ACI 308R-01
(Reapproved 2008)

Guide to Curing Concrete

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The term "curing" is frequently used to describe the process by which hydraulic-cement concrete matures and develops hardened properties over time as a result of the continued hydration of the cement in the presence of sufficient water and heat. While all concrete cures to varying levels of maturity with time, the rate at which this development takes place depends on the natural environment surrounding the concrete, and the measures taken to modify this environment by limiting the loss of water, heat, or both, from the concrete, or by externally providing moisture and heat. The word "curing" is also used to describe the action taken to maintain moisture and temperature conditions in a freshly placed cementitious mixture to allow hydraulic-cement hydration and, if applicable, pozzolanic reactions to occur so that the potential properties of the mixture may develop. Current curing techniques are presented; commonly accepted methods, procedures, and materials are described. Methods are given for curing pavements and other slabs on ground, for structures and buildings, and for mass concrete. Curing methods for several specific categories of cement-based products are discussed in this document. Curing measures, in general, are specified in ACI 308.1. Curing measures directed toward the maintenance of satisfactory concrete temperature under specific environmental conditions are addressed in greater detail by Committees 305 and 306 on Hot and Cold Weather Concreting, respectively, and by ACI Committees 301 and 318.

Keywords: cold weather; concrete; curing; curing compound; hot weather construction; mass concrete; reinforced concrete; sealer; shotcrete; slab-on-ground.

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ACI 308R-01 became effective August 14, 2001.

CHAPTER 1—INTRODUCTION

1.1—Introduction

This guide reviews and describes the state of the art for curing concrete and provides guidance for specifying curing procedures. Curing practices, procedures, materials, and monitoring methods are described. Although the principles and practices of curing discussed in this guide are applicable to all types of concrete construction, this document does not specifically address high-temperature or high-pressure accelerated curing.

1.2—Definition of curing

The term “curing” is frequently used to describe the process by which hydraulic-cement concrete matures and develops hardened properties over time as a result of the continued hydration of the cement in the presence of sufficient water and heat. While all concrete cures to varying levels of maturity with time, the rate at which this development takes place depends on the natural environment surrounding the concrete and on the measures taken to modify this environment by limiting the loss of water, heat, or both, from the concrete, or by externally providing moisture and heat. The term “curing” is also used to describe the action taken to maintain moisture and temperature conditions in a freshly placed cementitious mixture to allow hydraulic-cement hydration and, if applicable, pozzolanic reactions to occur so that the potential properties of the mixture may develop (ACI 116R and ASTM C 125). (A mixture is properly proportioned and adequately cured when the potential properties of the mixture are achieved and equal or exceed the desired properties of the concrete.) The curing period is defined as the time period beginning at placing, through consolidation and finishing, and extending until the desired concrete properties have developed. The objectives of curing are to prevent the loss of moisture from concrete and, when needed, supply additional moisture and maintain a favorable concrete temperature for a sufficient period of time. Proper curing allows the cementitious material within the concrete to properly hydrate. Hydration refers to the chemical and physical changes that take place when portland cement reacts with water or participates in a pozzolanic reaction. Both at depth and near the surface, curing has a significant influence on the properties of hardened concrete, such as strength, permeability, abrasion resistance, volume stability, and resistance to freezing and thawing, and deicing chemicals.

1.3—Curing and the hydration of portland cement

1.3.1 *Hydration of portland cement*—Portland cement concrete is a composite material in which aggregates are bound in a porous matrix of hardened cement paste. At the microscale, the hardened paste is held together by bonds that develop between the products of the reaction of cement with water. Similar products are formed from the reactions between cement, water, and other cementitious materials.

The cement-water reaction includes both chemical and physical processes that are collectively known as the hydration of the cement (Taylor 1997).[1] As the hydration process continues, the strength of the interparticle bonding increases, and the interparticle porosity decreases. Figure 1.1 shows particles of unhydrated portland cement observed through a scanning electron microscope. In contrast to Fig. 1.1, Fig. 1.2 shows the development of hydration products and interparticle bonding in partially hydrated cement. Figure 1.3 shows a single particle of partially hydrated portland cement. The surface of the particle is covered with the products of hydration in a densely packed, randomly oriented mass known as the cement gel. In hydration, water is required for the chemical

[1] “In cement chemistry the term ‘hydration’ denotes the totality of the changes that occur when an anhydrous cement, or one of its constituent phases, is mixed with water” (Taylor 1997).

formation of the gel products and for filling the micropores that develop between the gel products as they are being formed (Powers and Brownyard 1947; Powers 1948). The rate and extent of hydration depend on the availability of water. Parrott and Killoh (1984) found that as cement paste comes to equilibrium with air at successively lower relative humidity (RH), the rate of cement hydration dropped significantly. Cement in equilibrium with air at 80% RH hydrated at only 10% the rate as companion specimens in a 100% RH curing environment. Therefore, curing procedures ensure that sufficient water is available to the cement to sustain the rate and degree of hydration necessary to achieve the desired concrete properties at the required time.

The water consumed in the formation of the gel products is known as the chemically bound water, or hydrate water, and its amount varies with cement composition and the conditions of hydration. A mass fraction of between 0.21 to 0.28 of chemically bound water is required to hydrate a unit mass of cement (Powers and Brownyard 1947; Copeland, Kantro, and Verbeck 1960; Mills 1966). An average value is approximately 0.25 (Kosmatka and Panarese 1988; Powers 1948).

As seen in Fig. 1.2 and 1.3, the gel that surrounds the hydrated cement particles is a porous, randomly oriented mass. Besides the hydrate water, additional water is adsorbed onto the surfaces and in the interlayer spaces of the layered gel structure during the hydration process. This is known as physically bound water, or gel water. Gel water is typically present in all concrete in service, even under dry ambient conditions, as its removal at atmospheric pressure requires heating the hardened cement paste to 105 C (221 F) (Neville 1996). The amount of gel water adsorbed onto the expanding surface of the hydration products and into the gel pores is "about equal to the amount that is (chemically) combined with the cement" (Powers 1948). The amount of gel water has been calculated more precisely to be a mass fraction of about 0.20 of the mass of hydrated cement (Powers 1948; Powers and Brownyard 1947; Cook 1992; Taylor 1997).

Both the hydrate water and physically adsorbed gel water are distinct in the microstructure of the hardened cement paste, yet both are required concurrently as portland cement cures. Neville (1996) writes that continued hydration of the cement is possible "only when sufficient water is available both for the chemical reactions and for the filling of the gel pores being formed." The amount of water consumed in the hydration of portland cement is the sum of the water incorporated physically onto the gel surfaces plus the water incorporated chemically into the hydrate products themselves. (Neville 1996; Powers and Brownyard 1947; Mindess and Young 1981; Taylor 1997.) Because hydration can proceed only in saturated space, the total water requirement for cement hydration is "about 0.44 g of water per gram of cement,[2] plus the curing water that must be added to keep (the capillary pores of) the paste saturated" (Powers 1948). As long as sufficient water is available to form the hydration products, fill the interlayer gel spaces and ensure that the

[2]Other sources place this approximate value at 0.42 to 0.44 g of water for each gram of dry cement (Powers 1947; Taylor 1997; Neville 1996).

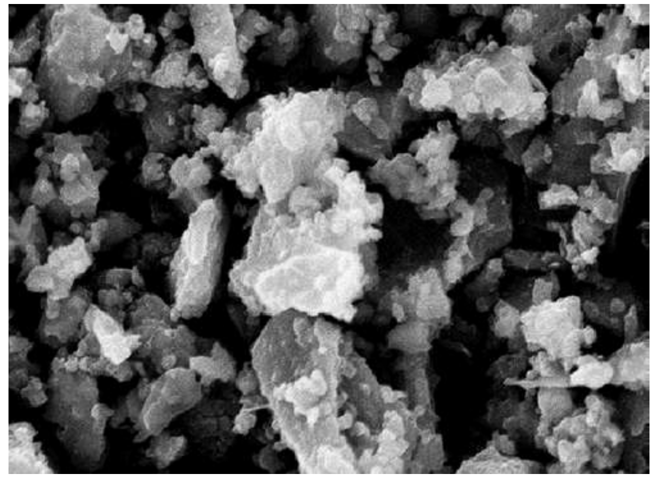

Fig 1.1—Unhydrated particles of portland cement—magnification 2000× (photo credit Fig. 1.1-1.3, Eric Soroos).

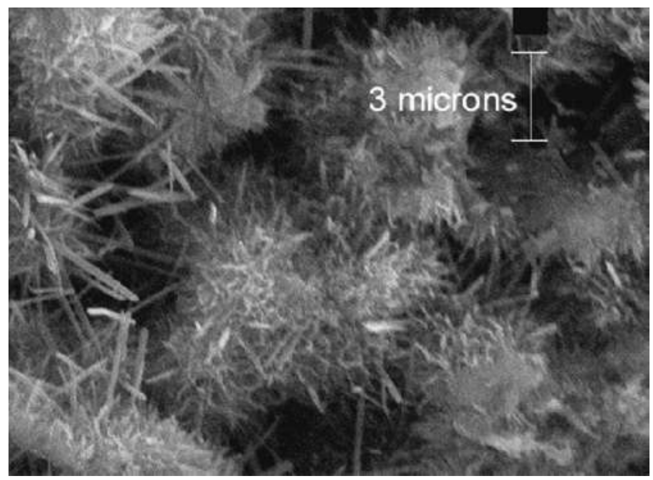

Fig 1.2—Multiple particles of partially hydrated portland cement—magnification 4000×.

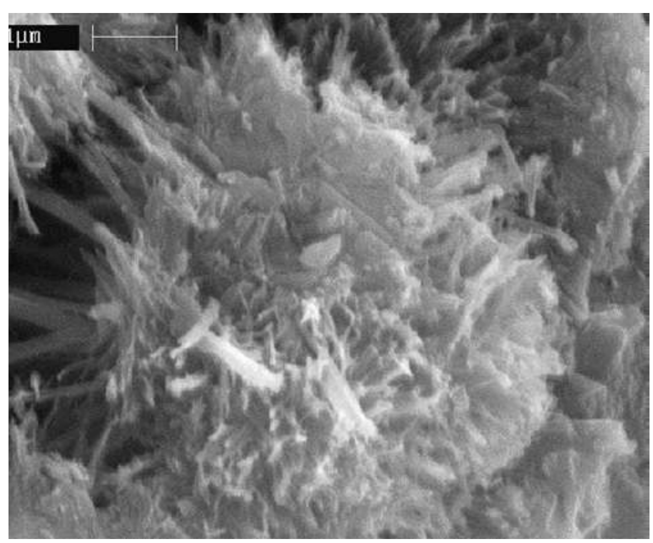

Fig 1.3—Close-up of a single particle of hydrated cement—magnification 11,000×.

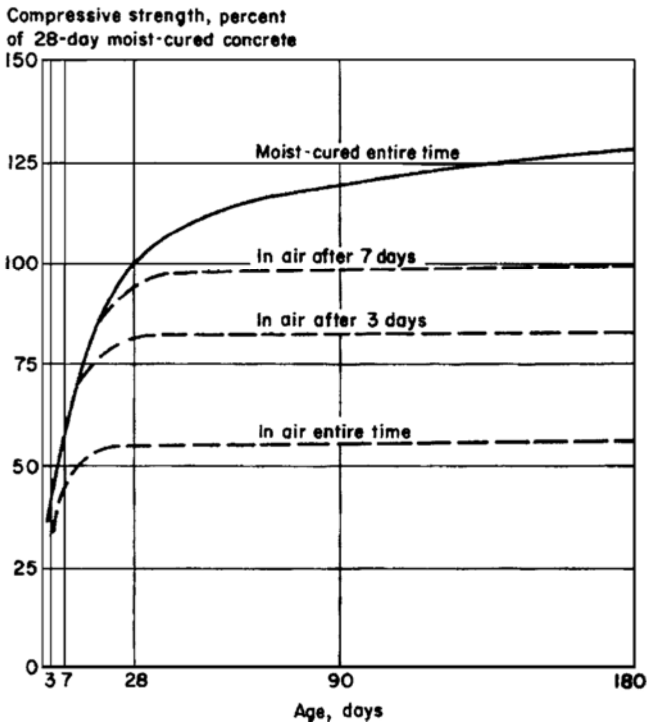

Fig 1.4—Compressive strength of 150 x 300 mm (6 x 12 in.) cylinders as a function of age for a variety of curing conditions (Kosmatka and Panarese 1988).

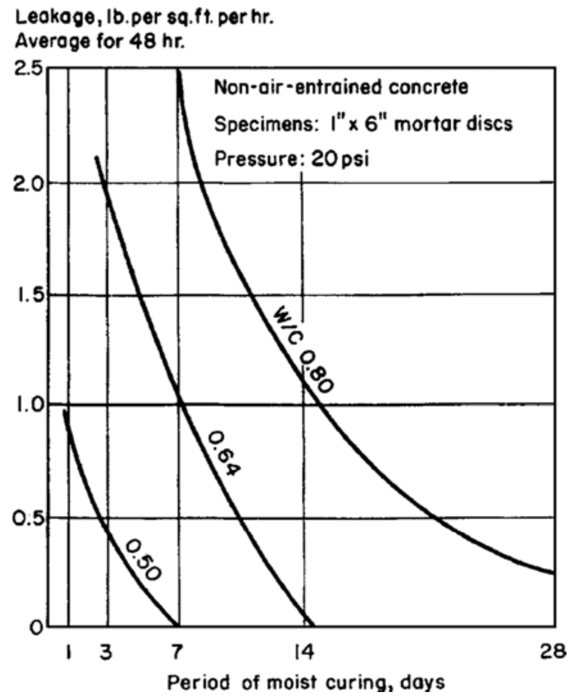

Fig 1.5—Influence of curing on the water permeability of mortar specimens (Kosmatka and Panarese 1988).

reaction sites remain water-filled, the cement will continue to hydrate until all of the available pore space is filled with hydration products or until all of the cement has hydrated.

The key to the development of both strength and durability in concrete, however, is not so much the degree to which the cement has hydrated but the degree to which the pores between the cement particles have been filled with hydration products (Powers and Brownyard 1947, Powers 1948). This is evident from the microperspective seen in Fig. 1.2 and from the macrobehavior illustrated in Fig. 1.4 and 1.5, in which it can be seen that the continued pore-filling accompanying sustained moist-curing leads to a denser, stronger, less-permeable concrete. The degree to which the pores are filled, however, depends not only on the degree to which the cement has hydrated, but also on the initial volume of pores in the paste, thus the combined importance of the availability of curing water and the initial water-cement ratio (*w/c*).

The pore volume between cement particles seen in Fig. 1.2 (darker areas of the photograph) was originally occupied in the fresh paste by the mixing water. As the volume of mixing water decreases relative to the volume of the cement, the initial porosity of the paste decreases as well. For this reason, pastes with lower *w/c* have a lower initial porosity, requiring a reduced degree of hydration to achieve a given degree of pore-filling. This is clearly demonstrated in Fig. 1.5, which shows the combined effects of curing and *w/c*. For the particular mortar specimens tested, a leakage rate of 2.4 $kg/m^2/h$ (0.5 $lb/ft^2/h$) was achieved after 21 days of moist curing for a *w/c* of 0.80. The same level of permeability, and same degree of pore-filling, was reached after 10 days for *w/c* = 0.64, and 2.5 days for *w/c* = 0.50.

This interaction of curing and *w/c* in developing the microstructure of hardened cement paste is potentially confusing. On one hand, it is important to minimize the volume of mixing water to minimize the pore space between cement particles. This is done by designing concrete mixtures with a low *w/c*. On the other hand, it is necessary to provide the cement with sufficient water to sustain the filling of those pores with hydration products. While a high *w/c* may provide sufficient water to promote a high degree of hydration, the net result would be a low degree of pore-filling due to the high initial paste porosity. The more effective way to achieve a high degree of pore-filling is to minimize initial paste porosity with a low *w/c* and then to foster hydration by preventing loss of the internal mixing water, or externally applying curing water to promote the maximum possible degree of hydration. The maximum degree of hydration achievable is a function of both *w/c* and the availability of water (Mills 1966).

