzolan, must be cured longer than systems not containing pozzolan or slag.

For purposes of this work, these phenomena are taken as largely representing the status of research up to about 10 years ago. The remainder of this section of the report largely focuses on research published in about the last 10 years, although literature on curing compounds is traced back somewhat farther.

A common feature in the recent research literature on concrete curing is the development of comparative data, which are useful in evaluating option, but often the data are difficult to use for actually designing guidance. For example, research will commonly compare effects among types of cementitious materials, among different mixture proportions, among different curing materials and practices. Conclusions of this research are often that one material or a class of materials are more sensitive than another class of materials, or that a certain procedure is better than another for a particular type of material. The design and intent of the research was not to determine optimum curing times or application rates of curing materials; thus, it is sometimes difficult to extract from this research recommendations for specific guidance on how to specify curing practices. However, the literature was reviewed with a particular focus on trying to get this kind of information from it.

Early research and guidance focused on effects of curing on properties of cement paste and on strength of concretes and mortars as the basic performance property. Guidance on curing is still largely based around strength. Strength is properly identified as the performance property of interest when determining when concrete can be load bearing. Durability against one or more of the degradation processes that affect concrete is also sometimes strongly affected by curing.

Some degradation processes are affected by the state of hydration of the entire section of concrete, such as strength. However, other curing related problems are more affected by the properties of the concrete at or near the surface than by the strength of the entire section of concrete. Examples include cracking resulting from near-surface drying strains, rate of penetration of water and waterborne salts from the concrete surface, and abrasion resistance. Obtaining adequate curing of the near-surface zone is more likely to be disrupted by inadequate choice of materials and practices, while concrete more than about 50 mm from the surface is often relatively immune to the effects of bad curing practices. Research on the relationship between curing and development of physical properties has tended to recognize both the strength aspect and the surface properties aspect of the problem. Some reports focus on one or the other of these features, while others attempt to deal with both.

GENERAL CONCEPTS

Burrows (1998) comments that lack of adequate curing is too often cited as the cause of cracking in structural concrete.[(116)] Contrary to this conventional wisdom, he argues that it is possible to cure concrete too much and cites literature demonstrating this concept. The strength, modulus of elasticity, and the creep capacity of paste are all increased by amount of curing. The amount of drying shrinkage that develops increases with increasing amounts of cement paste and with the amount of hydration of that paste. Hence, the combination of these effects results in higher probability of cracking when concrete is cured beyond the minimum amount needed to develop the needed physical properties. Altoubat and Lange (2001) also demonstrate this phenomenon in their study of creep, shrinkage, and cracking of concrete at early ages.[(117)]

Cather (1994) discusses the problem of curing in general and emphasizes the difficulty in translating knowledge developed from research into guidance that can actually benefit the performance of concrete.[(75)] He comments on the importance of developing specifications that can be verified. Sometimes in the spirit of setting all specification requirements in the format of performance specifications (as opposed to prescriptive specifications), unenforceable specifications develop. He further comments that it is commonplace to attribute many of the deficiencies in concrete to inadequate curing. In actuality, it is difficult to separate inadequate curing from other problems that occur in the early age of a concrete structure. Plastic shrinkage cracking is an exception to this. Another interesting point is the concept of using time to capillary discontinuity as a guide to determine length of curing requirements.

NEAR-SURFACE EFFECTS

The concrete near the surface of a concrete structure has been recognized as potentially different from concrete interior to the structure because of the potential for exposure to different environmental conditions, either during curing or during service. Curing deficiencies will likely have their strongest effect on this part of the concrete. A poorly cured near-surface zone is likely to be less durable than a well cured one because of the possibility of a less dense microstructure and the possible presence of some level of cracking. This truth has been known for a long time, as indicated by Gonnerman's (1930)[(118)] study, of the effect of curing on strength and abrasion resistance. Recent literature further investigates this (Dhir, Hewlett, and Chan, 1989[(119)] and 1991;[(120)] Parrott, 1995;[(121)] and McCarter and Watson, 1997.[(122)] Much of the research on curing in the last 10 years involves the near-surface zone in one way or another, mostly as it affects durability; development of test methods that measure near-surface properties have dominated the literature on curing test methods. This is discussed in a later section.

This thickness of the near-surface zone or curing-affected zone varies from a few millimeters to about 50 mm, depending on the composition of the concrete and on the climatic conditions (Cather, 1994).[75]

Hooton et al. (2002) examined effect of duration of curing on resistance of the near-surface zone to Chloride (Cl) penetration.[123] They found that there was little added benefit to curing beyond 3 days at 20 °C. They also found that the detrimental effects of poor curing were limited to the top 40 mm of concrete.

MOISTURE MOVEMENT AND EVAPORATION

There has been some research effort in the past 10 years to develop a better understanding of the physics of water movement and evaporative loss from concrete. This research is driven by two needs. One is to better understand properties required of curing compounds and evaporation retardants. The other is to estimate time required to dry concrete. The latter is driven primarily by the floor covering industry.

Coleman, as reported in Wang, Dhir, and Levitt (1994), described drying of a solid mass as a process that can be approximately classified into three phases.[124] Phase one represents evaporation from a saturated surface and is equivalent to evaporation from a free-liquid surface. Phase two occurs when the rate of evaporation from the surface exceeds the rate of liquid movement to the surface from the interior of the solid mass. Phase three represents the propagation of a drying front moving into the solid mass. The rate of liquid loss is highest in phase one, decreasing through phases two and three. They evaluated the applicability of this three-phase model to the loss of water from fresh concrete. They found that this model did not describe observed evaporation well. Evaporation rates were found to be higher than phase one rates (free surface) throughout the first 16 h after placing. Evaporation rates were found to be dominated by temperature rises in the concrete from the hydration of calcium aluminate and gypsum in the portland cement. This action generally occurs in the first few minutes of hydration. Evaporation rates were also dominated by hydration of C_3S and reactions involving calcium-sulfoaluminate phases, typically occurring within the first few hours of hydration.

Research on moisture movement, the objective of which is to understand the drying process, contributes indirectly to understanding of curing concrete. This research mostly focuses on moisture movements in concretes that contain only water vapor and the relationship between concrete properties and rate at which this vapor can be reduced to below about 80 percent and lower. Surface adhesion systems work best when the RH is below 70–80 percent, and mold growth is retarded at this RH. The following references represent recent work in this area and provide good descriptions of the physics of moisture movement and sorption behavior: Selih and Bremner, 1996;[125] Suprenant, 1997;[126] Suprenant and Malisch, 1998a[127] and 1998b;[128] Xi, Bazant, and Jennings, 1995a;[129] Xi, Bazant, Molina, and Jennings, 1995b;[130] and Hedenblad, 1997.[131]

The rate with which water moves into concrete can have important implications for some kinds of curing practices. Low water-cement ratio concretes (<0.40) are known to sometimes consume all of the mixing water during hydration so that, if additional hydration is needed, water must be added to the concrete during curing. But the capillary continuity among pores and with the surface of concrete tends to decrease rapidly in low water-cement ratio concretes, so that introducing appreciable water into the concrete may be difficult (Meeks and Carino 1999[(4)], Cather 1994[(74)]). The onset of capillary continuity varies with water-cement ratio. Table 23 gives times to capillary discontinuity from three different references. The numbers are similar but not in exact agreement.

Table 23. Curing time to capillary discontinuity.

Water-cement ratio	Powers and Brownyard (1947)[(76)]	Van der Molen (1979)[(77)]	Mindess and Young (1981)[(78)]
0.40	3 days	2 days	3 days
0.45	7 days	3 days	7 days
0.50	14 days	7 days	28 days
0.60	6 months	3 months	6 months
0.70	1 year	9 months	1 year
0.80	Never	>1 year	Never
>0.80		Never	

For purposes of curing concrete pavements, the principal point is that capillary discontinuity of 0.40 water-cement ratio concrete develops in 2 to 3 days, and that any attempt to introduce water into the concrete through wet curing methods will decrease sharply in efficiency after this time.

