

ACI 308R-16

Guide to External Curing of Concrete

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Guide to External Curing of Concrete

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Guide to External Curing of Concrete

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This guide reviews and describes practices, procedures, materials, and monitoring methods for the external curing of concrete and provides guidance for specifying curing procedures. Current curing techniques are presented and commonly accepted methods, procedures, and materials are described. Methods are given for curing structures and buildings, pavements and other slabs-on-ground, and for mass concrete. Curing methods for several specific categories of cement-based products are discussed in this document.

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

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

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CHAPTER 1—INTRODUCTION

1.1—Introduction

The principles and practices of external curing are applicable to all types of concrete construction. This document does not fully address curing for specialty concrete and special construction techniques (refer to 4.5), nor does it fully address internally cured concrete. For additional information on internally cured concrete using preconditioned absorptive lightweight aggregates, refer to ACI (308-213)R. 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 in ACI 305R, ACI 306R, ACI 301, and ACI 318.

The fundamental principles of external curing remain the same as in the past; however, new research and methods of curing are presented herein. Topics such as internal curing, curing at elevated temperatures, sustainability, curing of moisture-sensitive flooring, sensors for mass concrete curing, and new curing monitoring techniques have been added or enhanced in this document.

1.2—Curing

Curing is an action taken to maintain moisture and temperature conditions in a freshly placed cementitious mixture to allow hydraulic cement hydration and, if pozzolans are used, pozzolanic reactions to occur so that the potential properties of the mixture may develop. A mixture is properly proportioned and adequately cured when the properties of the in-place concrete equal or exceed the

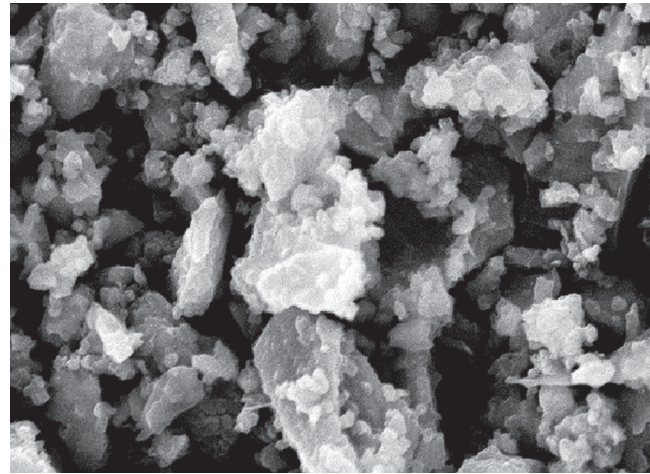


Fig. 1.3.1a—Unhydrated particles of portland cement—magnification 2000× (Soroos 1994).

design properties of the concrete. The curing period begins at placing and continues until the desired concrete properties have developed. The objectives of curing are to prevent the loss of moisture from concrete 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 is the chemical reaction that leads to changes that take place when portland cement reacts with water. 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, propensity for early-age cracking, and resistance to freezing and thawing and deicing chemicals.

The term “curing” has also been used in a more general sense to describe the process by which hydraulic cementitious concrete matures and develops hardened properties over time as a result of the continued hydration of the cementitious materials in the presence of sufficient water and heat. While all concrete hydrates to varying levels of maturity with time, the rate and extent to 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; externally providing moisture and heat; or incorporating special materials in the mixture design.

1.3—Curing and 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 and mechanically interlocks the aggregate. Similar products are formed from the reactions between cement, other cementitious materials, and water.

The cement-water reaction includes both chemical and physical processes that are collectively known as the hydration of the cement (Taylor 1997). As the hydration process continues, the strength of the interparticle bonding increases,

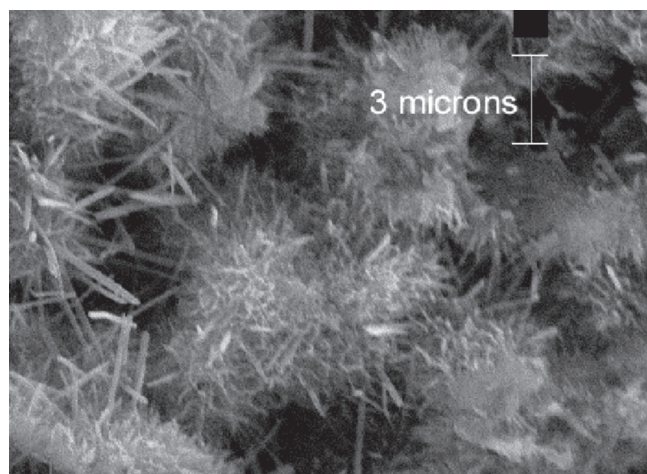


Fig 1.3.1b—Multiple particles of partially hydrated portland cement—magnification 4000 $\times$ (Soroos 1994).