1.3.2 *The need for curing*—If the amount of water initially incorporated into the concrete as mixing water will sustain sufficient hydration to develop the desired properties for a given concrete mixture, curing measures are required to ensure that this water remains in the concrete until the desired properties are achieved. At lower initial water contents, where advantage is being taken of lower *w/c* and lower initial porosity, it may be necessary to use curing measures that provide additional water to sustain hydration to the degree of pore-filling required to achieve desired concrete properties. In 1948, Powers demonstrated that concrete mixtures with a *w/c* less than approximately 0.50 and sealed against loss of moisture cannot develop their full potential hydration due to lack of water. Such mixtures would therefore benefit from externally applied curing water (Powers 1948). Powers also pointed out, however, that not all mixtures need to reach their full hydration potential to perform satisfactorily, and externally applied curing water is not always required for mixtures with *w*/*c* less than 0.50.

A related issue in concrete with a low *w*/*c*[3] is that of self-desiccation, which is the internal drying of the concrete due to consumption of water by hydration (Neville 1996; Parrott 1986; Patel et al. 1988; Spears 1983). As the cement hydrates, insufficient mixing water remains to sustain further hydration. Low *w*/*c* mixtures, sealed against water loss or water entry, can dry themselves from the inside. This problem is most commonly associated with mixtures with a *w*/*c* around 0.40 or less (Powers 1948; Mills 1966; Cather 1994; Meeks and Carino 1999) and is responsible for an almost negligible long-term strength gain in many low *w*/*c* mixtures. Given that water also interacts with cementitious materials such as fly ash, slag, and silica fume, self-desiccation can also arise with mixtures having low water-cementitious materials ratios (*w*/*cm*).

Self-desiccation can be remedied near the concrete surface by externally providing curing water to sustain hydration. At such low values of *w*/*c*, however, the permeability of the paste is normally so low that externally applied curing water will not penetrate far beyond the surface layer (Cather 1994; Meeks and Carino 1999). Conversely, the low permeability of low *w*/*c* mixtures prevents restoration of moisture lost in drying at the surface by migration of moisture from the interior. The surface of low *w*/*c* concrete can therefore dry quickly, calling attention to the critical need to rapidly provide curing water to the surface of low *w*/*c* concrete (Aïtcin 1999). This also means that surface properties, such as abrasion resistance and scaling resistance, can be markedly improved by wet-curing low *w*/*c* concrete, while bulk properties, such as compressive strength, can be considerably less sensitive to surface moisture conditions. (See Sections 1.5 and 1.6.)

1.3.3 *Moisture control and temperature control*—Curing procedures that address moisture control ensure that sufficient water is available to the cement to sustain the degree of hydration necessary to achieve the desired concrete properties. The hydration process—a series of chemical reactions—is thermally dependent—the rate of reaction approximately doubles for each 10 C (18 F) rise in concrete temperature. Curing procedures should also ensure that the concrete temperature will sufficiently sustain hydration. As early-age concrete temperatures increase, however, the rate of hydration can become so rapid as to produce concrete with diminished strength and increased porosity, thus requiring temperature control measures (see ACI 305R). Curing measures directed primarily toward the maintenance of satisfactory concrete temperature under specific environmental conditions are addressed in greater detail by ACI Committees 305 and 306 on Hot and Cold Weather Concreting, respectively, and by ACI Committees 301 and 318.

1.4—When deliberate curing procedures are required

Deliberate curing measures are required to add or retain moisture whenever the development of desired concrete properties will be unacceptably delayed or arrested by insufficient water being available to the cement or cementitious materials. Curing measures are required as soon as the concrete is at risk of drying and when such drying will damage the concrete or inhibit the development of required properties. Curing measures should be maintained until the drying of the surface will not damage the concrete, and until hydration has progressed so that the desired properties have been obtained, or until it is clear that the desired properties will develop in the absence of deliberate curing measures.

1.4.1 *Natural conditions*—Whether action is required to maintain an adequate moisture content and temperature in the concrete depends on the ambient weather conditions, the concrete mixture, and on desired properties of the hardened concrete. Under conditions that prevent excessive moisture loss from the concrete, or when the required performance criteria for the concrete are not compromised by early moisture loss, it is entirely possible that no deliberate action needs to be taken to protect the concrete. Guidance for predicting the impact of ambient conditions on the behavior of fresh concrete is found in Section 1.4 and in Chapters 2 through 4. The best source for guidance on the impact of ambient conditions on hardened concrete properties would be field experience with environmental conditions and the concrete mixture in question. Note that in most environments it is unlikely that favorable, natural conditions will exist for the duration of the curing period. The contractor should therefore be prepared to initiate curing measures as soon as ambient conditions change.

1.4.2 *Sequence and timing of curing steps for unformed surfaces*—Curing has traditionally been considered to be a single-step process, conducted some time after the concrete has been placed and finished. Adequate control of moisture, however, can require that several different procedures be initiated in sequence, culminating in a last step that is defined herein as final curing. This section will describe three stages of curing procedures, defined by the techniques used and the time at which they are initiated.

Initial curing refers to procedures implemented anytime between placement and final finishing of the concrete to reduce moisture loss from the surface. Examples of initial curing measures include fogging and the use of evaporation reducers.

Intermediate curing is sometimes necessary and refers to procedures implemented when finishing is completed, but before the concrete has reached final set. During this period, evaporation may need to be reduced, but the concrete may not yet be able to tolerate the direct application of water or the mechanical damage resulting from the application of fabric or plastic coverings. Spray-applied, liquid membrane-forming curing compounds can be used effectively to reduce evaporation until a more substantial curing method can be implemented, if required.

Final curing refers to procedures implemented after final finishing and after the concrete has reached final set. Examples of final curing measures include application of wet coverings such as saturated burlap, ponding, or the use of spray-applied, liquid membrane-forming curing compounds.

[3]Because the discussion focuses on the hydration of portland cement and not on the related reactions involving materials such as fly ash, ground-generated slag, or silica fume, the appropriate terminology is water-cement ratio (*w*/*c*) rather than the more generic water-cementitious materials ratio (*w*/*cm*).

Curing procedures and their time of application vary depending on when the surface of the concrete begins to dry and how far the concrete has advanced in the setting process. Curing measures should be coordinated with the sequence and timing of placing and finishing operations.

1.4.2.1 *Timing of placing and finishing operations*—Transport, placing, consolidation, strike off, and bull-floating of unformed concrete surfaces, such as slabs, all take place before the concrete reaches initial setting. Time of initial set is also known as the vibration limit, indicating that the concrete cannot be properly consolidated after reaching initial set (Tuthill and Cordon 1955; Dodson 1994). Surface texturing can begin at initial set but should be completed by the time the concrete has reached final set. Both initial and final set are defined on the basis of the penetration-resistance test (ASTM C 403/C 403 M) for mortar sieved from concrete (Kosmatka 1994; Dodson 1994). This concept is defined similarly for concrete (ACI 302.1R; Suprenant and Malisch 1998a,b,e; Abel and Hover 2000), as indicated in Fig. 1.6(a).

Surface finishing (beyond bull-floating) should not be initiated before initial set nor before bleed water has disappeared from the concrete surface. Before initial set, the concrete is not stiff enough to hold a texture nor stiff enough to support the weight of a finisher or finishing machine.

Furthermore, bleeding of the concrete also controls the timing of finishing operations. Bleed water rises to the surface of freshly cast concrete because of the settling of the denser solid particles in response to gravity and accumulates on the surface until it evaporates or is removed by the contractor (Section 1.4.2.2.2). Bleed water is evident by the sheen on the surface of freshly cast concrete, and its amount can be measured by ASTM Test Method C 232 (Suprenant and Malisch 1998a,e). Finishing the concrete surface before settlement and bleeding has ended can trap the residual bleed water below a densified surface layer, resulting in a weakened zone just below the surface. Finishing before the bleed water fully disappears remixes accumulated bleed water back into the concrete surface, thus increasing the *w*/*cm* and decreasing strength and durability in this critical near-surface region. Remixing bleed water can also decrease air content at the surface, further reducing durability. Proper finishing should not start until bleeding has ceased and the bleed water has disappeared or has been removed. In most cases, the concrete surface is drying while it is being finished.

The presence of bleed water is detected visually. The appearance of the concrete surface can be misleading, however, when the rate of evaporation equals or exceeds the rate of bleeding. In this case, the apparently dry surface would suggest that bleeding has stopped and that finishing can begin. In reality, however, finishing may yet be premature as bleed water is still rising to the surface. When it is necessary to evaluate this situation more carefully, a clear plastic sheet can be placed over a section of the concrete to block evaporation and to allow observation of bleeding.

Surface finishing should be completed before the concrete attains the level of stiffness (or penetration resistance measured by ASTM C 403) characterized by having reached final set (Abel and Hover 2000). Attempts to texture the concrete beyond final set usually require the addition of water to the surface. This practice should not be allowed because of the loss of surface strength and durability that results from the addition of water to the concrete surface. ACI 302.1R has coined the phrase "window of finishability" to denote the time period between initial and final set (Fig. 1.6(a)) (Suprenant and Malisch 1998e; Abel and Hover 2000).

1.4.2.2 *Timing of curing procedures*—Curing measures should be initiated when the concrete surface begins to dry, which starts as soon as the accumulated bleed water evaporates faster than it can rise to the concrete surface (Lerch 1957; Kosmatka 1994; Al-Fadhala and Hover 2001). The time at which drying and the need for curing begins depends not only on the environment and the resulting rate of evaporation, but also on the bleeding characteristics of the concrete, as shown schematically in Fig. 1.7. The figure illustrates the cumulative bleeding of three different mixtures, measured as a function of time since concrete placement. Superimposed on this diagram is the cumulative loss of surface water due to evaporation arising from three different environments, characterized by high, medium, and low evaporation rates (Rates 1, 2, and 3). Given that surface drying begins as soon as cumulative evaporation catches up with cumulative bleeding, it can be seen that there is a wide divergence in the time at which curing measures are required to control such drying.

1.4.2.2.1 *Evaporation*—The rate of evaporation is influenced by air and concrete temperatures, relative humidity, wind, and radiant energy from direct sunshine. The driving force for evaporation of water from the surface of concrete is the pressure difference between the water vapor at the surface and the water vapor in the air above that surface; the greater the pressure difference, the faster the evaporation. Vapor pressure at the concrete surface is related to the temperature of the water, which is generally assumed to be the same as the concrete surface temperature. The higher the concrete surface temperature, the higher the surface water-vapor pressure.

Because evaporation is driven by the difference between vapor pressure at the surface and in the air, factors that lower water-vapor pressure in the air will increase evaporation. While low humidity in the air increases evaporation rate, it is not as well known that low air temperature, especially in combination with low humidity, increases evaporation. Evaporation rate is high in hot, dry weather because the concrete temperature rises, not because the air is warm. Wind speed becomes a factor as well, because wind moves water vapor away from the surface as it evaporates. In still air, evaporation slows with time due to the accumulation of water vapor (increased humidity) in the air immediately over the evaporating surface. Direct sunlight also accelerates evaporation by heating the water on the surface.

There have been multiple attempts to mathematically estimate evaporation rate based on these factors, dating back to 1802 (Dalton). The most commonly used evaporation rate predictor in the concrete industry is that introduced by Menzel (1954) but developed from 1950 to 1952 by Kohler (1955) for hydrological purposes, as reported by Veihemeyer (1964) and Uno (1998). Most well-known is the evaporation rate nomograph that was reformatted from Menzel's earlier version

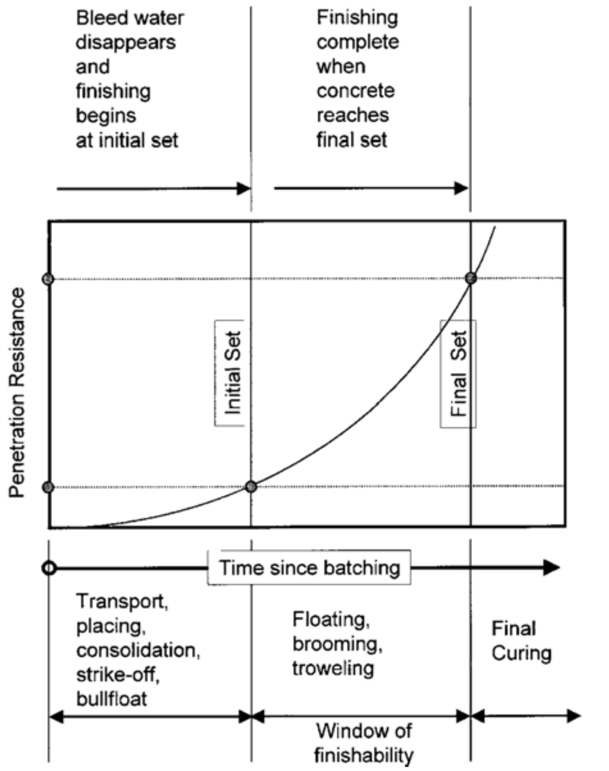

Fig. 1.6(a)—Conventional construction operations under ideal conditions: (1) Initial set coincides with the cessation of bleeding and all bleed water has just evaporated at the beginning of finishing operations; and (2) final set coincides with the completion of finishing. Final curing can begin immediately after finishing with final set.

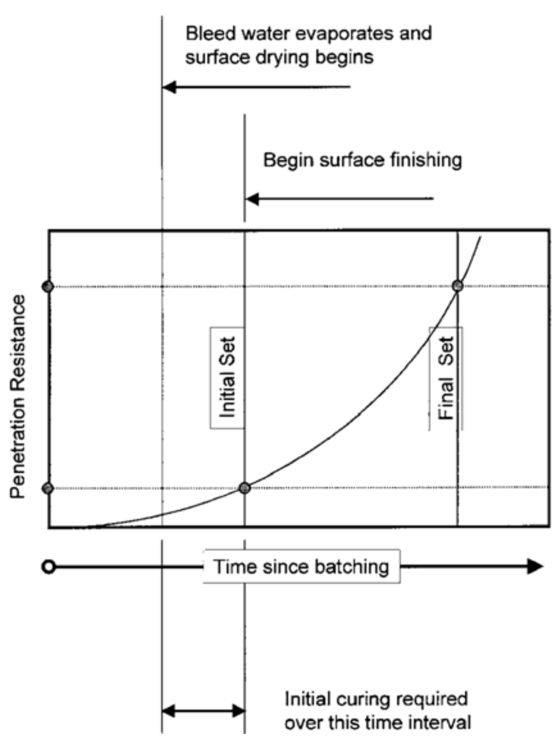

Fig. 1.6(b)—Bleed water disappears and surface drying commences at some time before beginning finishing. Initial curing is required to minimize moisture loss before and during finishing operations.

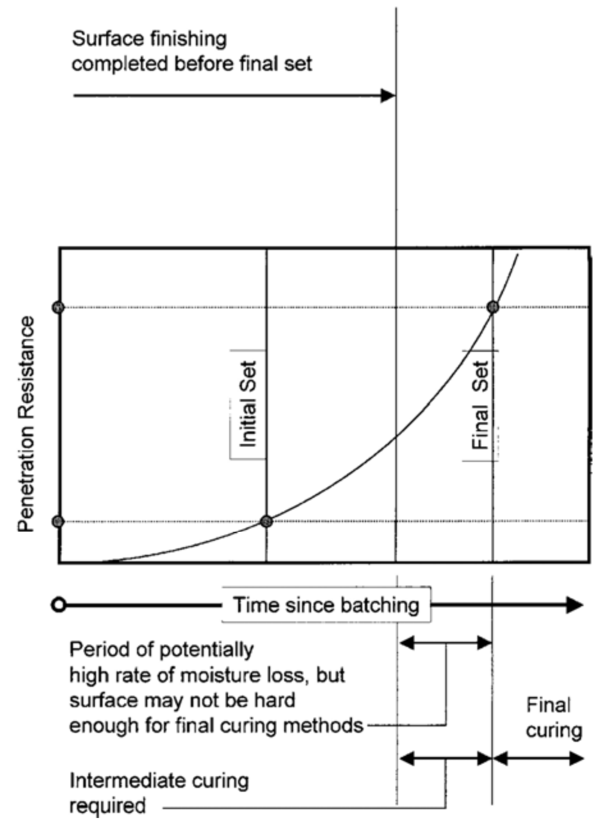

Fig. 1.6(c)—Surface finishing has been completed before the concrete surface has reached final set.