Berthane (1984)[(132)] measured water losses from fresh concrete specimens during the first few hours (up to 24) of exposure to a variety of evaporation conditions and compared the rates with those derived from the evaporation rate nomograph in figure 1 of ACI 308[(31)] (also published in a number of other places). This nomograph is commonly attributed to equations developed by Menzel. Berthane concluded that Menzel’s equations did not predict evaporations rates all that well.[(132)] The observed evaporation generally exceeded the rates predicted by Menzel’s equations. This was attributable to the fact that the heat of hydration of the cement caused the specimens to heat up, driving off additional water. This affect was most pronounced after the first several hours when the cement would have been expected to have set. Cement is known to have a significant heat of hydration at this time. From examination of the data in Berthane’s figures, it appears that the evaporation rates observed during the first 2 h, or so, were reasonably approximated by Menzel’s equation.[(132)]

PLASTIC SHRINKAGE CRACKING

Ravina and Shalon (1968) conducted laboratory tests to investigate the effects of water-cement ratio, cement content,(133) evaporation conditions, and tensile strength of fresh mortar on development of plastic shrinkage cracks. The range of mixture proportions covered overlapped with paving mixtures only a little, but two important things pertinent to concrete paving were evident. One was that mixtures that developed high tensile strengths, like paving mixtures, did not crack under the experimental conditions used (evaporation rates of 0.5–1.2 $kg/m^2/h$). Second, cracking in higher water-cement ratio mixtures usually occurred after evaporation of 2–3 kg/m^2 of mixing water. These cracks developed 0.5 to 2 h after all bleed water had disappeared. The authors concluded that tensile strength was a major variable determining susceptibility to plastic shrinkage cracking. Although not extensive with respect to numbers of mixtures and conditions, these results suggest that exposure for 30 min to evaporation conditions around 1 $kg/m^2/h$ might be acceptable. This limit exists in some State DOT guidance.

Radocea (1994) models shrinkage due to drying during the plastic phase, but does not attempt to include the tensile properties of the concrete and so the model does not extend to predicting cracking.(134)

Wang, Shah, and Phuaksuk (2001) investigated effects of fly ash and fibers on plastic shrinkage cracking.(135) Fibers generally reduced crack areas on laboratory specimens as did a Class F fly ash when used as 30 percent replacement for cement. A Class C fly ash increased the amount of plastic shrinkage cracking.

Mora et al. (2001) investigated the effect of fibers and shrinkage-reducing admixtures on plastic shrinkage cracking. Again, fibers reduced the amount of shrinkage cracking. Shrinkage-reducing admixtures are principally intended to reduce amounts of drying shrinkage, but were also found to reduce plastic shrinkage.(136)

Holt (2000) quantitatively measures evaporation, shrinkage, and development of cracking in laboratory concretes and describes the relationships among them.(70) Concrete used in the author's laboratory program showed that water losses in the range of 0.5–1.0 kg/m^2 would be sufficient to cause cracking if it occurred late in the initial curing period.

Hammer (2001)(137) examined shrinkage forces, as measured by pore-water pressure, in the presence and absence of silica fume and in the presence of mild drying. The author found that negative pore pressures developed within about 30 min under the drying conditions.

AUTOGENOUS SHRINKAGE

Autogenous volume change is defined in ACI 116R(1) as "change in volume produced by continued hydration of cement, exclusive of effects of applied load and change in either thermal condition or moisture content."

There are two autogenous phenomena that contribute to shrinkage (Powers et al., 1946–47).[76] One is the reduction in volume associated with the formation of hydrated cement paste, relative to the volume of the materials before hydration. The other is the partial desiccation of capillary pores due to consumption of mixing water by the hydration reaction.

At water-cement ratios greater than approximately 0.40 (depending on cement chemistry), these effects have long been considered to cause insignificant volume changes in concrete. With the more commonly used low water-cement ratios in much high-performance concrete, the contribution of autogenous effects is considered to be much larger (Baroghel-Bouny and Aitcin, 2001).[138] Autogenous shrinkage may be an increasing problem in paving as lower water-cement ratio mixtures seem to have become popular in recent years. Autogenous shrinkage problems are likely to appear in patching and fast-track concreting where use of low water-cement ratios are very common.

Bjontegaard and Sellevold (2001) investigated the combined effects of strains due to early changes in temperature associated with hydration and autogenous shrinkage.[139]

Beltzung and Wittmann (2001) develop the theoretical aspects of autogenous volume changes and measure effects at very early ages (from time of adding water until just past time of setting). There is significant shrinkage associated with the earliest reactions, that has practical significance in concretes with high cement contents.[140]

Sule and van Breugel (2001) investigated the interaction between autogenous shrinkage and cracks formed around reinforcing steel in very low water-cement ratio concretes (0.33).[141] Reinforcement tends to distribute strains, resulting in longer times to cracking and the formation of many small cracks rather than a few large ones.

van Breugel (2001) discusses some autogenous shrinkage modeling efforts and shows how these are able to separate and analyze the many components of this phenomenon.[142]

Altoubat and Lange (2001) make several significant points about autogenous shrinkage.[117] They found that autogenous shrinkage was a significant component of shrinkage even before time of setting in concretes with a water-cement ratio as high as 0.50, even with no drying. A high rate of stress during this early period, even if not producing cracking, does seem to condition the concrete to cracking at later ages. Holt (2000) draws this same conclusion.[70] The ability of the concrete to creep in tension, which is inversely related to the amount of hydration that occurs, is critical in preventing cracking at early ages. For structures prone to cracking, a curing regimen that includes periodic wetting is of great benefit in relaxing shrinkage strains.

DURABILITY

The effect of curing on concrete durability was recognized in some of the earliest literature, particularly the effects of curing on surface features such as abrasion resistance. Lack of adequate curing continues to be considered one of the most important causes of poor durability.

Stewart (1997) used probabilistic methods to calculate the influence of poor curing and compaction practices on the frequency of serviceability problems in concrete.(143) A survey of engineers in Australia showed that curing practice was considered to be poor on 44 percent of projects. The author attributes this to the sensitivity of concrete to the timing of start of curing and the attention to detail required in applying curing and sometimes throughout the curing period. He concluded that poor curing and compaction increased the probability of serviceability problems by an order of magnitude, with poor curing being responsible for most of this.

Kettle and Sadegzadeh (1987) reported the effects of different curing methods on abrasion resistance of concrete.(144) The principal variable was method of finishing, but adequate curing was also found to be important. Both plastic sheeting and curing compounds were effective in giving good abrasion resistance.

Malchow and Senbetta (1987)(145) demonstrated quantitatively the effect of good curing on abrasion resistance, scaling resistance, corrosion of steel, chloride penetration, shrinkage, and water absorptivity. Curing was continuous, either by sealing the surface of specimens with wax or curing compound, or by storage in a fog room, so no information on length of early curing could be derived.

Gowripalan et al. (1990) looked at effects of curing on properties that tend to correlate with susceptibility to a number of aggressive conditions for concrete: porosity, gas permeability, and water absorption.(146) The difference in these properties when compared between 2-day and 7-day moist curing was very large, but even 7-day curing did not completely overcome the slow hydration effects of fly ash or slag unless curing temperature was elevated to 35 °C.

Rasheeduzzafar, Al-Gahtani, and Al-Saaldoun (1989) investigated the effect of curing on time to corrosion in chloride environments and resistance to sulfate solutions.(147) Time to corrosion was linearly related to length of moist curing through 28 days, the maximum length investigated. Time to corrosion after 3 days was 12 percent of the 28-day value and was 25 percent after 7 days of curing. Sulfate resistance increased in a nonlinear way with length of curing. Very little improvement was realized after 14 days of curing. More than 50 percent of 28-day values (mass loss, strength) was realized with 7 days of curing.