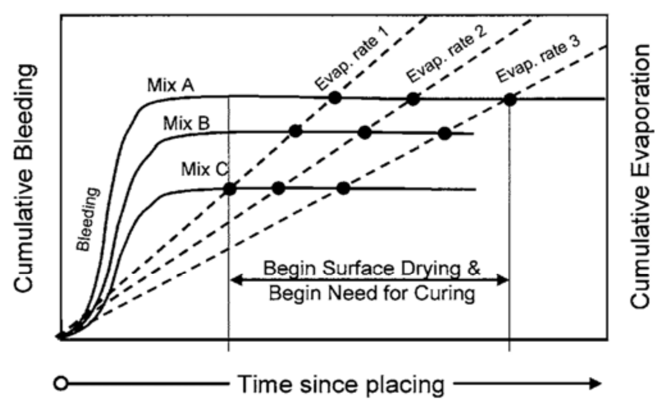

Fig. 1.7—Schematic illustration showing the combined influence of bleeding characteristics and evaporation in determining the time at which the surface of concrete begins to dry.

in 1960 by the National Ready Mixed Concrete Association (NRMCA) (1960). The use, limitations, and accuracy of this tool for estimating rate of evaporation are discussed in detail in Chapter 4, Sections 4.2.1.1 to 4.2.1.3.

1.4.2.2.2 *Bleeding*—Both the rate and duration of bleeding depend on the concrete mixture, the depth or thickness of the concrete, and the method of consolidation (Kosmatka 1994; Suprenant and Malisch 1998a). Although water content and *w*/*cm* are the primary compositional factors, cement, cementitious materials, aggregates, admixtures, and air content all influence bleeding. Thorough vibration brings bleed water to the surface earlier, and deep members tend to show increased bleeding compared with shallow members (Kosmatka 1994). The rate of bleeding diminishes as setting takes place, even in the absence of surface drying, so that surface drying will ultimately occur even under benign evaporation conditions (Al-Fadhala and Hover 2001). Mixtures with a low to negligible bleeding rate are particularly susceptible to surface drying early in the placing and finishing process. Such concrete mixtures often incorporate silica fume, fine cements, or other fine cementitious materials, low *w/cm*, high air contents, or water-reducing admixtures.

1.4.2.2.3 *Initial curing*—For mixtures with a low to zero bleeding rate, or in the case of aggressively evaporative environments, or both, surface drying can begin well before initial set and well before initiation of finishing operations, as indicated in Fig. 1.6(b). Under such conditions, it is necessary to reduce moisture loss by one or more initial curing techniques, such as fogging, the use of evaporation reducers, or by modifying the environment with sunshades, windscreens, or enclosures (Section 2.3). Because finishing can involve several separate and time-consuming operations, initial curing measures may need to be continued or reapplied until finishing is complete.

Initial curing measures should be applied immediately after the bleed water sheen has disappeared, because the concrete surface is protected against drying as long as it is covered with bleed water. When finishing begins immediately after the disappearance of the bleed water, it is unnecessary to apply initial curing measures. When the concrete exhibits a reduced tendency to bleed, when evaporative conditions are severe, or both, the concrete can begin to dry immediately after placing. Under such conditions, initial curing measures, such as fog-spraying to increase the humidity of the air or the application of a liquid-applied evaporation reducer, should be initiated immediately after strike-off, and in some cases, before bull floating. Such initial curing measures should be continuously maintained until more substantial curing measures can be initiated. Excess water from a fog spray or an evaporation reducer should be removed or allowed to evaporate before finishing the surface. (Refer to ACI 302.1R.)

Application of initial curing measures is also frequently required for concretes that exhibit low or negligible bleeding. Such concrete mixtures often incorporate silica fume, fine cements, or other fine cementitious materials, low *w/cm*, high air contents, or water-reducing admixtures. Initial curing measures are frequently required immediately upon placing such concrete to minimize plastic-shrinkage cracking. Plastic shrinkage is initiated by surface drying, which begins when the rate of evaporative water loss from the surface exceeds the rate at which the surface is moistened by bleed water. Refer to ACI 305R for further discussion on plastic shrinkage, and to ACI 234R for further discussion on curing concrete incorporating silica fume.

1.4.2.2.4 *Final curing*—The concrete surface should be protected against moisture loss immediately following the finisher or finishing machine. Significant surface-drying can occur when curing measures are delayed until the entire slab is finished because the peak rate of evaporation from a concrete surface often occurs immediately after the last pass of the finishing tool, as tool pressure brings water to the surface (Al-Fadhala and Hover 2001; Shaeles and Hover 1988). This is especially true when the finished texture has a high surface area such as a broomed or tined surface (Shariat and Pant 1984). Therefore, it is necessary to control moisture loss immediately after finishing (Transportation Research Board 1979).

When the conclusion of finishing operations coincides with the time of final set, as indicated in Fig. 1.6(a), final curing is applied at exactly the right time to reduce the peak rate of moisture loss. A delay in final curing can result in considerable water loss (Al-Fadhala and Hover 2001). Under some conditions, however, applying final curing measures immediately after completion of finishing can be deleterious. These conditions are described in the next section.

1.4.2.2.5 *Conditions under which intermediate curing is recommended*—Intermediate curing measures are required whenever the concrete surface has been finished before the concrete has reached final set. This can happen when the desired surface texture is rapidly achieved, when setting is delayed, or both.

A freshly finished concrete surface is not only vulnerable to the deleterious loss of moisture, but can be vulnerable to damage from the early application of curing materials. The need to protect against moisture loss can conflict with the need to prevent damage to the surface immediately following finishing. Of particular concern is concrete that has been surface-finished before the concrete has reached final set, as shown in Fig. 1.6(c).

Before reaching final set, the concrete surface is susceptible to marring by applying wet burlap, plastic sheets, or other curing materials. Furthermore, the bonds between the cement particles can be easily broken and the particles displaced by water added to the concrete surface and forced between the cement particles, resulting in weakening normally associated with the premature addition of water. For the reason that the earlier water is applied as a final curing measure, the more gently it should be applied to avoid displacement of cement particles. (Fogging is an example of a gentle application, as long as accumulated water is not finished into the surface.) As setting progresses with an increased strength of cement particle bonding, water can be applied to the surface more aggressively. In laboratory and field tests of this principle (Falconi 1996), application of wet burlap to concrete surfaces immediately after finishing reduced resistance to deicer salt scaling. When concrete slabs of the same mixture were lightly covered with plastic sheets immediately after finishing, and the plastic replaced with wet burlap when the concrete had reached final set (measured by ASTM C 403), wet-curing was consistently beneficial in increasing scaling resistance.

Intermediate curing methods can be a continuation of initial curing measures, such as evaporation reducers, or fogging, maintained until the final curing is applied. Membrane-forming curing compounds meeting the requirements of ASTM C 309 or C 1315 can be applied from a power sprayer, making it unnecessary to walk on the concrete surface, and can be applied immediately behind the final pass of the finishing tool or machine. Curing compounds have the advantage of being applicable before final set, as well as being a frequently acceptable final curing method. Curing compounds, therefore, can be an effective intermediate curing method or precursor to other final curing methods, such as water curing or protective coverings, minimizing water loss during the last stages of the setting process.

The combination of a curing compound as an intermediate curing method followed by water-saturated coverings as a final curing method is more common in bridge construction than in building construction (Krauss and Rogalla 1996). The curing compound can be spray-applied to the concrete surface from the perimeter of the bridge deck immediately behind the finishing machine or from the finishers' work bridge. After the curing compound has dried, the wet burlap or similar material is applied and soaker hoses or plastic sheets are installed. This is not a dual or redundant application of two equivalent curing methods. Curing compounds and so-called "breathable sealers" meeting the requirements of ASTM C 309 and C 1315, permit moisture transmission and have a variable capacity to retard moisture loss, depending on the quality of the product used, field application, and field conditions. Wet curing by ponding, sprinkling, or the application of saturated burlap not only prevents water loss but also supplies additional curing water to sustain cement hydration, which is important for low *w/cm* mixtures that can self-desiccate (Powers 1948; Mills 1966; Mindess and Young 1981; Neville 1996; Persson 1997; Carino and Meeks 1999).

1.4.2.3 *Preparation for casting and curing*—Curing procedures have to be initiated as soon as possible when the concrete surface begins to dry or whenever evaporative conditions become more severe. The curing measures to be used should be anticipated so that the required materials are available on site and ready to use if needed. Water or curing chemicals, coverings, and application equipment and accessories need to be ready, particularly when harsh environmental conditions may require rapid action. To be effective, sunshades or windbreaks (Section 2.7) should be erected in advance of concrete placing operations. Actions such as dampening the subgrade, forms, or adjacent construction, or cooling reinforcing steel or formwork are likewise required in advance of concrete placement. See ACI 301, 302.1R, 305R, and 306R for other commentary on preparedness.

1.4.3 *When curing is required for formed surfaces*—Moisture loss is a concern for both formed and unformed surfaces. Forms left in place reduce moisture loss if the forms are not water-absorbent. Dry, absorbent forms will extract water from the concrete surface. In addition, concrete usually shrinks from the form near the top of the section and it is not unusual to find dry concrete surfaces immediately after removing forms. After form removal, formed surfaces can benefit from curing (Section 3.3.3).

1.4.4 *When curing is required: cold and hot weather*—The environment dictates the need for curing and influences the effectiveness and logistical difficulty in applying the curing methods. For example, use of a fog spray as an initial curing method in freezing weather is impractical and may be of little value despite the critical need to limit surface evaporation under such conditions. Similarly, in hot, arid environments there is a critical need to prevent loss of water from the concrete surface. Such factors often influence the choice of curing methods in hot or cold weather. This choice should be made with consideration of not only the logistical and economic issues, but also of the relative effectiveness of the curing methods proposed in terms of surface strength, resistance to abrasion or deicer scaling, surface permeability, or other factors. The influence of the curing method on the desired properties of the concrete should be given first consideration in such decisions. See Sections 2.6 and 2.7 for details.

1.4.5 *Duration of curing*—The required duration of curing depends on the composition and proportions of the concrete mixture, the values to be achieved for desired concrete properties, the rate at which desired properties are developing while curing measures are in place, and the rates at which those properties will develop after curing measures are terminated. Tests have shown that the duration of wet curing required to bring pastes of different *w/c* to an equivalent permeability varied, from 3 days for low *w/c,* to 1 year for high *w/c* (Powers, Copeland, and Mann 1959). The duration of curing is sensitive to the *w/c* of the pastes because a lower *w/c* results in closer initial spacing of the cement particles, requiring less hydration to fill interparticle spaces with hydration products.

Curing should be continued until the required concrete properties have developed or until there is a reasonable assurance that the desired concrete properties will be achieved after the curing measures have been terminated and the concrete is exposed to the natural environment. Most likely, the continued rate of development of the concrete properties will be slower after curing measures have been terminated. Figure 1.4 shows the compressive strength of 150 x 300 mm (6 x 12 in.) cylinders for a particular concrete mixture as a function of curing time for a variety of curing conditions. The figure demonstrates that the rate of continued strength development decreases sharply after curing procedures are terminated. This post-curing rate of continued development should be considered in approving the termination of curing anytime before full attainment of specified concrete properties. For example, it is common to permit termination of curing measures when the compressive strength of the concrete has reached 70% of the specified strength. This is a reasonable practice if the anticipated postcuring conditions allow the concrete to continue to develop to 100% of the specified strength within the required time period. When postcuring conditions are not likely to allow the required further development of concrete properties, it may be more reasonable to require curing until the concrete has developed the full required properties.

In determining the appropriate duration of curing, concrete properties that are desired in addition to compressive strength should be considered. For example, if both high compressive strength and low permeability are required concrete performance characteristics, then the curing needs to be long enough to develop both properties to the specified values. The appropriate duration of curing will depend on the property that is the slowest to develop. Other considerations in determining the specified duration of curing include the cost of applying and subsequently maintaining various curing measures, and the risk and costs associated with not achieving the necessary

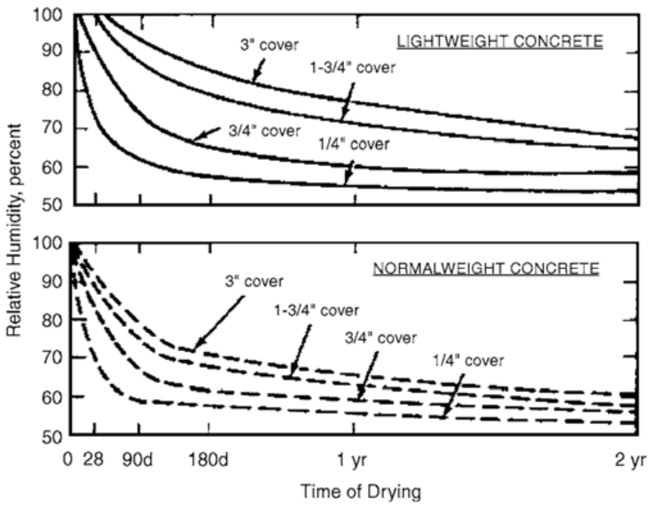

Fig. 1.8—Example of variation of internal relative humidity with depth from surface of concrete cylinder (Hanson 1968) [1 in. = 25.4 mm].

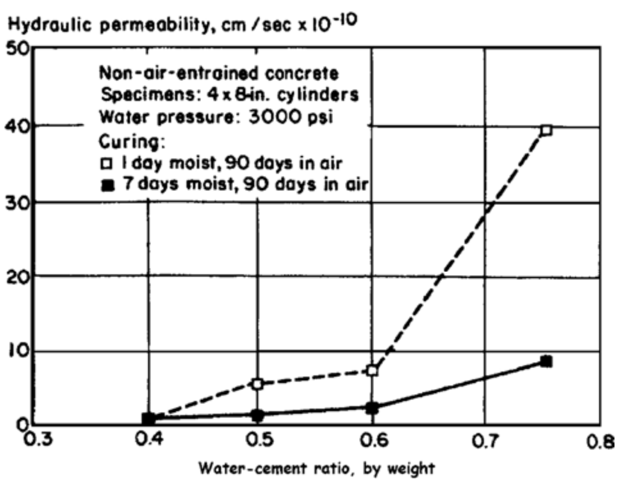

Fig. 1.9—Influence of curing on the water permeability of concrete (Kosmatka and Panarese 1988) (1 cm/s = 0.39 in./s).

concrete properties if curing is insufficient. See Section 2.8 for details on required duration of curing.

1.5—The curing-affected zone

Concrete is most sensitive to moisture loss, and therefore, most sensitive and responsive to curing at its surface, where it is in contact with dry, moving air or absorptive media such as a dry subgrade or porous formwork. Figure 1.8 shows an example how internal relative humidity varies with depth from the surface for a 150 x 300 mm (6 x 12 in.) concrete cylinder (Hanson 1968). (Concrete with an internal RH of 70%, for example, would gain or lose no moisture when placed in air at an RH of 70%.) The cylinder specimens had been moist cured for 7 days and then dried at 23 C (73 F) and 50% RH. For the specimen cast with normalweight aggregate, the humidity at 6.4 mm (1/4 in.) depth was approximately 70% at an age of 28 days, while the humidity was about 95% at the center of the cylinder. At 28 days, cement in the outer 6.4 mm (1/4 in.) would have ceased to hydrate, while that in the center of the cylinder would have continued to hydrate (Section 1.3). Cather (1992) defined the curing-affected zone as that portion of the concrete most influenced by curing measures. This zone extends from the surface to a depth varying from approximately 5 to 20 mm (1/4 to 3/4 in.), depending on the characteristics of the concrete mixture, such as *w/cm* and permeability and the ambient conditions (Carrier 1983; Spears 1983). Concrete properties in the curing-affected zone will be strongly influenced by curing effectiveness, while properties further from the surface will be less susceptible to moisture loss.

The lower the permeability of the concrete, the more slowly moisture moves between the surface and the interior. Similarly, the lower the permeability, the less-readily water from the interior can replenish water removed from the surface by evaporation (Pihlajavaara 1964, 1965). In such low-permeability concrete, surface-drying can inhibit the development of surface properties, while interior or bulk properties may develop more fully.

Surface hardness, abrasion resistance, scaling resistance, surface permeability and absorption, flexural tension strength (modulus of rupture), surface cracking, surface strain capacity, and similar surface-type properties are strongly influenced by curing. Further, the results of tests for such properties can be useful indicators of curing effectiveness (Chapter 4). Conventional compression tests of cores, cylinders, or cubes are useful as indicators of concrete strength within the bulk of the specimen, but are not necessarily representative of the surface properties. While tests of compressive strength have traditionally been used to demonstrate the effects of curing (Fig. 1.4), such tests are actually not as representative of curing effectiveness as tests of the surface properties listed above. This is because the curing-affected zone is not critical with regard to the compressive strength of cylinders or core, which fail away from their ends. For example, drilled cores can be misleading indicators of curing effectiveness when the curing-affected zone includes only the top 12 mm (1/2 in.) or so of the core sample (Montgomery, Basheer and Long 1992). In a typical core test, the concrete in the curing-affected zone is covered or reinforced with neoprene caps or capping compound, ground smooth, or cutoff altogether. Core tests, therefore, are not consistently reliable indicators of concrete performance in the curing-affected zone, nor are core tests necessarily reliable indicators of curing effectiveness as related to surface properties and performance.

1.6—Concrete properties influenced by curing

Because curing directly affects the degree of hydration of the cement, curing has an impact on the development of all concrete properties. The impact of curing on a broad range of concrete properties is illustrated by the following collection of data from various sources.

As seen previously, Fig. 1.4 indicates the influence of curing on compressive strength, and Fig. 1.5 and 1.9 indicate the influence of curing on the water permeability of hardened concrete. Figure 1.10 shows a 50% reduction in permeability achieved by extending the duration of moist curing from 1 to 3 days and a similar improvement achieved by further increasing the curing period to seven days. Figure 1.9 shows a similar trend.

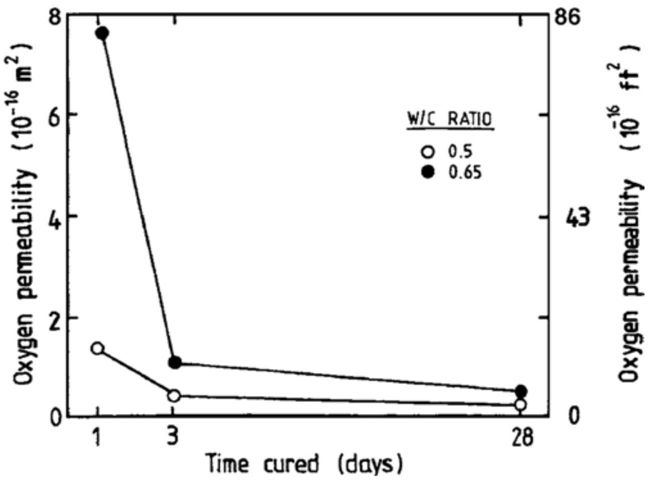

Fig. 1.10—The effect of curing on reducing the oxygen permeability of a concrete surface (Grube and Lawrence 1984; Gowriplan et al. 1990).

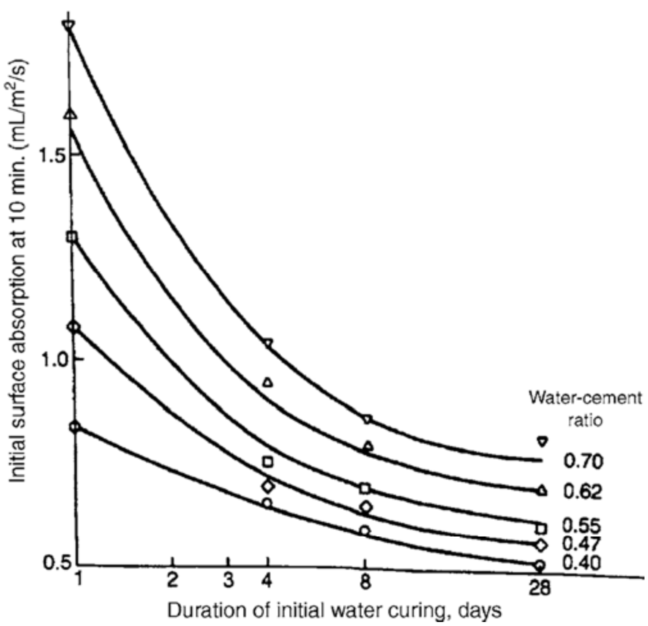

Fig 1.11—Surface absorption is reduced by 50% by extending water curing from 1 to 4 days (Dhir, Hewlett, and Chan 1987) (1 mL/m^2/s = 0.74 lb/ft^2/h).

Figure 1.10 shows the effect of curing on the reduction of the oxygen permeability on a concrete surface (Grube 1984; Gowriplan 1990). The significant reduction in permeability that accompanies a curing extension from one to three days is apparent.

The data in Fig. 1.11 indicate that surface absorption is reduced by about 50% by extending water curing from 1 to 4 days (Dhir, Hewlett, and Chan 1987).

Sawyer (1957) demonstrated the effects of curing on abrasion resistance (Fig. 1.12) and the effects of a 24 h delay in curing (Fig. 1.13). The number of test cycles is the number of successive applications of the abrasive wear test device. Dhir (1991) demonstrated a similar relationship between abrasion resistance and curing, as shown in Fig. 1.14.

Murdock, Brook, and Dewar (1991) showed a relationship between the duration of wet curing and the resistance to

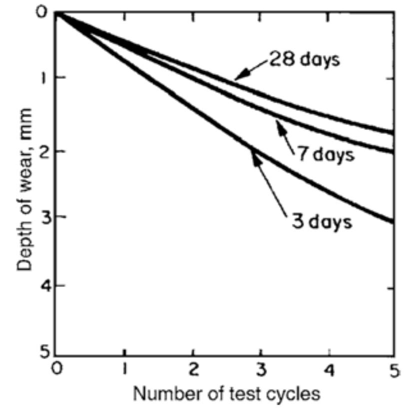

Fig. 1.12—Sawyer (1957) demonstrated the effects of curing on abrasion resistance (1 mm = 0.04 in).

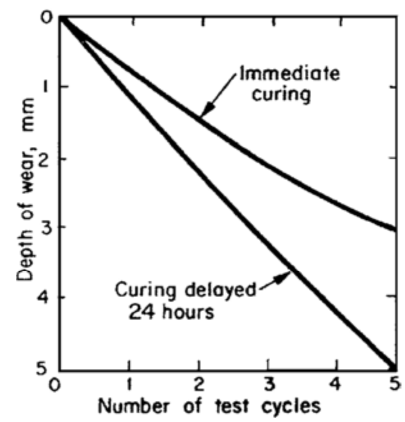

Fig. 1.13—Sawyer (1957) demonstrated the effects of delaying curing on abrasion resistance (1 mm = 0.04 in).

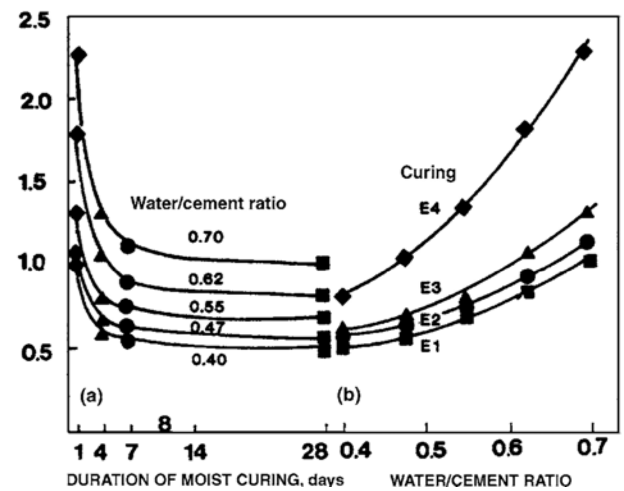

Fig. 1.14—Dhir, Hewlett, and Chan (1991) demonstrated the relationship between abrasion resistance and curing (1 mm = 0.04 in.). Note: E1= 24 h wet burlap followed by 27 days immersion curing in water at 20 C (68 F); E2= 24 h wet burlap followed by 6 days immersion curing in water at 20 C (68 F) and 21 days in air at 20 C (68 F) and 55% RH; E3= 24 h wet burlap followed by 3 days immersion curing in water at 20 C (68 F) and 24 days in air at 20 C (68 F) and 55% RH; and E4= 24 h wet burlap followed by 27 days in air at 20 C (68 F) and 55% RH.

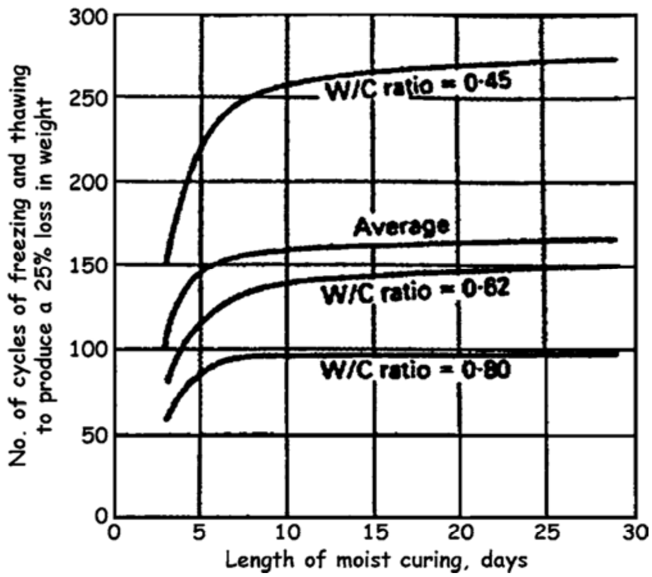

Fig. 1.15—Influence of duration of moist-curing time on freezing and thawing durability of concrete, also as a function of w/c *(Murdock, Brook, and Dewar 1991).*

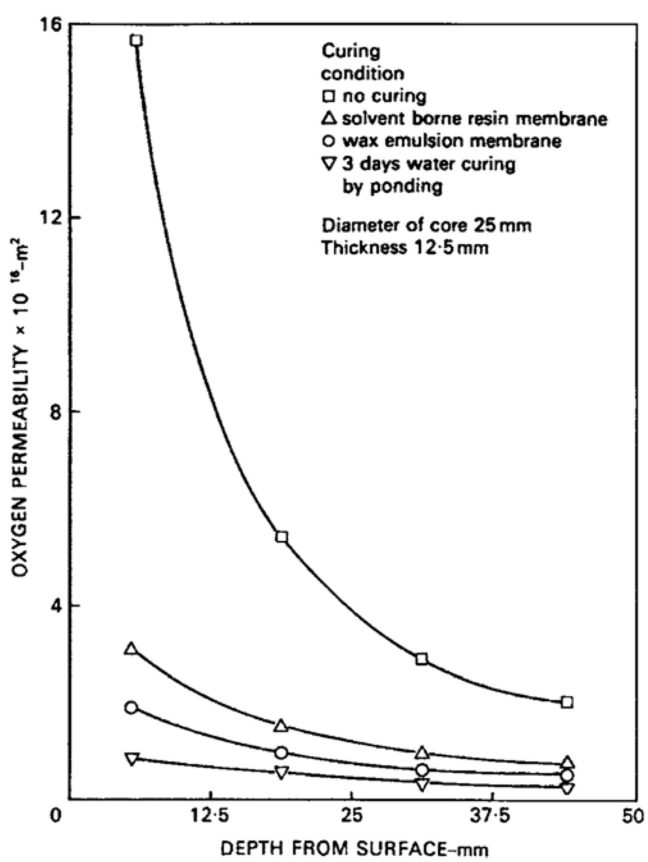

Fig. 1.16—The influence of various curing types on oxygen permeability at various depths (Gowriplan et al. 1990) (1 mm = 0.04 in; 1 m^2 = 10.76 ft^2).

freezing and thawing of air-entrained concrete, as shown in Fig. 1.15. For a *w/c* of 0.45 (ACI 318 maximum value for concrete exposed to freezing while moist), resistance to freezing and thawing continues to develop over the entire 28-day curing period.

Gowriplan et al. (1990) demonstrated a relationship between curing and oxygen permeability at various depths from the surface. This work included comparisons of various methods for curing (Fig. 1.16).

CHAPTER 2—CURING METHODS AND MATERIALS

2.1—Scope

Regardless of the materials or methods used for curing concrete, the concrete should maintain a satisfactory moisture content and temperature so that its properties develop. While there are many methods for controlling the temperature and moisture content of freshly placed concrete, not all such methods are equal in price, appropriateness, or effectiveness. The means and methods to be used will depend on the demands of each set of circumstances. The economics of the particular method of curing selected should be evaluated for each job, because the availability of water or other curing materials, labor, control of runoff (if water is continuously applied), and subsequent construction, such as the application of floor coverings or other treatments, will influence price and feasibility.

The two general systems for maintaining adequate moisture content vary in effectiveness depending on the concrete mixture and curing methods and materials used, the details of construction operations, and the ambient weather conditions. These two systems are the continuous or frequent application of water through ponding, fogging, steam, or saturated cover materials such as burlap or cotton mats, rugs, sand, and straw or hay, and the minimization of water loss from the concrete by use of plastic sheets or other moisture-retaining materials placed over the exposed surfaces, or by the application of a membrane-forming compound (commonly referred to as a curing compound) meeting the requirements of ASTM C 309 or C 1315.

This guide does not address all of the safety concerns, if any, associated with the use of curing materials. It is the responsibility of the user of this guide to establish appropriate safety and health practices and to determine the applicability of regulatory limitations before its use.

2.2—Use of water for curing concrete

The method of water curing selected should provide a complete and continuous cover of water that is free of harmful amounts of deleterious materials. Several methods of water curing are described as follows.

The curing water should be free of "aggressive impurities that would be capable of attacking or causing deterioration of the concrete" (Pierce 1994). In general, water that is potable and satisfactory as mixing water, meeting the requirements of ASTM C 94, is acceptable as curing water. Where appearance is a factor, the water should be free of harmful amounts of substances that will stain or discolor the concrete. Dissolved iron or organic impurities may cause staining, and the potential staining ability of curing water can be evaluated by means of CRD-C401 (U.S. Army Corps of Engineers 1975). The use of seawater as curing water is controversial, as is the use of seawater as mixing water. The potential effects are discussed by Eglington (1998).

Care needs to be taken to avoid thermal shock or excessively steep thermal gradients due to use of cold curing water. Curing water should not be more than 11 C (20 F) cooler than the internal concrete temperature to minimize stresses due to temperature gradients that could cause cracking (Kosmatka and Panarese 1988). A sudden drop in concrete temperature of about 11 C (20 F) can produce a strain of about 100 millionths, which approximates the typical strain capacity of concrete. (See also discussion in Mather [1987].)

2.3—Initial curing methods

As discussed in Section 1.4, initial curing refers to procedures implemented anytime between placement and finishing of concrete to reduce the loss of moisture from the concrete surface.

2.3.1 *Fogging*—Fogging provides excellent protection against surface drying when applied properly and frequently and when the air temperature is well above freezing. Fogging requires the use of an inexpensive but specially designed nozzle that atomizes the water into a fog-like mist. The fog spray should be directed above, not at, the concrete surface, as its primary purpose is to increase the humidity of the air and reduce the rate of evaporation. This effect lasts only as long as the mist is suspended in the air over the slab. This means frequent or continuous fogging is necessary, and the frequency of application should be increased as wind velocity increases over the concrete surface. (The droplets are fine enough and the application is continuous enough when a visible fog is suspended over the concrete surface.) Fogging is also useful for reducing the tendency for a crust to form on the surface of the freshly cast concrete. Fogging can precipitate water on the concrete surface and is not deleterious as long as the water from the sprayer does not mar or penetrate the surface. Water from fogging should not be worked into the surface in subsequent finishing operations. Water from fogging should be removed or allowed to evaporate before finishing.

2.3.2 *Liquid-applied evaporation reducers*—Evaporation reducers (Cordon and Thorpe 1965) are solutions of organic chemicals in water that are capable of producing a monomolecular film over the bleed water layer that rises to the top surface of concrete. If present in sufficient concentration, these chemicals form an effective film that reduces the rate of evaporation of the bleed water from the concrete surface.

Evaporation reducers can be sprayed onto freshly placed concrete to reduce the risk of shrinkage when the evaporation rate equals or exceeds the bleeding rate. Evaporation reducers are not to be used for the purpose of making it easier to finish concrete surfaces (materials designed for such purpose are often referred to as finishing aids), and should be used only in accordance with manufacturer's instructions.

2.4—Final curing measures

As discussed in Section 1.4, final curing refers to procedures implemented after final finishing and when the concrete has reached final set. As discussed in detail in that section, it may be necessary to use an intermediate curing technique when the concrete surface has been finished before the concrete reaches final set, as premature application of final curing may damage the freshly cast concrete.

2.4.1 *Final curing measures based on the application of water*

2.4.1.1 *Sprinkling the surface of the concrete*—Fogging or sprinkling with nozzles or sprays provides excellent curing when the air temperature is above freezing. Lawn sprinklers are effective after the concrete has reached final set and where water runoff is not a concern. A disadvantage of sprinkling is the cost of the water in regions where an ample supply is not readily available. Intermittent sprinkling should not be used if the concrete surface is allowed to dry between periods of wetting. Soaker hoses are useful, especially on surfaces that are vertical or nearly so. Care should be taken to avoid erosion of the surface.