Mangat and El-Khtib (1992) found that length of curing was not a good predictor of sulfate resistance, but that rate of sulfate attack was inversely related to depth of carbonation.(148)

Burrows (1998) challenges some of the conventional wisdom in concrete technology, including beliefs about curing.(116) While acknowledging that impermeability of concrete improves with amount of curing (up to some limiting value) and that this often improves durability, he contends that excessive curing results in concrete with high potential for drying shrinkage strains. Such concretes also have a relatively high modulus of elasticity and low capacity for creep, resulting in a high potential for cracking when under restraint. He contends that many of the cracked bridge decks are a result of such a combination of modern concretes (rich mixtures) and excessive curing.

POZZOLANS AND SLAG

In the United States, pozzolans and slags include coal fly ash, GGBFS, and silica fume. The current understanding of the hydration of cementitious materials containing these is that they require more attention to curing than does concrete containing only portland cement. However, if cured properly, the resulting microstructure of pozzolans or slag is often more dense than in pure portland cement concrete. Typically, concretes containing pozzolans, slag, or both, require relatively longer curing times, and they tend to benefit more from elevated temperatures than do simple portland cement concretes. Haque (1990, 1996, 1998) has been a proponent of curing concrete containing Class F fly ash for at least 7 days based on strength development and water absorption data. Additional curing was found beneficial, but the effect was reduced after 7 days.[149,150,151]

Swamy and Bouikni (1990) measured compressive and flexural strength, ultrasonic pulse velocity, and modulus of elasticity on concretes containing GGBFS.[152] Specimens containing 50 percent GGBFS were not more sensitive to curing than specimens containing only portland cement, but at 65 percent GGBFS they were. Other test properties, however, showed sensitivity to this absence of curing. Even 7 days of moist curing was not enough to totally prevent some microstructural problems that occur on drying. Longer curing times were not explored. This same conclusion was reached by Gowripalan et al. (1990) although elevated temperatures (35 °C) for 7 days, or moist curing for 28 days, was required to reach approximate equivalency to control concrete containing no pozzolan cured for 7 days.[146]

Austin et al. (1992) measured strength, ultrasonic pulse velocity (UPV), rebound number, water absorption, and air permeability of 50 percent slag concretes on specimens cured in air, under wet burlap with plastic on top, with curing compound, with plastic sheet, and in water.[153] They found the UPV to be the most sensitive measure of development of physical properties. Rebound number was the worst. Curing beyond 7 days was not examined (except in curing compound cured specimens). Temperatures above 20 °C strongly boosted the strength. The burlap curing was superior to the plastic sheeting and to the curing compound, indicating the added water was important for these concretes.

Ballim (1993) investigated curing in concretes containing 30 percent Class F fly ash and 50 percent GGBFS, as a mass fraction of cementitious materials, using oxygen permeability and water absorption as measures of physical property development.[154] The effects of curing (water immersion) times of 1, 3, 7, and 28 days were examined. Water absorption tests seemed to give the most easily interpretable set of test results. Near-surface concrete (0–15 mm) was most affected by length of curing. Curing up to 7 days resulted in relatively large changes in the measured properties. There were additional benefits with longer curing, but the increase was much smaller. This was true even for the mixtures containing no pozzolan or slag, but the effect of increasing curing time was strongest in the GGBFS mixtures.

Afrani and Rogers (1994) investigated the effect of method of curing on salt scaling of ordinary portland cement (OPC), GGBFS, fly ash (F), and silica fume concretes.[155] All specimens were cured for 14 days with either wet burlap, curing compound, and in a fog room. Best results were obtained with the wet burlap method. GGBFS mixtures did not do well in this test, even with wet burlap curing.

Haque (1990) investigated the effect of length of fog-room curing of OPC and Class F fly-ash concretes (30 percent of cementitious materials) on strength and depth of water penetration.(149) Curing times of 0, 7, and 28 days were examined. He concluded that at least 7 days moist curing was needed.

Ozyildirim and Halstead (1994) investigated concrete containing Type II and III portland cements, and various levels of replacement with Class F fly ash and silica fume.(156) Strength and chloride permeability were measured on specimens moist cured (presumably fog room) for 1, 3, and 14 days at 23 and 38 °C. Higher temperatures, longer curing, and addition of silica fume all significantly reduced chloride permeability. Specimens containing silica fume, fly ash, and Type III cement reached low permeability values after 1 to 3 days of moist curing if curing temperatures were at 38 °C.

Thomas and Matthews (1994) found that concrete containing no more than 30 percent fly ash needed no more curing than simple portland cement concrete, 3 days being generally adequate, as determined by permeability measurements, but that 50 percent fly ash concretes needed at least 7 days curing.(157) When well cured, the permeability of fly ash concretes is lower, but depth of penetration of carbonation is higher. Carbonation depths ranged from less than 5 mm to a maximum of 35 mm, correlating strongly with strength and type of exposure (interior concrete was more deeply carbonated than exterior concrete).

Ho, Cui, and Ritchie (1989) used surface absorption of water to evaluate the length of curing required of concretes containing fly ash and slag. They concluded that 7 days of moist curing is a minimum amount for these systems.(115)

HIGH-PERFORMANCE CONCRETE

Meeks and Carino (1999) recently completed a comprehensive review of information on curing of high-performance concrete.(4) Their description below of the objectives of a proposed work unit on curing high-performance concrete are pertinent to this project.

> The long-term goal of the proposed research is to provide the basis for modifying current ACI standards related to curing so that structures in service will perform as required. Curing requirements should consider economy of construction and not place undue demands on the construction team. On the other hand, curing requirements should assure the owner that the potential properties of the concrete in the structure are realized. To achieve these goals, emphasis should be placed on developing a system to verify the adequacy of curing on the job, such as for example, by requiring the measurement of in place properties of the [sic] at the end of the curing period. (p. 177).

The report concluded with a discussion of research needs, summarized briefly as follows:

1. Evaluation of curing methods should be done on full-scale models that accurately simulate field concrete in both dimensions, exposure conditions, and temperature history.

2. The idea that low water-cement ratio concretes will benefit from added-water types of curing should be investigated. There is a concern that added water may not penetrate into the concrete to any appreciable degree, so the effort may be wasted.

3. In-place test methods should be developed.

4. Curing requirements should be revised to better reflect the particular performance requirements of high-performance concrete (HPC).

A common feature of HPC design is development of high strength. Mixture proportions commonly involve low water-cement ratios. As has been mentioned elsewhere, water-cement ratios less than 0.40 are generally thought to create a condition where the concrete will internally desiccate due to consumption of all of the mixing water by hydration, and that if additional hydration is necessary, then water must be added during curing. But since low water-cement ratio concretes tend to be relatively impermeable, there is some question about how effective externally added water will be in penetrating the concrete. Persson (1997) studied relative humidity depth profiles in concrete at various water-cement ratios, with and without silica fume in the concrete.[158] As expected, the internal RH of low water-cement ratio concretes (<0.4) that were sealed against any evaporation begins to drop below 100 percent within 28 days, eventually dropping to about 75 percent after 450 days. This pattern is accelerated when silica fume is present. Similar specimens stored in water without any surface sealant show the same pattern, suggesting that the external water is in fact not getting into the concrete to any appreciable degree. The minimum depth analyzed was 50 mm.

Two types of HPC are pertinent to portland cement concrete paving: bridge decks and fast-track paving.

Bridge Decks

Bridge decks are not within the scope of this project, but information on some of the practices is useful and interesting in developing ideas about curing pavements. Information on bridge deck curing practices comes mostly from State DOTs and from several papers on current practice that have appeared recently. The principal concern with the concrete in bridge decks is usually that it not be excessively permeable to chemical compounds that promote corrosion of reinforcing steel, such as carbon dioxide and particularly chloride, and that they do not crack appreciably.