2.4.1.2 *Ponding or immersion*—Though seldom used, the most thorough method of water curing consists of immersion of the finished concrete in water. Ponding is sometimes used for slabs, such as culvert floors or bridge decks, pavements, flat roofs, or wherever a pond of water can be created by a ridge, dike, or other dam at the edge of the slab. (Van Aardt documented dilution of the paste and weakening of the surface resulting from premature application of ponding [Van Aardt 1953]).

2.4.1.3 *Burlap, cotton mats, and other absorbent materials*—Burlap, cotton mats, and other coverings of absorbent materials can hold water on horizontal or vertical surfaces. These materials should be free of harmful substances, such as sugar or fertilizer, or substances that may discolor the concrete. To remove soluble substances, burlap should be thoroughly rinsed in water before placing it on the concrete. Burlap that has been treated to resist rot and fire is preferred for use in curing concrete. Burlap should also be dried to prevent mildew when it is to be stored between jobs. The thicker the burlap, the more water it will hold and the less frequently it will need to be wetted. Double thickness may be used advantageously. Lapping the strips by half widths when placing will give greater moisture retention and aid in preventing displacement during high wind or heavy rain. A continuous supply of moisture is required when high temperature, low humidity, or windy conditions prevail. The concrete surface should remain moist throughout the curing period. When burlap is permitted to dry, it can draw moisture from the surface of the concrete.

Absorbent mats made of cotton or similar fibers can be applied much the same as burlap, except that due to their greater mass, application to a freshly finished surface should be delayed until the concrete has hardened to a greater degree than for burlap.

Whenever concrete slabs are so large that the workers have to walk on the freshly placed concrete to install the curing materials, it will be necessary to wait until the concrete has sufficiently hardened to permit such operations without marring the surface.

2.4.1.4 *Sand curing*—Wet, clean sand can be used for curing provided it is kept saturated throughout the curing period. The sand layer should be thick enough to hold water uniformly over the entire surface to be cured. Sand should meet ASTM C 33 or similar requirements for deleterious

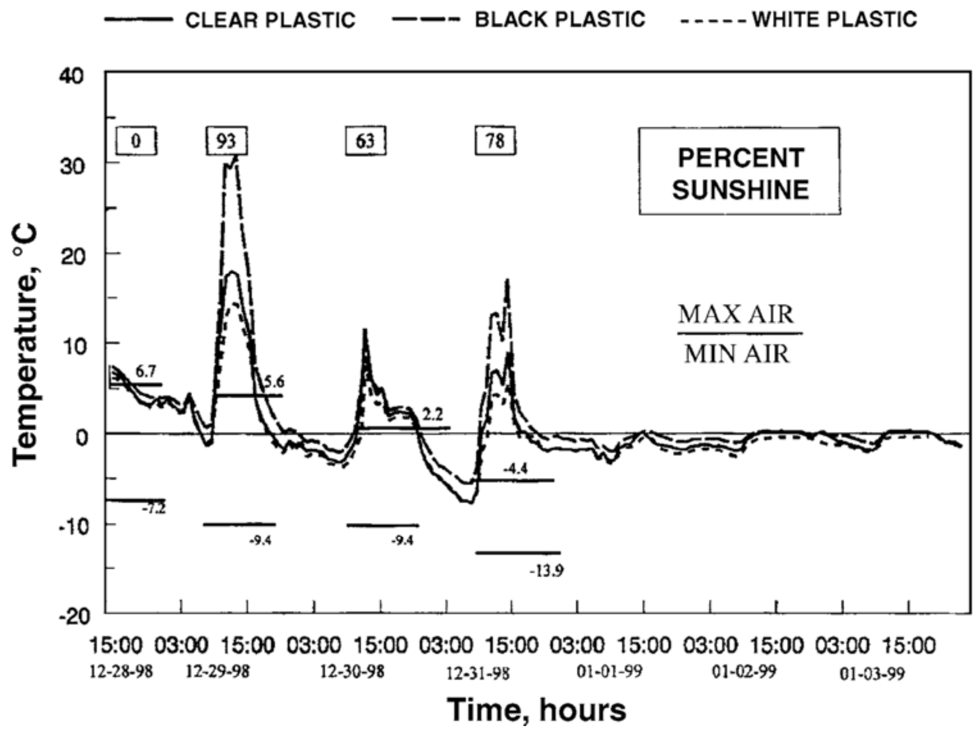

Fig. 2.1—Temperature variations under clear, black, and white plastic (Wojokowski 1999).

materials in fine aggregate to minimize the risk of damage to the concrete surface from deleterious materials.

2.4.1.5 *Straw or hay*—Wet straw or hay can be used for wet-curing small areas, but there is the danger that wind might displace it unless it is held down with screen wire, burlap, or other means. There is also the danger of fire if the straw or hay is allowed to become dry. Such materials may discolor the surface for several months after removal. If these materials are used, the wetted layer should be at least 150 mm (6 in.) deep and kept wet throughout the curing period.

2.4.2 *Final curing methods based on moisture retention*—Curing materials are sheets or liquid membrane-forming compounds placed on concrete to reduce evaporative water loss from the concrete surface.

These materials have several advantages:

1) They do not need to be kept wet to ensure that they do not absorb moisture from the concrete;

2) They are easier to handle than burlap, sand, straw or hay; and

3) They can often be applied earlier than water-curing methods.

As discussed in Section 1.4.2.2.5, curing materials can be applied immediately after finishing without the need to wait for final setting of the concrete.

2.4.2.1 *Plastic film*—Plastic film has a low mass per unit area and is available in clear, white, or black sheets. Plastic film should meet the requirements of ASTM C 171, which specifies a minimum thickness of 0.10 mm (0.004 in.). White film minimizes heat gain by absorption of solar radiation. Clear and black sheeting have advantages in cold weather by absorption of solar radiation but should be avoided during warm weather except for shaded areas. The general effect of the color of plastic sheeting on concrete surface temperature is shown in Fig. 2.1 (Wojokowski 1999). Wojokowski placed clear, black, and white plastic over a hardened concrete surface and measured the temperature over a period of one week during winter. Within the week four separate 12-h periods were evaluated for minimum and maximum air temperature, and for percentage of the period in which the sun was shining. Sunshine varied from 0 to 93%, and the outside air temperatures varied over the time periods as shown by the pairs of horizontal lines indicating maximum and minimum values. The concrete under plastic was as much as 25 C (45 F) degrees warmer than the air. The temperature under black plastic was approximately 15 C (27 F) warmer than under clear plastic and almost 20 C (36 F) warmer than under white plastic. The temperature difference was negligible in the absence of sunshine. (When plastic covers freshly cast concrete, heat is also provided from the hydration of the cement.)

Care should be taken to avoid tearing or otherwise interrupting the continuity of the film. Plastic film reinforced with glass or other fibers is more durable and less likely to be torn.

Where the as-cast appearance is important, concrete should be cured by means other than moisture-retaining methods because the use of smooth plastic film often results in a mottled appearance due to variations in temperature, moisture content, or both (Greening and Landgren 1966). Curing methods requiring the application of water may be necessary because mottling can be minimized or prevented by occasional flooding under the film. Combinations of plastic film bonded to absorbent fabric help to retain and more evenly distribute moisture between the plastic film and the concrete surface have been effective in reducing mottling.

Plastic film should be placed over the surface of the fresh concrete as soon as possible after final finishing without marring the surface and should cover all exposed surfaces of the concrete. It should be placed and weighted so that it remains in contact with the concrete during the specified duration of curing. On flat surfaces such as pavements, the film should extend beyond the edges of the slab at least twice the thickness of the slab. The film should be placed flat on the concrete surface, avoiding wrinkles, to minimize mottling. Windrows of sand or earth, or pieces of lumber should be placed along all edges and joints in the film to retain moisture and prevent wind from getting under the film and displacing it. Alternatively, it is acceptable and generally more economical to use a narrow strip of plastic film along the vertical edges, placing it over the sheet on the horizontal surface and securing all edges with windrows or strips of wood. To remove the covering after curing, the strip can be pulled away easily, leaving the horizontal sheet to be rolled up without damage from tears or creases.

2.4.2.2 *Reinforced paper*—Composed of two layers of kraft paper cemented together with a bituminous adhesive and reinforced with fiber, reinforced paper should comply with ASTM C 171. Most papers used for curing have been treated to increase tear resistance when wetted and dried. The sheets of reinforced paper can be cemented together with bituminous cement to meet width requirements.

Paper sheets with one white surface to give reflectance and reduce absorption of solar radiation are available. A reflectance requirement is included in ASTM C 171. Reinforced paper is applied in the same manner as plastic film (Section 2.4.2.1). Reinforced paper can be reused as long as it is effective in retaining moisture on the concrete surface. Holes and tears should be repaired with a patch of paper cemented with a suitable glue or bituminous cement. Pin holes, resulting from walking on the paper or from deterioration of the paper through repeated use, are evident if the paper is held up to the light. When the paper no longer retains moisture, it should be discarded or used in double thickness.

2.4.2.3 *Liquid membrane-forming compounds*—Liquid membrane-forming compounds for curing concrete should comply with the requirements of ASTM C 309 or C 1315 when tested at the rate of coverage to be used on the job. Compounds formulated to meet the requirements of ASTM C 309 include: Type 1, clear; Type 1D, clear with fugitive dye; Type 2, white pigmented; Class A, unrestricted composition (usually used to designate wax-based products); and Class B, resin-based compositions. A note in ASTM C 309 states: “Silicate solutions are chemically reactive rather than membrane-forming, therefore, they do not meet the intent of this specification.” ASTM C 156 is the test method used to evaluate water-retention capability of liquid membrane-forming compounds. ASTM C 1151 provides an alternative laboratory test for determining the efficiency of liquid membrane-forming compounds.

Membrane-forming curing compounds that meet the requirements of ASTM C 309 permit the loss of some moisture and have a variable capacity to reduce moisture loss from the surface, depending on field application and ambient conditions (Mather 1987, 1990; Shariat and Pant 1984; Senbetta 1988).

Compounds formulated to meet the requirements of ASTM C 1315 have special properties, such as alkali resistance, acid resistance, adhesion-promoting qualities, and resistance to degradation by ultraviolet light, in addition to their moisture-retention capability as measured by ASTM C 156. Curing compounds are classed according to their tendency to yellow or change color with age and exposure and by whether they are clear or pigmented. Products meeting the requirements of ASTM C 1315 are often referred to as “breathable membrane sealers” after they have performed the function of a curing membrane used during the final curing. When these products are tested in accordance with ASTM C 156, the allowable moisture loss is 0.40 kg/m^2 (0.08 lb/ft^2) in 72 h when applied at a curing compound coverage rate of 5.0 or 7.4 m^2/L (200 or 300 ft^2/gal.) for Type I or Type II compounds, respectively. When performing the ASTM C 156 test in a laboratory to verify compliance with either ASTM C 309 or C 1315, the surface of the test specimen is relatively smooth, and the laboratory-applied coverage rates specified in the test method can be readily obtained. Achieving the same coverage, and therefore achieving the same moisture-retention effectiveness in the field, is more difficult, given the variable surface texture and the need to evenly cover the concrete. ASTM C 1315 notes that agencies can require a substantially greater application rate on deeply textured surfaces. Further, the specified evaporative environment for the ASTM C 156 test corresponds to an evaporation rate from a free water surface varying between about 1/2 to 1 kg/m^2/h (0.1 to 0.2 lb/ft^2/h), which may be less severe than encountered in a given construction environment. For these reasons, the water loss experienced by concrete in the field may vary from the values specified by ASTM for compliance with the requirements of C 309 or C 1315.

Curing materials can be composed of wax or other organic material thinned with a solvent. The solvent can make the use of the curing compound subject to various restrictions or regulations governing the transport, storage, or use of hazardous materials. When appropriate, adequate ventilation should be provided and other safety precautions should be taken when using solvent-based compounds. Other similar curing compounds based on water-soluble solids or a water emulsion are available. When the concrete surface is to receive paint, finishes, or toppings that require positive bond to the concrete, it is critical that the curing procedures and subsequent coatings, finishes, or toppings be compatible to achieve the necessary bond. Curing compounds meeting the requirements of ASTM C 1315 have been formulated to promote such adhesion, and ASTM C 1315 includes references to test methods for evaluating the bonding of tile and other floor coverings. Testing to establish compatibility among the curing compound, subsequent surface treatments, concrete moisture content, and the actual finished surface texture of the concrete is recommended when performance is critical. Such testing is beyond the scope of this document, but useful references include Suprenant and Malisch (1998d,1999a,b).

Alternatives to ensuring compatibility of the curing compound with subsequent surface treatments include deliberate removal of the curing compound in accordance with manufacturer’s recommendations, the use of an alternative water-retention curing method, or water curing.

Some organic resin-based curing compounds will degrade over time with exposure to ultraviolet light (direct sunlight). Dissipation is accelerated in the presence of water. A self-dissipating resin compound is expected to break down some time after application and can be used on troweled or floated surfaces receiving subsequent finishes. Some of these products may not dissipate fast enough in interior or shaded locations and are not recommended if dissipation is the expected method of removal. Mechanical or chemical removal should be specified when self-dissipating compounds are used in interior applications.

For floors and slabs designed for high wear resistance, optimum top surface strength development, durability, and minimal cracking, the curing compound should meet or exceed the moisture retention requirements of ASTM C 1315.

In accordance with the manufacturer recommendations, liquid membrane-forming curing compounds should be stirred or agitated before use and applied uniformly at the manufacturer's recommended rate. The curing compound should be applied in two applications at right angles to each other to ensure uniform and more complete coverage. On very deeply textured surfaces, the surface area to be treated can be at least twice the surface area of a trowelled or floated surface (Shariat and Pant 1984). In such cases, two separate applications may be needed, each at 5 m^2/L (200 ft^2/gal.), with the first being allowed to become tacky before the second is applied. A curing compound can be applied by hand or power sprayer, using appropriate wands and nozzles with pressure usually in the range of 0.2 to 0.7 MPa (25 to 100 psi). If the job size is large, application by power sprayer is preferred because of speed and uniformity of distribution. For very small areas such as repairs, the compound can be applied with a wide, soft-bristled brush or paint roller. Application rates are most readily verified by recording the number of containers of compound used, or the number of sprayer tanks or buckets of compound applied to the surface.

For maximum beneficial effect, liquid membrane-forming compounds should be applied immediately after the disappearance of the surface water sheen following final finishing. Delayed application of these materials not only allows drying of the surface during the period of peak water loss, but also increases the likelihood that the liquid curing compound will be absorbed into the concrete and hence not form a membrane.

When the evaporation rate exceeds the rate of bleeding of the concrete, the surface will appear dry even though bleeding is still occurring. Under such conditions, finishing the concrete or the application of curing compound, or both, can be detrimental because bleed water can be consequently trapped just below the concrete surface. Clearly identifying this condition in the field is difficult, and it is always risky to delay finishing and curing. In such cases where it is important to diagnose this problem, a transparent plastic sheet can be placed over the unfinished, uncured concrete to shield the test area from evaporation, and any bleed water can be seen accumulating under the plastic.

Another consequence of applying curing compound to a freshly cast concrete surface that appears dry is that evaporation will be temporarily stopped, but bleeding might continue, resulting in map cracking of the membrane film with the subsequent reduction in moisture-retention capability. This situation would require reapplication of the curing compound.

When using curing compounds to reduce moisture loss from formed surfaces, the exposed surface should be wetted immediately after form removal and kept moist until the curing compound is applied. The concrete should be allowed to reach a uniformly damp appearance with no free water on the surface, and then application of the compound should begin at once. As with flatwork, dampening the concrete prevents absorption of the curing compound, allowing the curing membrane to remain on the concrete surface, which will then provide a proper membrane for moisture retention.

2.4.2.4 *Linseed oil-based curing compounds*—Various linseed oil emulsions have been successfully used as curing compounds by some highway agencies (Sedgwick County 1999; Minnesota Department of Transportation 1998). Although not strictly a membrane-forming compound, these products should conform with Formulation 6325-39-2 of the Oilseed Crops Laboratory, U.S.D.A., and meet the requirements of ASTM C 309 (AASHTO M 148) with the exception of the four hour maximum drying time requirement.