Concretes used in bridge decks commonly contain silica fume and or other pozzolans or slag, and are proportioned at low water-cement ratios. If properly cured, these concretes will have very low permeability. However, cracking has been a persistent problem. Mohsen (1999) investigated causes of bridge deck cracking.[38] The investigation included variables such as damage due to physical causes, for example vibration from passing traffic (partial road closures), concrete mixture proportions, and curing. It was concluded that curing, including both moisture and temperature management, was the most important variable. Excess water in the concrete was considered the next most important variable.

Bridge decks typically get more attention to curing than conventional concrete paving. Practices vary among State DOTs, but usually considerable attention is paid to keeping the surface wet continuously after finishing to prevent shrinkage cracking. Some combination of curing compounds, water, wet burlap, and curing blankets are used for the duration of the curing, which is typically about 7 days.

One popular practice that exists is to use either an evaporation retardant or fogging to keep the concrete wet until conditions are right to apply curing compound. After the curing compound is applied, some kind of wet curing is applied. The additional water probably does not penetrate into the concrete to contribute to hydration to any appreciable extent because of the curing compound cover, but is probably more important for temperature control and possibly to compensate for any curing compound deficiencies.

Healy and Lawrie (1998) investigated cracking in highway bridge decks in Maryland. Two large bridges had almost 100 percent of surface area cracked.[37] They investigated mechanical causes, but determined that shrinkage cracking was the principal cause and that curing practices were deficient. It was reported that the Maryland DOT standard specifications require curing with curing compound along with burlap, plastic sheet, or cotton mats (apparently dry) for 7 days. A number of practices were investigated, but they found the most improvement with use of fiber-reinforced concrete or with use of curing compound together with wet burlap. The effect of the wetted burlap apparently was to help control temperature. The curing compound with fogged burlap was adopted into revised guidance along with guidance on time-of-day scheduling of construction to avoid major solar heating effects.

Ozyildirim (1999) of the Virginia Highway Research Council reported bridge deck curing was executed with wet burlap covered under plastic sheeting.[159] Concrete was designed to be low permeability, using the rapid chloride permeability test (ASTM C 1202)[160] and the chloride ponding test (AASHTO T 259).[161] Curing requirements are for 7-day moist curing or 70 percent f_c'. Fogging is used to protect the surface from excessive evaporation until the burlap-plastic sheet curing system could be put into place. The bridge deck concrete contained slag or Class F fly ash with water-cement ratios of 0.40 to 0.45.

Waszczuk and Juliano (1999) of the New Hampshire DOT, reported on bridge deck concrete that contained silica fume with a water-cement ratio of 0.38.[162] Once concrete had been dragged, it was covered within 15 min to prevent plastic shrinkage cracking. Curing was with cotton mats (stitched burlap with cotton bat filler) which were installed dry, then wetted and kept wet for 4 days. Concrete was not placed unless evaporation rates were less than or equal to 0.5 kg/m^2/h (it was not reported whether this was determined empirically or taken from the nomograph) and temperature was less than or equal to 29 °C.

Ralls (1999) reported on a bridge deck construction by the TxDOT. Bridge decks were cast in place.[163] Concrete was portland cement fly ash (approximately 30 percent), with a water-cement ratio of 0.43. Concrete was fogged until curing compound could be applied, followed by wet cotton mats as soon as the concrete could be walked on. TxDOT standard specifications require 10 days of wet mat curing for concrete containing fly ash.

Beacham (1999) reported on a bridge deck construction by the Nebraska Department of Roads.[34] Concrete was designed for a 56-day compressive strength of 55,158 kPa and a chloride permeability limit of 1800 coulombs at 56 days. Abrasion resistance was also a property of interest, but not a specification requirement. The concrete contained 445 kg/m^3 of Type IP cement and 44.5 kg/m^3 of Class C fly ash, at a water-cement ratio of 0.30. Concrete could only be placed if evaporation rates were below 0.75 kg/m^2/h as determined by the nomograph. Maximum allowable ambient temperature for placing was 27 ^{o}C. Requirements were for 8 "curing days." A curing day is one in which the shade temperature is greater than or equal to 10 ^{o}C for at least 19 h, or surface temperature of concrete is at leas 4 ^{o}C for the entire 24 h. The project plan apparently required misting until time of setting, then curing with wet mats. Misting was found to be impractical because of wind, so curing compound application was substituted, then the wet mats, as required. This appeared to work well.

Fast-Track Paving

Fast-track paving is a technology by which road pavements are placed and opened to traffic quickly, usually within 24 to 48 h. Strength gain of most conventional concrete mixtures is too slow to allow this. One technique that has been used in fast-track paving is to take advantage of the heat of hydration of the cementitious materials to create an elevated curing temperature, thus accelerating strength gain. A more common approach is to proportion the concrete with a high cement content and low water-cement ratio (<0.40) and perhaps to use a high-early strength cement, like ASTM C 150[44] Type III cement. Even though no steps are taken to accelerate hydration, sufficient strength can be obtained in 24 h to bear traffic loads. Curing is of necessity abbreviated in time, which is not too important in the context of strength development, since that has been accommodated by mixture proportioning. However, there might be some concern about the near-surface qualities of the concrete.

The Iowa DOT was involved in much of the early work on fast-track techniques (Knutson and Riley, 1988;[164] Grove et al., 1990;[165] Public Roads 1988[166]). This work used a Type III portland cement with a supplemental 12-hour strength requirement of 8,963 kPa. Curing blankets were also used.

Grove (1989) explored the use of insulated blankets to elevate curing temperatures in the first 24 h after placing.[167] The objective was to try to accelerate strength enough to avoid the special purpose Type III cement. Temperature and strength differentials of rich concrete mixtures (355–415 kg/m^3) at 5 to 8 ^{o}C were achieved 7 to 17 h after placing relative to uninsulated concrete. A leaner mixture (263 kg/m^3), also containing fly ash (44 kg/m^3), showed almost as much temperature rise, but the strength increase was much smaller. The results showed that insulation could not completely compensate for the higher strength gain of the special Type III cement, but that sufficient strength gain could be achieved to meet many project needs for rapid opening. The most advantageous aspect of using blankets is that it prevents the nighttime temperature drops and evens out the temperature of the concrete. One potential disadvantage is that solar radiation is blocked from the concrete, which may be a desirable source of heat in cool weather.

The American Concrete Pavement Association (ACPA) pamphlet "Concrete Paving Technology: Fast-Track Concrete Pavements" (ACPA 1994) has considerable advisory information on curing this type of concrete technology, as summarized below.[(168)] In addition to the information summarized above, the ACPA guidance recommends accelerators be considered. Also, monitoring heat development in the concrete is recommended so insulation can be adjusted. This is critical to anticipate the "sawing window," strength development (which determines when pavement can be opened for traffic), and to prevent cracking. Application of maturity testing concepts is recommended (ASTM C 1074).[(39)]

White pigmented curing compounds (ASTM C 309, Type 2, Class A) are recommended with an application rate of 5.0 m^2/L.[(23)] In mountainous and arid climates, heavier applications of 3.75 m^2/L and use of white pigmented resin based materials (ASTM C 309, Type 2, Class B) is recommended.[(23)] Bonded overlays less than 152 mm require application rates of 2.5 m^2/L because of the larger surface-volume ratio. Since fast track technologies cause rapid consumption of mixing water, the concrete is more susceptible to plastic shrinkage cracking. Early curing is very important; therefore, curing compound should be applied as soon as possible. Tire friction will wear some of the curing compound off, but the cement is believed to have sufficient hydration at this point that no problems result.

Blanket insulation is needed in cool weather, along with curing compound. The ACPA pamphlet contains a tabulation that allows the user to make use of ambient temperature projections and available curing times (allowable road closure times) to determine whether insulation is needed or not.[(168)] There is no consideration for the variable heat of hydration of various cementitious materials. "R" ratings of at least 0.035 m^2 Kelvins per watt (K/W) are recommended for insulating materials. Insulation constructed of a layer of closed-cell polystyrene foam with a protective layer of plastic is recommended. Additional blankets may be needed if temperatures fall below 4 °C. Time of day of concrete placing is important because of the interaction between early hydration reactions and temperature gain from thermal radiation.

When evaporation rate exceeds 1.0 kg/m^2/h, using the evaporation-rate nomograph in ACI 308, plastic-shrinkage cracking is considered likely.[(31)] To be conservative, it is recommended that particular attention be paid to moisture conditions in the concrete when evaporation exceeds 0.5 kg/m^2/h.

It is recommended that flexural strength be used to determine the time when pavement can be opened to traffic, and hence deliberate curing ends. Recommended guidance is given on the flexural strength (ASTM C 78) needed for different situations.[(169)] It is also recommended that other field measurement methods might be preferable to C 78 and gives some guidance on correlating these with flexural strength.[(169)]

CURING COMPOUNDS

Curing compound use dates to the early 1930s. Jackson and Kellerman (1939) describe the historical development of pavement curing methods.[2] The traditional method was to cover the concrete with wet burlap as soon as possible after finishing. The concrete was kept wet until the following day, when the burlap was replaced with a covering of earth or straw kept continuously wet for 7 to 10 days. This method worked well, but it "required constant and efficient supervision to insure full compliance," (p. 482).[2] This method was practical since daily placement rates were rather low. As construction techniques became more efficient, daily placement rates increased, so that the traditional methods became too expensive. "As was bound to happen, this condition has resulted within the last several years in the introduction of numerous substitute methods of curing, designed to accomplish the same purpose without the use of water," (p. 483).[2] Early products included waterproof paper, sodium silicate, liquid bituminous products, rubber emulsions, and calcium chloride. Use of calcium chloride and liquid bituminous products has ceased over the years. Sodium silicate has been found to have little value as a curing compound. Currently available curing compounds typically fall either into an organic-solvent type or a water based type. The membrane-forming compounds may be either waxes or some type of polymerizing resin or oil.

The earliest reference to the use of curing compounds found in this literature search was in the construction of a canal lining in the Yakima Reclamation Project, Washington (Ruettigers and Whitmore (1930)).[170] Water curing was the predominant form of curing used on this project, but the last 6 miles were cured with an asphaltic compound as an experiment. There was no comment on the resulting performance.

Gonnerman (1930) conducted a systematic study of curing compounds being marketed at that time.[118] This work was specifically in support of new curing methods for use in highway construction. Prior to this, highway concrete curing was accomplished by maintenance of surface moisture with earth, straw, ponding, etc. The curing compounds were asphaltic products (McEverlast paint, Tarvia K.P., and Curcrete), linseed oil, and paraffin.

Application rates were generally about 4.5 m^2/L, applied immediately after finishing. The effects of curing on both strength development and durability were recognized in this work. Performance measures were strength gain (compressive and flexural), abrasion resistance, water absorption, surface hardness. Performance of these curing materials was found to be approximately equivalent to that of 14 days of moist curing.

Meissner and Smith (1938) reviewed use of currently available curing compounds for use by the U.S. Department of Interior's Bureau of Reclamation.[171] These were mostly coal-tar or asphalt-based materials that had been dissolved in an organic solvent (cut backs). At that time, the Bureau of Reclamation required concrete be moist cured for 14 days, and so required that any curing compounds demonstrate equivalent performance in lab tests. Curing compounds at that time were found to perform well in moderate weather conditions, but did not do well in very hot weather. Another problem with the curing compounds of the day was the dark color, which caused solar heating and sometimes resulted in thermal cracking problems. Application rates were determined by what could be made to adhere to a vertical surface. These ranged from

3.5 to 4.7 m^2/L. Moisture loss at 100 °C, 15 percent RH ranged from about 0.5 to 1.0 kg/m^2 at 9 days, depending on application rate and product. Abrasion resistance, along with moisture loss, was the performance measure. It was concluded that these products could give the equivalent of 14 days moist curing. It was strongly recommended that curing compounds be applied immediately after finishing.

Jackson and Kellerman (1939) published results of an evaluation of a number of curing methods for use on concrete pavements.[(2)] They found the curing compounds of the day to be distinctly inferior to wet burlap curing, but that their performance improved substantially if the test specimens were wet cured for 24 h before application of curing compound. Their study, which was on mortar specimens, was criticized as employing unduly harsh conditions.

In another Bureau of Reclamation study, Blanks, Meissner, and Tuthill (1946) again reviewed performance of currently available curing compounds, comparing fog-room cured specimens with specimens coated with curing compound.[(172)] Elastic modulus and moisture loss were the measures of performance. They recognized then that other physical properties, such as surface hardness and abrasion resistance, could be used, but thought moisture loss was a particularly simple and direct measure. They classified curing compounds into three classes: (1) bituminous–coal tar and asphaltic cut backs, and asphaltic emulsions; (2) clear compounds–solvent type and emulsions; and (3) white pigmented. The clear, solvent types included a number of materials including resins, waxes, drying oils, and water repellent solids. The white pigmented compounds were basically clear solvent types to which a white pigment had been added.

Based on these comparisons with fog-cured concretes, they concluded that moisture loss in a standard test configuration could be used to evaluate the effectiveness of curing compounds. A test method and specification were presented. The test method is very similar to ASTM C 156[(18)] (ASTM C 156-44T[(173)] existed at that time, but it is not clear from this report whether the Bureau of Reclamation test method is the same or some slight variant). Moisture loss of a standard mortar specimen was measured after 7 days at 38 °C, 21 percent RH (saturated $CaCl_2$). Application rate was 3.7 m^2/L. A maximum moisture loss of 40 g (equivalent to 0.87 kg/m^2) of water was determined to represent material that would result in water retention equivalent to 14 days moist curing (the standard Bureau of Reclamation moist-curing requirement). The method was reported to have "reasonably close duplication."

For simplicity of inspection and to avoid thermal problems with the use of the black bituminous compounds, the Bureau of Reclamation prescribed use of white pigmented curing compound that met the above moisture loss requirement, applied in a single coat at 3.7 m^2/L.

Rhodes and Evans (1949) reported a major investigation of curing using curing compounds. They found that curing compounds work well if two conditions are met.[(174)] One is the early concrete temperature and the other is prevention of excessive drying before application of curing compound. Time of day is also heavily emphasized. Concrete placed in the early morning tends to develop maximum peak temperatures (through a combination of environmental and heat of hydration effects), and concretes placed early showed a temperature rise of 19 °C, while those placed late in the afternoon showed a 3 °C rise.

Burnett and Spindler (1952) measured moisture loss, abrasion resistance, and compressive strength of specimens in response to different times of application of curing compound, ranging from immediately after finishing to 18 h after.(175) Moisture loss increased with increasing time of application, but strength and abrasion resistance reached peak values when application was made 30 to 100 min after finishing. The explanation for this was that allowing bleeding and then evaporation of bleed water before curing compound application resulted in an effective reduction in the water-cement ratio. If more time passes before application of the curing compound, then too much water evaporates, affecting performance. The recommendation was to apply curing compound at time of setting, plus or minus 30 min. Application of the curing compound before bleed water evaporated did not substantially impair the physical integrity of the resulting membrane, although it did not appear to bond as well to the concrete surface as when it was applied later.

Mather (1953),(176) in a discussion of Burnett and Spindler (1952),(175) took exception to their conclusion that time of setting was a good indicator of the proper time to apply curing compound. He argued that the time when surface water has just disappeared is the best time to apply curing compound, and that this does not necessarily correspond to time of setting.

Carrier and Cady (1970) reported an investigation on some details of moisture distribution—from the surface of concrete to several inches of depth—that result from different curing compound practices.(51) The curing compound was apparently a very good one, given moisture loss of
0.26 kg/m^2, as tested by C 156.(18) They found that below about 5 mm, the application rate of the curing compound was inconsequential in causing changes is relative humidity in the concrete exposed to a dry environment. Application rates of 2.5–10 m^2/L were used. They concluded that application rate was not a particularly important part of practice.