These products are used as an ASTM C 309 Type A curing compound for retaining moisture in freshly cast concrete and in some cases are used as a surface treatment to increase the durability of hardened concrete. This latter use is beyond the scope of this document. When used as a curing compound, however, linseed oil-based compounds are intended for application directly after final texturing. Some retardation of setting time may result from the use of these products.

2.5—Termination of curing measures

During the curing period, saturated cover materials should not be allowed to dry and absorb water from the concrete. At the end of the required wet-curing period, cover materials should be allowed to dry thoroughly before removal to provide uniform, slow drying of the concrete surface. Controlled and gradual termination of wet or moist curing is particularly critical in cold weather when there is a risk of freezing the freshly exposed and water-saturated surface. ACI 306R and ACI 301 contain recommendations for gradual termination of curing and protection.

2.6—Cold-weather protection and curing

Cold weather puts immature concrete at risk in at least four ways. First, the rate of evaporation of water from the surface of concrete can be higher in cold weather than in warm weather, particularly when the concrete is warm and the humidity is low. Second, if the concrete temperature greatly decreases, pore water can freeze in the pores of the concrete, leading to frost damage. Third, cold concrete temperature slows the rate of hydration of the cement, slowing the rate at which all concrete properties develop. Fourth, when protection is removed at the end of the curing period, there is a risk of rapid drying, and a rapid drop in temperature can crack the concrete. In cold weather, control of moisture should be accompanied by control of temperature. Wet-curing in freezing weather can be as beneficial to the long-term serviceability of the concrete as it is in warm weather, but only if the moist concrete is kept from freezing. Air-entrained concrete should be used whenever the concrete is expected to be subjected to freezing temperature while in a moist condition.

Water curing in cold weather can require the construction of a heated, temporary enclosure. For these reasons cold-weather curing procedures frequently include evaporation reducers as an initial curing, followed by membrane-forming curing compounds, or by covering with dry plastic sheets (or similar coverings), or by both a membrane-forming curing compound and a covering in place of curing by the direct application of water. These techniques may or may not produce the equivalent concrete surface properties as providing added water, but the risk of freezing damage to the concrete surface is reduced.

Cold-weather curing further requires that water supplies, the water distribution system, and the runoff water also should be kept from freezing, and workers should be protected against ice-related hazards and cold injury such as frostbite.

ACI 306.1 provides specification requirements for cold-weather concreting, and additional information is found in ACI 306R.

2.6.1 *Protection against rapid drying in cold weather*—The rate of evaporation from a freshly placed concrete surface can be greater in cold weather than in hot weather, especially when the concrete has been heated by the addition of hot water that evaporates into cold, dry air. Further, cold weather is often accompanied by faster average wind speeds. Senbetta and Brury (1991) have discussed the likelihood of developing plastic shrinkage cracking in cold weather. To minimize plastic shrinkage cracking and to sustain hydration of the cement, concrete placed in cold weather should be maintained at a high moisture content at the surface.

2.6.2 *Protection against frost damage*—Maintenance of a high moisture content at the surface when the air temperature may drop below freezing increases the risk of frost damage, scaling, and aggregate pop-outs. If freezing and thawing is anticipated at any time during construction or in service, when either the cement paste or the aggregates are critically saturated near the surface of the concrete, air-entrained concrete should be used. For such conditions, properly air-entrained concrete containing the air contents required by ACI 318 or ACI 301, or recommended by ACI 201.2R, should be used. Damage from freezing at early ages should be prevented by protecting the concrete from freezing, and by curing without the addition of external water until a compressive strength of at least 3.5 MPa (500 psi) is developed. If it is likely that the concrete will be critically saturated when subsequently exposed to freezing and thawing temperatures, protection and curing should be continued until a compressive strength of about 28 MPa (4000 psi) is reached. For resistance to deicer scaling, a compressive strength of 31 MPa (4500 psi) should be attained before such exposure is permitted (Klieger 1956; Powers 1962; Mather 1990). These general rules may not apply for concretes incorporating special cements or other special ingredients or for concrete that is cured at high temperature (Pfeifer and Marusin 1982; Heinz and Ludwig 1987; Kelham 1996).

2.6.3 *Rate of concrete strength development in cold weather*—When added-water curing is required in freezing weather, ACI 306 and ACI 318 require that the temperature of the moist concrete be kept above 10 C (50 F). Although concrete continuously maintained at a curing temperature of 10 C (50 F) in the field will be protected against freezing, such concrete will develop compressive strength at about half the rate of a companion cylinder cured in the lab at 23 C (73 F). This reduced rate of strength gain can have significant impact on construction operations such as form and shore removal, or the introduction of construction or service loads. When rate of strength development is critical in cold weather, it may be necessary to increase the curing temperature on the basis of tests with the specific concrete mixture. In-place tests may be necessary.

2.6.4 *Removal of cold-weather protection*—When water curing is used, either by retention or application of water, and the ambient air temperature is or will be below freezing, the concrete should be allowed to dry for at least 12 h before discontinuing or removing the temperature protection to minimize the likelihood of a nearly saturated surface condition when the concrete is exposed to freezing temperatures. Otherwise, a moist and perhaps warm concrete surface can be rapidly cooled and dried, resulting in freezing and, in some cases, cracking. Therefore, cold-weather curing coverings should be removed in stages to slow the rates of cooling and drying.

2.7—Hot-weather protection and curing

Hot weather can include warm, humid environments like summer along the Gulf of Mexico or within large river valleys that can be relatively benign in regard to concrete curing, or the more hostile warm and dry environments like arid regions of the west or southwest U.S. In these dry environments, it is critical to maintain adequate moisture content in the concrete, and under such conditions, the added curing water itself can evaporate so quickly that it requires constant replacement. This is complicated by the limited availability of curing water in such environments.

Hot weather is defined as any combination of high air temperature, low relative humidity, and wind velocity that impairs the quality of fresh or hardened concrete, or otherwise results in undesirable concrete properties. Because hot weather can lead to rapid drying of concrete, protection and curing are critical. Additional information about curing concrete in hot weather is contained in ACI 305R.

Hot-weather curing starts before the concrete is placed, with steps taken to ensure that the subgrade, adjacent concrete, or formwork do not absorb water from the freshly placed concrete. This problem can be minimized by spraying the formwork, existing concrete, reinforcement, and subgrade with water before placement, which can also lower the temperature of those surfaces. Quality-control measures should be used to avoid standing or ponded water on these surfaces while placing the concrete.

During hot weather, initial curing methods should be used immediately after placing, and before and during the finishing process. Steps for initial curing should be taken to slow the evaporation of the bleed water or to replenish the bleed water. Evaporation rate is reduced by windscreens or sunscreens that block wind and radiant energy, and by fogging that temporarily increases the humidity of the air above the concrete. Some of the fog droplets fall to the concrete surface and augment the bleed water. Training, judgment, and quality-control measures are required to replace the evaporated bleed water. At no time is it proper to mix surface water with the top layer of cement paste in subsequent finishing operations. Mixing of water into the paste increases the *w/cm* at the surface, reducing strength and durability in this critical portion of the concrete. When high temperatures with wind, low humidity, or both, prevail, an evaporation-reducing film may need to be applied one or more times during the finishing operation to reduce the risk of plastic shrinkage cracking and crusting (Section 2.3.2).

Final curing methods can be used once the concrete surface will not be damaged by the application of curing materials or water. The need for continuous curing is greatest during the first few days after placement of the concrete in hot weather. During hot weather, provided that favorable moisture conditions are continuously maintained, concrete can attain a high degree of maturity in a short time. Water-curing, if used, should be continuous to avoid volume changes due to alternate wetting and drying. Liquid membrane-forming compounds with white (Type II) pigments should be used to reflect solar radiation.

2.8—Accelerated curing

A variety of proprietary products and specialized curing procedures have been developed to rapidly cure concrete products. These include insulating the concrete to accelerate curing by retaining heat of hydration or the addition of heat via steam or other methods. Such procedures, alone or in combination, are used to reduce the total time required for the concrete to achieve sufficient strength to permit handling. High-temperature, high-pressure, or steam curing are beyond the scope of this document. See Pfeifer and Marusin (1982), Heinz and Ludwig (1987), and Kelham (1996).

2.9—Minimum curing requirements

2.9.1 *General*—Curing should be continued long enough to ensure that 100% of the specified value for concrete properties will be developed in a reasonable time period after deliberate curing measures have been terminated, especially for mechanical properties such as strength or modulus of elasticity, and for durability-related properties, such as low permeability, abrasion or scaling resistance, initial surface absorption, or resistance to freezing and thawing. After curing measures are terminated and the concrete is fully exposed to the natural environment, the rate at which mechanical- or durability-related properties continue to develop could be reduced significantly. In the case of concrete properties in the curing-affected zone, further development may cease altogether upon drying of the near surface. For these reasons, it is always best to maintain deliberate curing until the desired in-place properties have been achieved. Termination of deliberate curing at some time short of full development of desired properties may be reasonable when based on experience with a given concrete mixture in a given environment. Thus, when strength is the essential performance criterion, it is common to maintain curing measures until a minimum of 70% of the specified 28-day strength f'_c, has been achieved (ACI 301). When the structure's performance requires that the in-place strength or other concrete property reaches 100% of the specified value, curing should be extended until tests prove that the specified property has been reached. The temperature and moisture content of small, field-cured cylinders can differ significantly from that of the larger concrete placement that they are meant to represent, however. The in-place strength can be verified by tests such as penetration resistance (ASTM C 803), pullout tests (ASTM C 900), maturity measurement (ASTM C 1074), or tests of cast-in-place cylinder specimens (ASTM C 873). Also refer to ACI 228.1R for procedures to implement these in-place tests.

When performance criteria, such as surface hardness, abrasion resistance, resistance to freezing and thawing, surface absorption, or permeability are required, curing may need to be extended until the required values for such properties are achieved. It may be necessary to perform laboratory tests to evaluate the effect of curing on various concrete properties. Useful standard tests for this purpose may include C 666, C 642, C 1151, C 1202, C 944, C 418, C 779, and C 1138. (See also Liu [1994].) In-place tests for surface penetrability are discussed in 228.2R and in Chapter 4 of this document.

2.9.2 *Factors influencing required duration of curing*—The duration of curing required to achieve the desired levels of strength, durability, or both, depends on the chemical composition and fineness of the cementitious materials, *w/cm*, mixture proportions, aggregate characteristics, chemical and mineral admixtures, the temperature of the concrete, and the effectiveness of the curing method in retaining moisture in the concrete. This complex set of factors makes it difficult to confidently state the minimum curing time required to achieve the desired level of performance with the particular mixture in question. For concrete with and without pozzolans and chemical admixtures, a 7-day minimum duration of curing will often be sufficient to attain approximately 70% of the specified compressive strength. It is not necessarily true, however, that durability characteristics, such as abrasion resistance or surface absorption, will reach satisfactory levels in the same minimum time. Certain cement and admixture combinations, and high temperature are likely to reduce the time required to less than 7 days, while other combinations of materials, cooler concrete temperatures, or both, will extend the time required.

In general, when the development of a given strength or durability is critical to the performance of the concrete during construction or in service, the minimum duration of curing should be established on the basis of tests of the required properties performed with the concrete mixture in question. It is the responsibility of the designer and specifier to determine which properties are critical to the performance of the concrete under the intended service conditions and to develop a testing program to verify that the curing has been maintained long enough so that such properties have been achieved.

Table 2.1—Recommended minimum duration of curing for concrete mixtures*

	Minimum curing period
ASTM C 150 Type I	7 days
ASTM C 150 Type II	10 days
ASTM C 150 Type III or when accelerators are used to achieve results demonstrated by test to be comparable to those achieved using ASTM C 150 Type III cement	3 days
ASTM C 150 Type IV or Type V cement	14 days
Blended cement, combinations of cement and other cementitious materials of various types in various proportions in accordance with ASTM C 595, C 845, and C 1157	Variable. See Section 2.9.

*with various cement types when no testing is performed and no concrete properties are specified

When natural weather conditions of temperature, humidity, and precipitation combine to cause zero net evaporation from the surface of the concrete, no curing measures are required to maintain adequate moisture content for as long as those natural conditions remain. In most climates, however, such conditions can change hourly, or daily, and rarely persist for the time required to foster development of the required concrete properties. It is therefore necessary to take steps to protect the concrete against loss of moisture. When no data are available from experience, values are not specified for concrete strength or durability, and when testing is not performed to verify in-place strength, concrete should be maintained above 10 C (50 F) and kept moist for the minimum curing periods shown in Table 2.1. Table 2.1 is not intended to apply to accelerated curing under high temperature, high pressure, or both.

CHAPTER 3—CURING FOR DIFFERENT TYPES OF CONSTRUCTION

3.1—Pavements and other slabs on ground

3.1.1 *General*—Slabs on ground include highway pavements, airfield pavements, canal linings, parking lots, driveways, walkways, and floors. Slabs have a high ratio of exposed surface area to volume of concrete. Without preventive measures, the early loss of moisture due to evaporation from the concrete surface could be so large and rapid as to result in plastic shrinkage cracking. Continued loss of moisture, and the accompanying decrease in the degree of hydration, would have a deleterious effect on strength, abrasion resistance, and durability. When moisture loss is predominantly at the top surface of the concrete, the gradient in moisture content leads to greater shrinkage at the top than at the bottom, which in turn leads to an upwards curling of the slab (Ytterberg 1987a,b,c). Alternatively, moisture can be lost from the bottom surface due to absorption into a dry subgrade, causing the opposite moisture gradient if the top surface is kept moist. This also leads to distortion of the slab. To minimize the development of such gradients in moisture content, both the top and bottom of slabs on ground should be uniformly moist or uniformly dry. Uniformly moist conditions are usually required if the properties of the concrete surface are important for the performance or appearance of the slab. This is achieved by prewetting the subgrade, and minimizing moisture loss at the top surface through initial, intermediate, and final curing as described in Chapter 1. Similarly, when an impervious membrane or vapor barrier is installed below the slab, maintaining the top surface in a moist condition is imperative to minimize curling. Placement of a 100 mm (4 in.) compacted, drainable fill on top of membranes and vapor retarders helps to dry the bottom of the slab so that curling is reduced while both the top and bottom surfaces dry (ACI 302.1R). The final tendency for distortion of the slab due to differential volume change, however, will depend on the moisture gradient after curing measures have been terminated.

3.1.2 *Curing procedures*—To maintain a satisfactory moisture content and temperature, the entire surface of the newly placed concrete should be treated in accordance with one of the water-curing methods (Section 2.2), one of the curing material methods (Section 2.4.2), or a combination thereof, beginning as soon as possible after finishing operations, without marring the surface.

To avoid plastic-shrinkage cracks, protective measures such as sun shields, wind breaks, evaporation reducers, or fog spraying should be initiated immediately to reduce evaporation. Exposed surfaces of the slab should be entirely covered and kept wet until the required concrete properties have developed to the desired level.

Mats used for curing can either be left in place and kept saturated for completion of the curing, or can be subsequently replaced by a liquid membrane-forming curing compound, plastic sheeting, reinforced paper, straw, or water. If the concrete has been kept continuously moist since casting and finishing, drying of the concrete with its accompanying shrinkage can begin only when the curing procedures are discontinued. Therefore, the surface should be protected against rapid loss of moisture upon the termination of curing by replacing wet burlap with plastic sheets until the surface has dried under the sheets.

3.1.3 *Duration of curing*—When the average ambient daily temperature (computed as the average of the highest and lowest temperature from midnight to midnight) is above 5 C (40 F), the recommended minimum period of maintenance of moisture and temperature for all procedures is as shown in Table 2.1 (Section 2.9.2) or it is the time necessary to attain an in-place compressive strength of the concrete of at least 70% of the specified compressive or flexural strength, whichever period is longer. If testing is not performed to verify in-place strength, concrete should be maintained above 10 C (50 F) and kept moist for the time periods shown in Table 2.1, unless otherwise directed in the specifications. Strength-based criteria should be replaced or augmented with durability-related criteria when appropriate. When concrete is placed at an average daily temperature of 5 C (40 F) or lower, precautions should be taken to prevent damage by freezing as recommended in ACI 306R. These general-purpose recommendations can be insufficient if durability-related surface properties are required.

3.2—Buildings, bridges, and other structures

3.2.1 *General*—Concrete in structures and buildings includes cast-in-place walls, columns, slabs, beams, and all other portions of buildings except slabs-on-grade, that are covered in Section 3.1. It also includes small footings, piers, retaining walls, tunnel linings, and conduits. Not included are mass concrete (see Section 3.3), precast concrete, and other constructions as discussed in Section 3.4.