Mather (1987,(177) 1990(178)) reviewed the state-of-the-art of curing practice, and specifically curing-compound practice in the latter reference. This information largely provided the basis of the current ACI 308.(31) He chaired the ACI Committee 308 when the original version of that document was written. It was last revised in 1992, but has remained the standard practice to the present time. A new guide is currently being written by ACI Committee 308.

Not much literature was found reporting research on curing compounds in the last 10 years; however, two papers were found that seem to be particularly pertinent to developing improved practice. Two others were found that touch tangentially on the subject.

Dhir, Levitt, and Wang (1989) developed a concept for describing the performance of curing compounds that is based on measuring a water vapor permeability coefficient of a product.(28) This coefficient is based on a Darcy's Law application to evaporation through a thin layer. This coefficient includes membrane thickness and time in its calculation, so the property is independent of a specific application rate or time of measurement, as with the current moisture loss requirement. The water vapor permeability coefficient concept would allow a more sophisticated approach to designing curing to be developed because it more completely describes the full time-dependent and application-dependent properties. The paper also describes a test method and test apparatus for measuring this property. The within-laboratory coefficient of variation of this test method was found to be 4.2 percent.

Wang, Dhir, and Levitt (1994)[124] in follow up work to the work reported in Dhir, Levitt, and Wang (1989),[29] described water evaporation from an air-cured concrete as generally being higher than expected from simple evaporation from a free-water surface. The higher rates occur at two times in the early history of the concrete. The first occurs immediately after placing from the free bleed water that forms on the surface; however, its rate of evaporation exceeds that expected from a free-water surface because of the thermal warming from the heat of hydration occurring in the first few minutes involving the aluminate and calcium sulfate phases of the cement. The second peak in water loss occurs after several hours and appears to be driven by the hydration of cement phases at that time. Tricalcium silicate (C_3S) and calcium-sulfoaluminate phases typically evolve significant heat. Application of curing compound tends to eliminate water loss due to the second phenomenon.

Three types of curing compounds were also investigated in this work: resin-solvent based, chlorinated-rubber based, and wax-water based. The wax-water based compound appeared not to work as well as the others, but only one product was examined.

This paper also reported the effect of time of application of curing compound on retardation of water evaporation. It was concluded that the current general guidance that curing compound be applied after surface water has disappeared may not be optimal. Improved performance was observed when curing compound was applied while surface water was still present. This effect was particularly strong in rich concrete mixtures. The effect was hypothesized to be the result of capillary suction potential that develops when the surface of concrete dries. This potential in effect “sucks” holes in the curing compound film before it develops adequate strength. While recognizing the potential problems associated with application of curing compound when concrete is too dry, Mather (personal communication) believes that the bulk of experience has shown that application of curing compound when surface water is still apparent does not result in performance that is as good as when applied to a surface that has just lost this surface water.[179]

This result and recommendation is counter to existing guidance in ACI 308, which directs that curing compound not be applied until the bleed water has disappeared by evaporation.[31] There is the caution that when the evaporation rate exceeds the bleeding rate, the surface bleed water will disappear before the bleeding has stopped. If curing compound is applied then, it might soak into the first few millimeters of the surface, then as the bleed water continues to form, will lift off that few millimeters of surface. This can happen when the evaporation rate exceeds 1 $kg/m^2/h$. ACI 308 lists precautions to take to avoid this situation.[31]

Kettle and Sadegzadeh (1987), in a study of effects of construction practices on abrasion resistance, found that concrete surfaces that were rough tended to show reduced abrasion resistance because of poor curing.[144] This was attributed to the curing compound flowing off of high spots after application, leaving insufficient coverage in spots. This paper also reported that the single water-based curing compound included in the study performed worse than the two resin-based curing compounds used.

Gowripalan et al. (1990) found that the two curing compounds included in their general study of durability, performed almost as well as curing with ponded water for 3 days, but that exactly equivalent properties were achieved only at a depth of 50 mm into the concrete.[146] Concrete nearer the surface did not perform quite as well. This result contrasts with older literature on curing compounds that indicated they gave curing approximately equivalent to 14 days moist curing.

Recent U.S. Environmental Protection Agency regulations require curing compounds meet low VOC limits of ≤ 350 g/L VOC. Many products are now available that meet this requirement. Whiting (2003) compared water retention performance of some VOC compliant compounds with non-VOC compliant materials and found no patterns in performance that distinguish these classes of materials.[180] Low VOC curing compounds are reputed to have drying time problems in very humid climatic conditions, but no literature was found on this.

White and Husbands (1990)[85] investigated the relationship between water-retention properties of curing compounds and curing performance, as measured by water absorption (ASTM C 1151).[27] Curing compounds varied in water loss, as measured in ASTM C 156, from 0.12 to 1.40 kg/m^2 at 72 h.[18] ASTM C 309 limits water losses to 0.55 kg/m^2. In ASTM C 1151, a slab of mortar is cured with the subject materials and cores taken, prepared and water absorption measured on the exposed surface and on the interior surface.[23] Water-cured and air-cured (evaporation rates of 1.65 kg/m^2/h) specimens were used as reference conditions. When water losses were up to approximately 1 kg/m^2, the membrane-cured specimens showed water absorption values essentially identical to water-cured specimens and to the surface of the specimen that represented the interior of the mortar. The curing compound that allowed loss of 1.4 kg/m^2 showed evidence of deficient performance in the water absorption test.

Tining concrete pavements is a common practice which effectively increases the surface area of the concrete. Shariat and Pant (1984) examined the effect of this on water retention and found that the amount of curing compound necessary for adequate water retention needed to be increased, relative to the control condition, in approximate proportion to the increase in surface area.[74] Increases in surface area of 25 to 50 percent can occur, depending on the tining pattern.

TEST METHODS

Test Methods for Curing Materials

Jackson and Kellerman (1939) published one of the earliest test methods for curing materials.[2] The method was based on solid rectangular lean-mortar specimens exposed to a temperature of 38 °C and a relative humidity of 32 percent for 7 days. Performance was measured by flexural strength and by moisture loss. Test results were expressed as a curing efficiency, using results from wet cured and uncured specimens as a frame of reference. The method was criticized as being too harsh in that the temperature and RH conditions were extreme. Also the lean mortar was much more prone to drying than a well-proportioned concrete would have been, so that some curing methods or materials believed to be satisfactory, in practice were reported to have relatively low curing efficiencies. The method appears to be very similar to ASTM C 156, which was introduced several years later.[18]

ASTM C 156[18] was first published as C 156-44T.[173] This method has been widely criticized for poor precision and has been modified significantly to improve on this (Leitch and Laycraft, 1971).[181] Poor between-laboratory precision is particularly undesirable, especially for buyer-seller transactions. Blanks, Meissner, and Tuthill (1946) reported that a similar Bureau of Reclamation method has reasonable precision, but no quantitative data were offered.[172] It is entirely likely that their estimation of the precision is based on within-laboratory data. This statistic often tends to be substantially better than between-laboratory precision.

Mather (1990)[178] commented on the data of Leitch and Laycraft (1971),[181] which showed that by modifying the requirements for C 156[18] the standard deviation could be reduced from 0.13 kg/m^2 to 0.05 kg/m^2. Mather (1990)[178] suggested that a repeatable moisture loss method could be developed.

Although there are many variants of C 156 in use, there have not been many methods proposed that offer substantial improvement.[18] As reported in Gowripalan et al. (1990)[146] there was an effort to develop a test method that works very much like ASTM C 156[18], but is simplified by using a desiccant in a container with the specimen to control RH. The mass change of the desiccant was used to detect the amount of water that passed the curing membrane. It was found that the mass change of the desiccant was relatively insensitive to the difference between concretes treated with a curing compound and concretes not treated at all. The original report on this work was not located.

As mentioned above, Dhir, Levitt, and Wang (1989) developed a test method for measuring the permeability coefficient of curing membranes.[29] To our knowledge, this method has not been standardized.

Cabrera, Gowripalan, and Wainwright (1989)[107] describe a test method for determining the effectiveness of curing compounds based on the oxygen permeability of mortar specimens. Determinations are made on uncoated and coated specimens, and curing efficiency is calculated as a percent reduction in the permeability of the uncoated specimen. Within-laboratory precision (CV) is about 3 percent for three materials with a curing efficiency of more than 80 percent, and about 7 percent for one material with a curing efficiency of 50 percent.

Test Methods that Validate Curing

Test methods that verify the quality of curing have traditionally relied on strength or some correlate of strength. There is a more recent trend towards measurement of near-surface properties, such as surface hardness, permeability, and water absorption. The International Union of Laboratories and Experts in Construction Materials, Systems and Structions (RILEM) Technical Committee (TC) 116-PCD on “Permeability of concrete as a criterion of its durability,” is developing methods for measuring near-surface properties as a general approach to evaluating potential durability of concrete (RILEM, 1999).[182] In addition to these, Cather

(1994) cited capillary porosity as a potentially useful method. He mentions ultrasonic pulse velocity as a potential test method, but dismisses it as probably not sensitive to the near-surface zone.[74]

Dinku and Reinhardt (1997) developed an in situ gas-permeability test for this purpose.[183] In this test, a hole is drilled into the concrete and hardware is arranged so that a fixed volume of pressurized gas (in this case nitrogen) is delivered to the hole. The rate at which the pressure drops as the gas permeates the concrete around the hole is related to the permeability of the of the near-surface concrete. The test is affected by the moisture condition of the concrete, which is determined separately and a correction is applied.

Ho and Lewis (1984,[184] 1992[185]) describe test methods for water sorptivity, carbonation, and abrasion resistance (based on ASTM C 418[186]) as measures of the quality of curing. The Roads and Traffic Authority of New South Wales (Australia)[110] uses water sorptivity as an acceptance test for curing of concrete. Specification limits on this property are presented in this report under the section on Australian curing guidance.

Carrier and Cady (1970) developed an RH-sensitive button (results in a color change) that could be used as a field test for the presence of surface water, but no other information on the subsequent development or use of this method was found.[51]

A state-of-the-art report prepared by RILEM TC 116-PCD[182] on performance of concrete as a criterion of its durability (Kropp and Hilsdorf 1995)[50] contains two chapters on test methods for physical properties of concrete that are believed to be critical for concrete durability. These properties are also considered quite sensitive to the degree of hydration of the portland cement, and hence their development is strongly related to curing. The report also summarizes methods for determining the moisture conditions in concrete.

Chapter 9 of Kropp and Hilsdorf (1995), by Geiker, covers laboratory test methods.[50] Methods include steady-state water permeation, nonsteady state water penetration, capillary suction, gas permeability, gas diffusion, ion transport (along concentration gradients), and ion transport (along electrical potential gradient).

Chapter 10 of Kropp and Hilsdorf (1995), by Paulmann and Molin, covers onsite methods.[50] These include capillary suction, water penetration, and gas permeability. The methods are all relatively simple in concept, but not particularly simple in execution. The required equipment could reasonably be assembled without excessive cost, but individual determinations appear to require enough time to setup and collect the data. Thus, they probably are not suitable for routine inspection and verification of curing. These methods do appear to be plausible for field investigations of relatively small areas of concrete.

Appendix A of Parrott (1995) covers methods to determine the moisture conditions in concrete.[121] These include destructive methods, RH, resistivity, dielectric properties, thermal properties, infrared absorption, and neutron scattering. Most of the methods do not appear to be suitable for monitoring of large amounts of concrete pavement, but one method, infrared absorption, appears to have potential. Water has characteristic infrared absorption wavelengths that can be used as an indicator for the amount of water present. Equipment exists that can illuminate an area of a surface with an infrared beam of the required wavelength, the reflected light is sensed and the moisture content of that surface analyzed. Not discussed by Parrott but plausible, is the possibility that curing compounds have an infrared spectrum that can be used as the basis for measuring membrane thickness.[121]

Another, infrared method that could be used for concrete curing is infrared thermography. This method uses an infrared sensitive video camera image of a concrete surface. Moisture conditions affect heat flow through the surface, resulting in variations in surface temperature that could be sensed by the infrared camera. This method would appear to have application in analyzing the quality of cover of curing compounds.

Al-Manaseer and Aquino (1999)[187] reported an evaluation of the Windsor probe (ASTM C 803[95]) for in situ measurement of concrete strength. They reported good results, but the method seems to rely on properties of the concrete considerably deeper that the near-surface zone, which is critical to evaluating curing. The method appears to have value for estimating in place strength, but probably has less value as a method for evaluating the near-surface zone.

White and Husbands (1990) investigated several methods for evaluating the effectiveness of curing compounds, including capillary porosity, water absorption, abrasion resistance, chemically combined water, and splitting tensile strength.[85] Abrasion resistance, capillary porosity, and water absorption appear to be the best from a sensitivity and precision viewpoint. Water absorption was found to be the most practical.

MATURITY

Strength gain in concrete is a time-temperature dependent phenomenon commonly called maturity. The bulk of concrete testing and concrete research is conducted under standard temperature conditions, usually about 23 °C. Estimating strength nondestructively under nonstandard temperature conditions may be of considerable practical value in actual construction. If some fundamental properties of a concrete are known, the rate of strength gain can be represented by a mathematical model that allows incorporation of nonstandard temperature conditions if the time-temperature history is known. ASTM C 1074 is a standard test method based on this principle, called the maturity method.[39]

Two basic approaches are described in C 1074.[39] One is based on a simple integration of the time-temperature curve to give a measure of maturity in units of degree-days. Maturity values are then calibrated to strength estimates using a concrete mixture similar to the job mixture. The maturity model is called the Nurse-Saul model. The Arrhenius model is also used in C 1074.[39] This model is based on the chemical kinetic model of that name, which represents the dependency of simple chemical reaction rate constants on temperature. The rate of strength gain is treated as though it were the rate constant of a simple chemical reaction.

There is considerable literature on determining the mathematical representations of the maturity phenomenon, and on verifying the accuracy of the method (Carino, 1984,[188] Parsons and Naik, 1985;[189] Chengju, 1989;[190] Malhotra and Carino, 1991;[191] Carino, Knab, and Clifton, 1992;[192] Carino and Tank, 1992;[193] Kjellsen and Detwiler, 1993[194]). Grove et al. (1990)[165] and Okamoto and Whiting (1994)[36] demonstrated the application of this technique for predicting strength development in fast-track paving. The method required some adjustments to the calibration procedure to account for the effects of the early temperature rise of the concrete. Pavements were placed at approximately 30 °C, but reached temperatures of 50–60 °C during the first 8 h. Hover (1992)[195] reported on use of this method in cold weather concreting to help predict strength development in structural concrete.

The maturity method might also be used to calculate the length of curing necessary under some anticipated time-temperature regimen.

CONCRETE TEMPERATURE

For purposes of protection of newly placed concrete from temperature or temperature-gradient extremes, it is of considerable practical value to be able to anticipate project concrete temperature from properties of the concrete materials and proportions and from anticipated ambient conditions. These properties and conditions include heat of hydration of cement, composition of the concrete, dimensions of the structure, and heat transfer rates to and from the surrounding environment. Kapila et al. (1997) report one mathematical development for this kind of analysis and their model predicted temperature-time measurements on a bridge deck placement very well.[60] These same concepts are being developed into a computer program, called HIPERPAV™, under a contract with FHWA.[13] This program allows the user to input information on concrete materials, mixture proportions, environmental conditions, and design details of a pavement, and then to have output on strength gain and tensile stresses associated with thermal effects to predict cracking. In its final form, the program will also incorporate effects of curing procedures on temperature.