3.2.2 *Curing procedures*—Under usual placing conditions, curing should be accomplished by one or a combination of methods discussed in Chapters 1 and 2.

Additional curing should be provided after the removal of forms when the surface strength or durability of underside surfaces is deemed important, or when it is necessary to minimize dusting. Additional curing is done by either applying a liquid membrane-forming curing compound or by promptly applying sufficient water to keep the surface continuously moist. Water curing of vertical surfaces can be done by using wet burlap covered with polyethylene. Water curing of the bottom of slabs and beams is not recommended and is rarely effective. Form removal should be done when curing has been sufficient.

After the concrete has hardened and while the forms are still in place on vertical and other formed surfaces, form ties may be loosened when damage to the concrete will not occur and water applied to run down on the inside of the form to keep the concrete wet. Care should be taken to prevent thermal shock and cracks when using water that is significantly cooler than the concrete surface. Curing water should not be more than about 11 C (20 F) cooler than the concrete (Section 2.2.1). Immediately following form removal, the surfaces should be kept continuously wet by a water spray or water-saturated fabric or until the membrane-forming curing compound is applied. Curing measures should include treatment of top surfaces.

3.2.3 *Duration of curing*—When the daily mean ambient temperature is above 5 C (40 F), curing should be continuous for the time periods shown in Table 2.1, or for the time necessary to attain a minimum of 70% of specified compressive (or flexural strength if appropriate), whichever period is longer. If concrete is placed with daily mean ambient temperatures at 5 C (40 F) or lower, precautions should be taken as recommended in ACI 306R. Strength-based criteria should be replaced or augmented with durability-related criteria when appropriate (See Section 2.9.1 and Chapter 4).

3.3—Mass concrete

3.3.1 *General*—Mass concrete is any volume of cast-in-place concrete with dimensions large enough to require measures be taken to cope with the generation of heat and attendant volume change and to minimize cracking. It is most frequently encountered in piers, abutments, dams, heavy footings, and similar massive constructions; although, the impact of temperature rise and thermal gradients should be considered in all concrete, whether the concrete is reinforced or not. Such problems are exacerbated where high strength and high cementitious materials contents are required. Recommendations for the control of temperature and thermal gradients in mass concrete are found in ACI 207.1R and ACI 207.2R.

3.3.2 *Methods and duration of curing*—Mass concrete is often cured with water for the additional cooling benefit in warm weather; however, this can be counterproductive when the temperature gradient between the warmer interior and the cooler surface generates stress in the concrete. Horizontal or sloping unformed surfaces of mass concrete can be maintained continuously wet by water spraying, wet sand, or water-saturated fabrics. For vertical and other formed surfaces, after the concrete has hardened and the forms are still in place, the form ties may be loosened and water supplied to run down the inside of the form to keep the concrete wet (Section 3.2.2). Immediately following form removal, the surfaces can be kept continuously wet by a water spray or water-saturated fabric. Curing water should not be more than approximately 11 C (20 F) cooler than the concrete, because induced surface strains may cause cracking.

Liquid membrane-forming curing compounds may be the best alternative in some instances. During cold weather, for example, after the initial protection period from freezing, application of a liquid membrane-forming curing compound, in lieu of spraying surfaces with water, will adequately reduce drying and provide satisfactory curing conditions without icing problems. The use of curing compounds may be permitted if the surface is not a construction joint or if the membrane is removed before placing adjacent concrete. A self-dissipating membrane-forming curing compound can be used on concrete surfaces that are to receive an additional layer of concrete or other bonded surface treatment. The surface should be cleaned before the new concrete is placed. Use of the membrane-forming curing compound, however, may alter the appearance of the concrete surface.

Curing should start as soon as the concrete has hardened sufficiently to prevent surface damage. For unreinforced massive sections not containing ground granulated blast-furnace slag or pozzolan, curing should be continued for not less than 2 weeks. Where ground granulated blast-furnace slag or pozzolan is included in the concrete, the minimum time for curing should be not less than 3 weeks. For reinforced mass concrete, curing should be continuous for a minimum of 7 days or until 70% of the specified compressive strength is obtained, if strength is the key concrete performance criterion. For construction joints, curing should be continued until resumption of concrete placement or until the required curing period is completed.

3.3.3 *Form removal and curing formed surfaces*—Forms for mass concrete can be removed as soon as removal operations can be safely performed without damage to the concrete or impairment to the serviceability of the structure. During cold weather, the protection afforded by forms can make it advantageous to leave the forms in place until the end of the minimum protection period or even longer. When forms are removed and protection is discontinued, the concrete should be cooled gradually to ambient temperature at rates not exceeding 14 C (25 F) in 24 h. The concrete can be cooled gradually by replacing the forms with coverings that retain less heat when the forms are removed. When the temperature differential between the concrete surface and the ambient air is less than 14 C (25 F), forms can be removed and protection discontinued without the need for gradual cooling.

3.4—Curing colored concrete floors and slabs

Concrete can be colored by applying a dry-shake hardener or using integral coloring pigments. The goal is normally to obtain a colored surface with minimal variations. It is imperative that the curing process be prompt, continuous, and uniform. The following methods have been used successfully to provide satisfactory moisture retention, adequate strength development for the wearing surface, and to minimize cracking:

- Application of a clear membrane-forming curing and sealing compound meeting ASTM C 1315, Type I, Class A. (Note that even nonyellowing compounds will discolor over time.) For colored industrial floors subjected to moderate or heavy traffic, the curing compound should limit moisture loss to 0.040 kg/m^2 (0.008 lb/ft^2) at a coverage rate of 7.4 m^2/L (300 ft^2/gal.);
- Application of a matching pigmented membrane-forming curing compound. (Note that a significant color difference can be expected when the curing compound wears off);
- Application of a removable curing compound. The removal process should be thoroughly discussed before applying these materials. The timing of the removal process is affected by many factors. One such factor is the rate of top surface strength development;
- Application of an approved nonstaining sheet membrane. This membrane has plastic on the outer surface and felt (or similar absorptive, nonstaining material) on the inner surface. This membrane should be placed flat on the concrete surface to minimize mottling due to differential moisture loss. The use of polyethylene alone is not recommended because the contact between the polyethylene and the surface of the concrete is variable, resulting in a mottled appearance; and
- Application of ponding or other equivalent moist-curing or water-retention methods. The surface should be kept continuously moist for 7 days or longer without periodic drying. Ponding can affect the appearance of the colored concrete. Check the water source for minerals or compounds that can stain or modify the color of the concrete. Also check any water-retention coverings that can discolor the concrete.

Placement of a test slab is recommended to visually assess the appearance achieved by the combination of concrete coloring and curing methods. The test slab should be larger than 10 m^2 (100 ft^2) and should be prepared using the concrete mixture and finishing and curing techniques planned for the project. The environmental conditions should be the same or similar to those expected for the project. Several different curing methods can be used on the test slab(s).

3.5—Other constructions

Previous chapters and sections have addressed curing for normal cast-in-place concrete. Curing for specialty concrete and special construction techniques is referenced in Table 3.1.

CHAPTER 4—MONITORING CURING AND CURING EFFECTIVENESS

4.1—General

Most specifications for curing freshly placed concrete prescribe a curing method or acceptable alternatives combined with a specified duration over which the methods must be used. Monitoring the effectiveness of the curing methods used or evaluating the environment in which the concrete has been placed can be of value but is rarely done. Several of the techniques currently available for such monitoring are listed as follows and are discussed in detail later in this chapter. Some of these techniques will likely be developed further to evaluate the need for curing, the effectiveness of the curing methods used, and compliance with applicable specifications. The following actions can be taken to evaluate curing and curing effectiveness:

- Monitor the environmental conditions in which the concrete is placed to evaluate the need for temperature and moisture control;
- Verify that the specified curing procedures have been used;
- Monitor the quantitative changes in the immediate environment as a result of curing procedures;
- Monitor the moisture content and temperature in the concrete; and
- Monitor the physical properties of the concrete, as influenced by the application of curing procedures. Properties of the concrete near to the surface are the most sensitive to curing and are often the most useful or reliable indicators of curing effectiveness.

Table 3.1—Curing for specialty concrete

Specialty concrete	ACI committee report
Refractory concrete	547.1R
Insulating concrete	523.1R
Expansive cement concrete	223
Roller-compacted concrete	207.5R
Architectural concrete	303R
Shotcrete	506.2
Fiber-reinforced concrete	544.3R
Vertical slipform construction	313

4.2—Evaluating the environmental conditions in which the concrete is placed

The need for moisture control in freshly placed concrete depends on the rate of moisture loss from that concrete. Moisture loss depends on the water content, the ease with which water can move through the fresh concrete, the rate of bleeding, the rate of absorption into forms or subgrade, and the rate of evaporation of water from the exposed surfaces of the fresh concrete. The rate of evaporation from the surface of concrete further depends on the temperature and other properties of the mixture, construction operations, surface texture, and ambient environmental conditions (Section 1.4.2.2.1). Finally, evaporation from the surface depends on whether the surface is directly exposed to the air or is covered with bleed water, curing water or chemical treatments, or with surface coverings.

Evaporation depends on environmental factors that include the temperature of the concrete, the temperature of the water on the surface of the concrete, the temperature and RH of the air above the surface of the concrete, and the wind speed close to the concrete surface (Section 1.4.2.2.1). These factors combine with the characteristics of the concrete mixture and surface texture to promote or hinder evaporation of water from the concrete surface.

4.2.1 *Estimating evaporation rate*—Approximate methods for estimating the rate of evaporation of water from a water-covered surface have been proposed since the early 1800s (Brutsaert 1982; Veihmeyer 1964; Uno 1998). Each of these methods has in common the estimation of rate of evaporation on the basis of measurements of air temperature and relative humidity, water temperature, and wind speed. The most common of these approximate methods used by the concrete industry is the relationship adopted from hydrological applications (Menzel 1954; Veihmeyer 1964; Uno 1998). This was subsequently reformatted by the National Ready Mixed Concrete Association (NMRCA 1960) to produce the nomograph shown in Fig. 4.1.

The nomograph is most commonly used to estimate evaporation rate for the purpose of evaluating the risk of plastic shrinkage cracking (Lerch 1957; NRMCA 1960). This is based on Lerch's supposition that the surface begins to dry when the evaporation rate exceeds the bleeding rate. Because bleeding rates vary for different mixtures from 0 to over 1.0 $kg/m^2/h$ (0.2 $lb/ft^2/h$), vary over time after casting, and are not normally measured in the field, a value is most often assumed for the bleeding rate that then becomes an implicitly assumed value for critical rate of evaporation. The most commonly quoted value is 1.0 $kg/m^2/h$ (0.2 $lb/ft^2/h$) based on work originally reported in 1954 and 1955 (Menzel 1954; Lerch 1957). Recent experience with high-performance bridge deck overlays containing silica fume that exhibited a sharply reduced bleeding rate has led to specified maximum allowable evaporation rates of only 0.25 $kg/m^2/h$ (0.05 $lb/ft^2/h$) for overlays (Virginia DOT 1997). Other specifications reflecting a reduced bleeding rate with modern concretes vary from 0.50 to 0.75 $kg/m^2/h$ (0.10 to 0.15 $lb/ft^2/h$) (Krauss and Rogalla 1996). When the concrete mixture has a zero bleeding rate, the critical evaporation rate above which the surface will dry is zero. Zero bleeding rates are characteristic of dense mixtures incorporating fly ash, silica fume, ground-granulated blast-furnace slag or other pozzolans, high cement contents, low *w/cm*, fine cements, or high air contents. Further, all concrete mixtures exhibit a diminishing bleeding rate during setting with an eventual bleeding rate of zero.

4.2.1.1 *The Menzel/NRMCA nomograph*—The nomograph[4] (Fig. 4.1) and its underlying equations characterize the evaporative environment and are not intended to estimate the actual rate at which water is being lost from the concrete surface. The nomograph provides an estimate of "evaporativity," which is the maximum rate "at which the atmosphere can vaporize water from a free water surface" (Jalota and Prihar 1998; Uno 1998). The nomograph is therefore most useful as a means of approximately characterizing the environment into which the concrete is being placed. This can be helpful for forecasting the need for curing and protection measures and for estimating the likely effects of changes in air or concrete temperature, humidity, or wind speed on evaporation. The limitations inherent in the method are discussed in Section 4.2.1.2.

4.2.1.2 *Limitations and accuracy*—Because the nomograph was derived from an experimental fit of actual evaporation rates with measurements of wind speed, temperature, and humidity, environmental measurements in the field should be taken as in the original experiments, as follows:

- The air temperature is to be taken 1.2 to 1.8 m (4 to 6 ft) above the evaporating surface, in the shade;
- The temperature of the water being evaporated at the surface is equal to the temperature of the concrete, and direct sunlight is not contributing to evaporation;
- The relative humidity should be measured in the shade, on the windward side (upwind) of, and 1.2 to 1.8 m (4 to 6 ft) above the evaporating surface;
- The wind speed should be measured at a height of 0.5 m (20 in) above the surface of the concrete. It is further assumed that the wind velocity profile (variation of wind speed with height above the evaporating surface) is identical to that which prevailed in the experiments that led to development of the equation.

These measurement conditions were defined in the original work by Menzel but were inadvertently deleted from the nomograph in 1960 and in all subsequent versions.

Uno (1998), Hover (1992), Shaeles and Hover (1988), and Al-Fadhala and Hover (2001) have discussed the accuracy of the nomograph and its sensitivity to the measuring protocols. In wind-tunnel testing under controlled conditions, Al-Fadhala and Hover (2001) demonstrated that when measurements were taken as originally defined in Menzel's paper (1954), estimates based on the nomograph were within ± 25% of actual evaporation rates up to 1.0 $kg/m^2/h$ (0.2 $lb/ft^2/h$). At higher evaporation rates the nomograph consistently overestimated the actual rate by up to 50% at 1.8 $kg/m^2/h$ (0.36 $lb/ft^2/h$).

The most common error in using the nomograph is to measure wind speed at other than 0.5 m (20 in.) above the evaporating surface in question. Because the surface air speed defines the evaporative environment and is highly variable based on ground clutter and the prevailing wind velocity profile, measurements taken from nearby weather stations at heights varying from 2 to 12 m (6 to 36 ft) will almost always lead to overestimates of evaporation rate. Furthermore, because wind speed fluctuates widely over even a short period of time, the average evaporation rate over the time required to cast a concrete slab, for example, is related to an average wind speed over that period. Therefore, a spot measurement of wind speed can be misleading in estimating evaporation rate.