Temperature gradients can be the cause or contribute to cracking in concrete. As reviewed under standard guidance, there is guidance on the types of gradients that can usually be tolerated in concrete. These values are typically in the range of 10 °C to 13 °C between the concrete surface and the interior (e.g., 50 mm). Lykke et al. (2000) report that values in the range of 15 °C to 20 °C can be tolerated in pavements.[196]

It is well known that the temperature history of concrete affects the early and the ultimate strength of concrete in opposite ways. High temperatures increase early strength and decrease ultimate strength. There are some data on this in ACI 305R on hot weather concreting.[12] Kim et al. (1998) simulated some high early-temperature events and found that concrete cured at 40 °C for the first 24 h developed strengths 2.4 times that at 20 °C, and that the 28-day strengths were about 13 percent lower.[197]

NEW TECHNOLOGY

Yu et al. (1998) investigated the effect of "electron water" on rate of strength development of concrete.[198] Electron water is produced by charging electricity through water in a tank for several hours or days. Such water has been found to have higher activity in biological systems, as measured by growth rates. Strength increases of 10 to 20 percent in concretes cured with electron water were observed, compared to curing in normal water. The effect is attributed to changes in the way water molecules cluster. This is reminiscent of the literature from the Soviet Union in the 1960s and 1970s about the higher concrete strengths produced by magnetic water, i.e., water that has passed through a strong magnetic field before being used as mixing water in concrete.

Weber and Reinhardt (1997),[199] Reinhardt and Weber (1998),[200] and Bentur et al. (2001)[201] investigated use of saturated lightweight aggregate as a reservoir for curing water in low water-cement ratio concretes. The intention was to overcome the problem of getting added water into such concretes, which tend to internally desiccate due to consumption of mixing water by hydration reactions. There was evidence that this technique resulted in continued hydration through 1 year. This technology was used when more water was calculated to be needed to produce the required expansion when Type K expansive cement was used for tunnel plugs than could be tolerated as water-cement-ratio water. The water needed beyond that allowed by selected water-cement ratio was introduced as absorbed water in the low-density aggregate.

Several years ago, a series of papers was published describing performance of a curing admixture (Dhir et al. 1994;[202] Dhir, Hewlett, and Dyer 1995,[203] 1996;[204] Klapperich, Potter, and Willocq, 1995[205]). This admixture acts to reduce the vapor pressure of water by forming hydrogen bonds with the water molecules in the liquid phase, thus reducing evaporation rates. Six products were included in the investigation. Performance with four of the products was not equivalent to water or curing compound curing, but two products produced almost equivalent results. Some products caused an acceleration of cement hydration. One resulted in reduced strength, apparently because it interfered with the formation of calcium hydroxide, which normally comprises the predominant material in the cement-aggregate interfacial zone. No later literature, including commercial literature, was found on this technology.

Knutson and Riley (1988) briefly mention that the ACPA was investigating use of a biodegradable foam for use as a curing material in cooler weather.[164] This material would have an advantage in that it could be washed away after concrete had reached adequate strength.

APPENDIX C: REFERENCED STANDARDS AND COMMITTEE REPORTS BY ORGANIZATION

AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS (AASHTO)

AASHTO M 148. Same as ASTM C 309-94.[24]

AASHTO M 171.[17] Same as ASTM C 171-95.[99]

AASHTO M 182-91. Specification for Burlap Cloth Made from Jute or Kenaf.[20]

AASHTO T 97-97.[102] Specification for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading). Also ASTM C 78-94.[169]

AASHTO T 155-91 (1996).[55] Specification for Water Retention by Concrete Curing Materials. Also ASTM C 156-95.[18]

AASHTO T 259-80. Method of Test for Resistance of Concrete to Chloride Ion Penetration.[161]

AASHTO Guide Specifications for Highway Construction (1998).[33]

AASHTO Quality Assurance Guide Specification (1996)[100]

AASHTO Construction Manual for Highway Construction (1990).[101]

AMERICAN CONCRETE INSTITUTE (ACI)

The following documents are found in the ACI *Manual of Concrete Practice*.

ACI 116R-90. Cement and Concrete Terminology.[1]

ACI 228.1R-95. In-Place Methods for Determination of Strength of Concrete.[49]

ACI 301-96. Standard Specification for Structural Concrete[43]

ACI 305R-91. Hot Weather Concreting.[12]

ACI 306R-88. Cold Weather Concreting.[14]

ACI 308-92. Standard Practice for Curing Concrete.[31]

ACI 308.1-98. Standard Specification for Curing Concrete.[45]

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)

All of the following standards are found in the 1998 *Annual Book of ASTM Standards*, volume 04.02.

ASTM C 94-98. Specification for Ready-Mixed Concrete.[15]

ASTM C 156-95. Test Method for Water Retention by Concrete Curing Materials.[18]

ASTM C 171-97a. Specification for Sheet Materials for Curing Concrete.[17]

ASTM C 309-98. Specification for Liquid Membrane-Forming Compounds for Curing Concrete. The 1998 revision has been published separately, and is not in volume 04.02 for 1998.[23]

ASTM C 418-98. Test Method for Abrasion Resistance of Concrete by Sandblasting. The 1998 revision has been published separately, and is not in volume 04.02 for 1998.[186]

ASTM C 597-97. Test Method for Pulse Velocity Through Concrete.[97]

ASTM C 670-96. Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials.[26]

ASTM C 803-97. Test Method for Penetration Resistance of Hardened Concrete.[94]

ASTM C 805-97. Test Method for Rebound Number of Hardened Concrete.[79]

ASTM C 873-94. Test Method for Compressive Strength of Concrete Cylinders Cast in Place in Cylindrical Molds.[93]

ASTM C 900-94. Test Method for Pullout Strength of Hardened Concrete.[95]

ASTM C 1067-87 (93). Practice for Conducting a Ruggedness or Screening Program for Test Methods for Construction Materials.[30]

ASTM C 1074-93. Practice for Estimating Concrete Strength by the Maturity Method.[39]

ASTM C 1150-96. Test Method for the Break-Off Number of Concrete.[96]

ASTM C 1151-91. Test Method for Evaluating the Effectiveness of Materials for Curing Concrete.[27]

ASTM C 1202-97. Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration.[159]

ASTM C 1315-95. Specification for Liquid Membrane-Forming Compounds Having Special Properties for Curing and Sealing Concrete.[24]

ARMY CORPS OF ENGINEERS (USACE)

USACE standards are no longer available in print, but can be accessed at the following WEB site: http://www.usace.army.mil/inet/usace-docs/. Documents are in PDF format and can be downloaded or printed from the WEB site.

TM 5-822-7. Standard Practice for Concrete Pavements (1987).[25] Also Air Force AFM 88-6, Chapter 8.[104]

CEGS 03300-95. Guide Specification for Cast-in-Place Structural Concrete.[19]

CEGS 03301-94. Guide Specification for Cast-in-Place Structural Concrete for Civil Works[102]

CRD-C 300-90. Specifications for Membrane-Forming Curing Compounds for Curing Concrete[83]

CRD-C 302-79. Test Method for Sprayability and Unit Moisture Loss Through the Membrane Formed by a Concrete Curing Compound[105]

CRD-C 400-63. Requirements for Water for Use In Mixing or Curing Concrete.[16]

EM 1110-2-2000. Standard Practice for Concrete (1994).[8]

OTHERS

British Standards Institution (BS)

BS 1881: Part 1 (1997) "Structural Use of Concrete": Part 1 "Code of Practice for Design and Construction."

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European Committee for Standardization (CEN)

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13. HIPERPAV software. Additional information on HIPERPAV can be found at www.hiperpav.com and www.fhwa.gov.

14. ACI 306R-88, "Cold Weather Concreting," *ACI Manual of Concrete Practice,* American Concrete Institute, Farmington Hills, MI.

15. ASTM C 94-98, "Specification for Ready-Mixed Concrete," *Annual Book of ASTM Standards*, 1998, vol. 04.02.

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