Because the output of the nomograph is the rate of water loss from a water-covered surface under the same environmental conditions (such as a lake, reservoir, or a water-filled evaporation pan), the computed result approximates the water loss from concrete only when the concrete surface is covered with bleed water. Al-Fadhala and Hover showed that for the short time that concrete specimens were covered with bleed water, the rate of evaporation from the concrete was fairly well-approximated by the value obtained from the nomograph. The actual rate of water loss from the concrete surface decreased to approximately 50% of the free-water evaporation rate at 3 h after batching, however, diminishing to 10% at approximately 8 h. This is similar to the results obtained by Berhane (1984) and

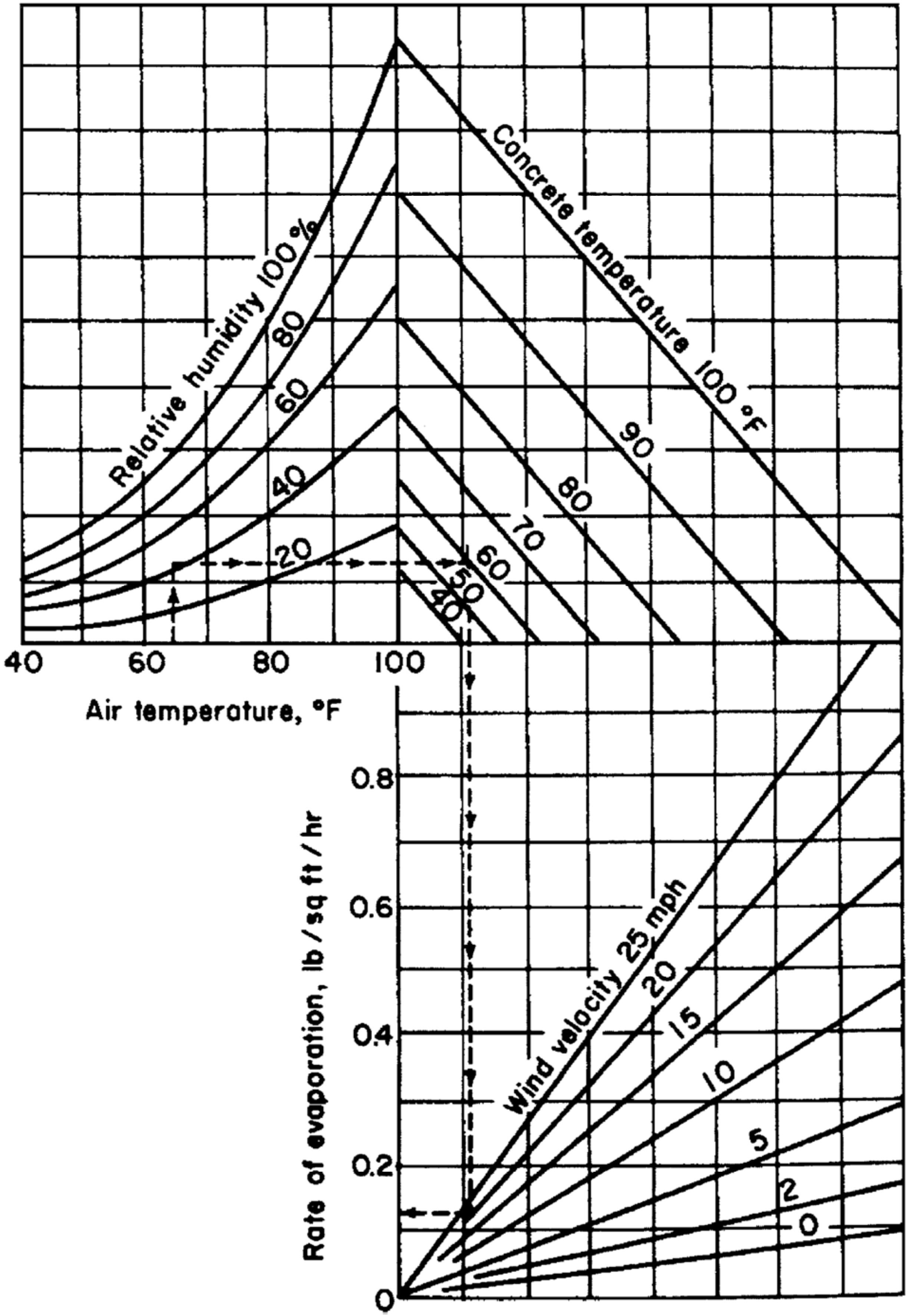

Fig. 4.1—Nomograph for estimating the maximum potential rate of evaporation of the environment, assuming a water-covered surface in which the water temperature is equal to the concrete temperature (Menzel 1954; NRMCA 1960).

is due to the reduction of paste porosity that accompanies hydration of the cement, which in turn hinders the movement of water out of the concrete. No standardized technique is available to estimate the rate of evaporation from a concrete surface not covered with water (Berhane 1984, 1985; Mather 1984; Shaeles and Hover 1988; Al-Fadhala and Hover 2001).

Given the inherent variability in fluctuating environmental conditions and the empirical nature of the nomograph itself, this method is primarily useful for characterizing the environment in an approximate manner. The method correctly identifies the factors controlling evaporation and allows the user to predict how the various factors interact to either increase or decrease the severity of the evaporative environment. When field measurements are taken, the nomograph produces an estimate that is likely to be within 25% of the actual evaporativity of the construction environment. Alternative evaporation predictors are available in the hydrologic literature. Several methods for estimating evaporation rate are reviewed by Uno (1998), Brutsaert (1987), and Shaeles and Hover (1988).

4.2.1.3 *Alternative technologies for estimating evaporation rate*—Remote sensing devices have been developed for agricultural applications to estimate the rate of evaporation from the surface of field crops. In limited tests, one such instrument based on the horticultural work of Idso (1968) and Idso et al. (1969) was useful for estimating the rate of evaporation from the surface of concrete.

More accurate estimates of the actual rate of evaporation at the surface of the concrete can be made by typical agricultural or meteorological methods of evaporation pans and recording devices. A modification of these methods was used in which containers of the concrete mixture were exposed to evaporative conditions and periodically weighed to estimate the rate of evaporation from the concrete surface (Shaeles and Hover 1988; Al-Fadhala and Hover 2001; Krauss and Rogalla 1996).

Regardless of the method used to estimate evaporative conditions, the key requirement is to recognize that the rate of evaporation can vary considerably over a given localized area, and that the most significant evaporation rate is that measured at the concrete surface at the time of concrete placing, finishing, and curing. Data obtained from nearby weather stations, airports, or furnished by a local news service are questionable when estimating the conditions at a particular job site, or over a particular concrete surface on that site, and can lead to significant errors in calculating the rate of evaporation (Falconi 1996).

4.3—Means to verify the application of curing

When a particular curing process is specified, one can assess the application of curing in accordance with those specifications. For example, if the specifications require a 3-day water cure, one can monitor the duration over which the concrete surfaces were continuously exposed to water. Similarly, if covering with plastic or other materials is required, one simply observes whether this was done or not, and whether the concrete surface remained continuously covered.

On the other hand, when a liquid-applied curing membrane is used and a particular rate of application is required (either directly by the specifications or by reference to manufacturer's instructions), an average rate of application can be determined by monitoring the volume of liquid applied over a measured area. While this can be done by counting empty drums of curing material at the conclusion of several concrete placements, more reliable estimates are made by first-hand observation of the application of the material. When power spray equipment is used, it is sometimes possible to monitor the flow rate from the hose or nozzle. Verification of curing-compound coverage rate is more difficult for deeply textured surfaces, however, where the contact surface area can be more than twice the projected horizontal area of a slab (Shariat and Pant 1984). This is true not only for slabs, but also for architecturally formed surfaces with bold relief.

To develop a sense for the degree of saturation or coverage corresponding to the required rate of application, apply the material in question to a small measured trial area. For example, at heavy rates of application, the liquid-applied curing material often forms a visible sheen over the surface and will sometimes stand in puddles at low spots. Once it is determined that this is the appropriate appearance for a sufficiently heavy application, it would become obvious that a light coating that is barely visible would not comply with the applicable specification.

4.4—Quantitative measures of the impact of curing procedures on the immediate environment

Some curing procedures, such as using a fog spray, erecting wind screens, or heating the air around the concrete being cast, modify the immediate environment. The effectiveness of such procedures can be directly monitored by temperature, humidity, or wind speed measurements as discussed previously.

The effect of curing procedures on the rate of evaporation can be assessed either by estimating evaporative conditions before and after the application of curing, or by other indirect methods. Indirect assessment of evaporation rate comes from recognition of the impact of evaporative cooling on the surface temperature of concrete. Thus, a drop in surface temperature can be the result of an increase in the rate of cooling. In the absence of other factors causing a change in concrete surface temperature, Folliard[4] observed that the application of a high-solids curing compound immediately reduced the evaporation rate and resulted in a rapid increase in surface temperature. This experiment was performed indoors without incident sunlight.

4.5—Quantitative measures of the impact of curing procedures on moisture and temperature

Curing reduces the loss of internal and surface moisture, and controls the temperature of concrete to permit sufficient hydration of the cementitious materials. Therefore, monitoring the effectiveness of the curing procedures can be performed by monitoring either the degree to which the temperature and internal moisture content have been controlled, or the degree to which hydration has progressed and developed improved concrete properties.

[4]Folliard, K., and Hover, K. C., 1989, "National Science Foundation Research for Undergraduates Program, Cornell University (NSFREU)," *Report of Activities*, Aug., 1989.

Direct measurements of concrete temperature are readily performed by a variety of techniques. Typical insertion thermometers used to measure the temperature of fresh concrete are of little value after setting, while embedded thermocouples are an inexpensive means of monitoring multiple locations and various depths in both fresh and hardened concrete (ACI 306R). Specially designed surface thermometers are useful. Pyrometers and infrared devices can be used to measure surface temperature remotely.

Internal moisture content or internal relative humidity can be measured with instruments of a variety of levels of sophistication. Relatively inexpensive, embeddable moisture gages are available, as are electronic moisture and humidity gages. (Refer to Section 4.7 for references on use of gages and interpretation of results.)

Through the use of such devices, one can comply with a performance specification for curing that requires that the concrete remain within a particular range of temperature and internal moisture content for a specified period of time.

Such instrumentation may also be valuable in assessing the tendency for undesirable phenomena such as shrinkage, cracking, and curling. Such phenomena are related to mixture composition and proportions, internal temperature and moisture content, and thermal and moisture gradients within the concrete.

4.6—Maturity method

The maturity method has been developed as a means of estimating the cumulative effect of time and temperature during curing on the development of concrete properties. The method is based on the influence of temperature on the rate of the reaction between cement and water, and assumes that the higher the concrete temperature, the more rapidly the cement hydrates, and therefore, the more rapid the development of strength and related properties. Concrete matures as the degree of hydration increases.

Application of the maturity method requires monitoring in-place concrete temperature in a structure over time and computation of the effect of that time-temperature history on the maturity of the in-place concrete. Accompanying laboratory work on the same concrete mixture correlates maturity to strength (or other property of interest) by testing standard specimens after exposure to various curing temperatures for varying lengths of time. In-place strength in the structure is inferred from the level of maturity determined in the field and from the strength-maturity relationship developed in the lab. Throughout this process, it is necessary to make sure that the concrete mixture used in the structure is the same as that used in the specimens for developing the correlation between maturity and strength, and that there is sufficient water for hydration. The maturity method is described in detail in ASTM C 1074 and in multiple references (Carino 1991; ACI 306R; ACI 228.1R).

The temperature record required for maturity calculations directly indicates the effectiveness of curing measures for controlling concrete temperature. Moisture control is not recorded in most current applications of maturity because it is assumed that the moisture condition of the structure and that of the test specimens is the same such that temperature differences alone control the relative rates of hydration. An error can be introduced into the maturity approach when an inadequate supply of moisture inhibits hydration of the cement. For example, a strength-maturity relationship developed on the basis of wet-cured test specimens would lead to an over-

Table 4.1—Concrete characteristics in the curing-affected zone

Near-surface property affected by curing	Reference
Degree of hydration	Wainwright et al. 1990
Pore size distribution mercury-intrusion porosimetry	Wainwright et al. 1990
Oxygen or air permeability	Wainwright et al. 1990
	Ballim 1993
	Kollek 1989
	Nolan et al. 1997
	Basheer et al. 1990
	Dhir et al. 1995
	Ben-Othman and Buenfeld 1990
	Parrott 1995
	Dinku and Reinhardt 1997
	Figg 1973
	Tang and Nilson 1986
	Montgomery et al. 1992
Initial surface absorption	BS 1881: Part 5, 1970; Part 122, 1983; Part 208, 1996
	ASTM C 1151; Senbetta and Scholer 1984
	Hooton et al. 1993
	DeSouza et al. 1997
	DeSouza et al. 1998
Surface permeability/absorption test devices	Nolan et al. 1997
	Basheer et al. 1990
	McCarter et al. 1996
	Balayssac et al. 1993
	Ballim 1993
	Figg 1973
	Concrete Society 1988
	Dhir et al. 1987
	McCarter 1995
	Price and Bamforth 1991
	Sabir et al. 1998
	Balayssac et al. 1998
	Montgomery et al. 1992
Internal moisture content	Parrott 1995
	McCarter et al. 1996
	Nolan et al. 1997
	Persson 1997
Tension strength of surface concrete pull-off testing	Nolan et al. 1997
	Long and Murray 1984
	Montgomery et al. 1992
Depth of carbonation	Dinku and Reinhardt 1997
	RILEM Recommendations CPC-18 1988
	Nolan et al. 1997
	Balayssac et al. 1993
	Bier 1987
Abrasion resistance	Montgomery et al. 1992
	Sawyer 1957

estimate of strength for in-place concrete that was allowed to dry even though it was kept warm. Future developments in the maturity theory would allow the quantitative evaluation of the effects of both temperature and moisture on the development of concrete properties, and would direct a new interest in comprehensively monitoring curing effectiveness.

4.7—Measuring physical properties of concrete affected by temperature and moisture control to assess curing effectiveness

Because the ultimate goal of proper curing is the development of appropriate concrete properties, the final test of the effectiveness of curing is whether those properties are developed (Wainwright, Cabrera, and Gowriplan 1990). While virtually all concrete properties are sensitive to curing, the adequacy of curing is most readily observed in the properties of concrete at the curing-affected zone.

The curing-affected zone (Cather 1992) will vary in thickness depending on the properties of the concrete, the severity of the ambient conditions, and the curing time involved. For example, in low *w/c* concrete with a specified 28-day cylinder compressive strength of 55.2 MPa (8000 psi), the resulting curing-affected zone was observed to extend from 6 to 10 mm (1/4 to 3/8 in.) from the surface after a period of 1 year of continuous wet curing (Hover 1984). In more conventional concretes, this zone may be 10 to 13 mm (3/8 to 1/2 in.) deep at an age of 28 days (Hover 1984; Cather 1992; Dhir et al. 1986-92). Regardless of the shallowness of the zone, however, the concrete properties in this zone are most frequently those that determine the durability and serviceability of the concrete. In the case of an industrial floor, for example, the top 6 mm (1/4 in.) is the most critical part of the entire concrete installation and is vital to satisfactory performance.

Given the shallowness of the curing-affected zone, test techniques that evaluate the properties of the concrete at depth, such as measuring the compressive strength of drilled cores, have a limited sensitivity to the effectiveness of curing. Concrete characteristics in the curing-affected zone that are likely to be more sensitive to curing effectiveness, along with a listing of references for test methods for these properties, are shown in Table 4.1.

CHAPTER 5—REFERENCES

5.1—Referenced standards and reports

The standards and reports listed below were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

AASHTO Material Standards

M148 Liquid Membrane Forming Curing Compounds
M182 Burlap Cloth Made From Jute or Kenaf
T26 Quality of Water to be Used in Concrete

ACI Standards and Reports

116R Cement and Concrete Terminology
201.2R Guide to Durable Concrete
207.1R Mass Concrete
207.2R Effect of Restraint, Volume Change, and Reinforcement on Cracking of Massive Concrete
207.5R Roller-Compacted Mass Concrete
223 Shrinkage-Compensating Concrete
228.1R In-Place Methods to Estimate Concrete Strength
232.2R Use of Fly Ash in Concrete
233R Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete
234R Guide for Use of Silica Fume in Concrete
301 Standard Specification for Structural Concrete
302.1R Guide for Concrete Floor and Slab Construction
303R Cast-in-Place Architectural Concrete
305R Hot Weather Concreting
306R Cold Weather Concreting
306.1 Standard Specification for Cold Weather Concreting
308 Standard Practice for Curing Concrete
308.1 Standard Specification for Curing Concrete
313 Design and Construction of Concrete Silos and Stacking Tubes for Storing Granular Materials
318/318R Building Code Requirements for Structural Concrete and Commentary
506.2 Specification for Shotcrete
523.1R Guide for Cast-in-Place Low-Density Concrete
544.3R Guide for Specifying, Proportioning, Mixing, Placing and Finishing Steel Fiber Reinforced Concrete
547.1R Refractory Plastics and Ramming Mixes
548.1R Guide for the Use of Polymers in Concrete

ASTM Standards

C 33 Specifications for Concrete Aggregates
C 94 Specification for Ready Mixed Concrete
C 125 Terminology Relating to Concrete and Concrete Aggregate
C 156 Test for Water Retention by Concrete Curing Materials
C 171 Specification for Sheet Materials for Curing Concrete
C 232 Test Method for Bleeding of Concrete
C 309 Specification for Liquid Membrane-Forming Compounds for Curing Concrete
C 403/C 403M Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance
C 418 Test method for Abrasion Resistance of Concrete by Sandblasting
C 666 Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C 672/C 672M Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
C 779 Test Method for Abrasion Resistance of Horizontal Concrete Surfaces
C 803/C 803M Test Method for Penetration Resistance of Hardened Concrete
C 805 Test for Rebound Number of Hardened Concrete

C 873	Test for Compressive Strength of Concrete Cylinders Cast-in-Place in Cylindrical Molds
C 900	Test for Pullout Strength of Hardened Concrete
C 944	Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by Rotating-Cutter Method
C 1074	Practice for Estimating Concrete Strength by the Maturity Method
C 1138	Test Method for Abrasion Resistance of Concrete (Underwater Method)
C 1151	Test Methods for Evaluating the Effectiveness of Materials for Curing Concrete
C 1202	Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration
C 1315	Specification for Liquid Membrane-Forming Compounds Having Special Properties for Curing and Sealing Concrete

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