and the interparticle porosity decreases. Figure 1.3.1a shows particles of unhydrated portland cement observed through a scanning electron microscope. In contrast, Fig. 1.3.1b shows the development of hydration products and interparticle bonding in partially hydrated cement. Figure 1.3.1c 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 formation of the gel products and for filling the micropores that develop between and within 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 percent RH hydrated at only 10 percent the rate of companion specimens in a 100 percent RH curing environment. Snyder and Bentz (2004) observed that exposure to 90 percent or less RH is sufficient to suspend hydration at early ages. 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 completely hydrate a unit mass of cement depending on its phase composition (Powers and Brownyard 1947; Copeland et al. 1960; Mills 1966). An average value is approximately 0.25 (Kosmatka and Panarese 1988; Powers 1948). Coefficients for chemically bound water for the various clinker mineral phases are available in Molina (1992) and range between 0.21 for dicalcium silicate to 0.4 for tricalcium aluminate.

As seen in Fig. 1.3.1b and 1.3.1c, the gel that surrounds the hydrated cement particles is a porous, randomly

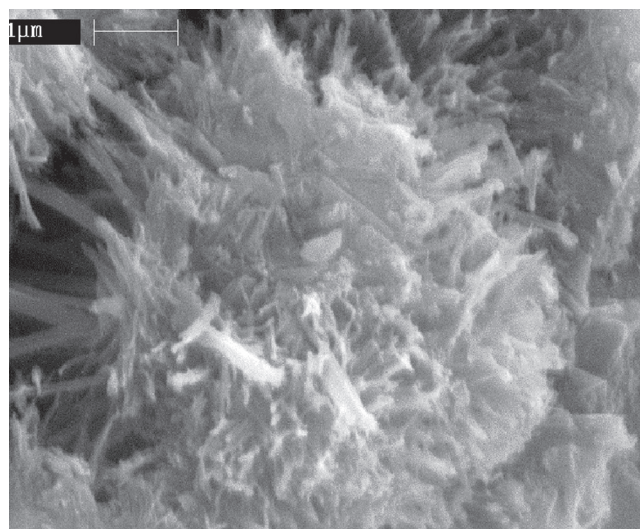


Fig 1.3.1c—Close-up of single particle of hydrated cement—magnification 11,000 $\times$ (Soroos 1994).

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 221°F (105°C) (Neville 1996). The amount of gel water adsorbed onto the expanding surface of the hydration products and into the gel pores is approximately 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 approximately 0.20 for a unit mass of 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 hydrates. 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 (Neville 1996). 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 approximately 0.44 g of water per gram of cement plus the curing water that needs to be added to keep the capillary pores of the paste saturated (Powers 1948). Other sources place this approximate value at 0.42 to 0.44 g of water for each gram of dry cement (Powers and Brownyard 1947; Taylor 1997; Neville 1996). As long as sufficient water is available to form the hydration products, to fill the interlayer gel spaces and ensure that the reaction sites remain water-filled, the cement will continue to hydrate until all of the available pore space is filled with hydration products.

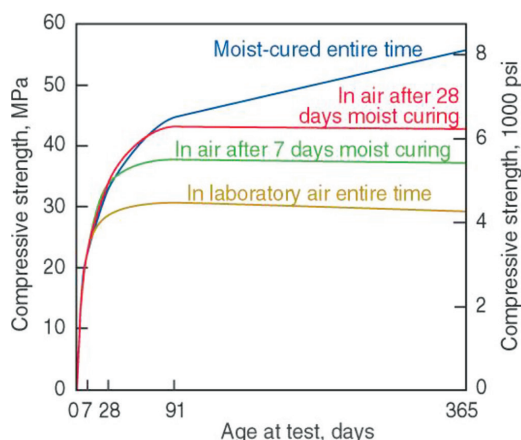


Fig. 1.3.1d—Compressive strength of 6 x 12 in. (150 x 300 mm) cylinders as a function of age for a variety of curing conditions (Kosmatka and Wilson 2011).

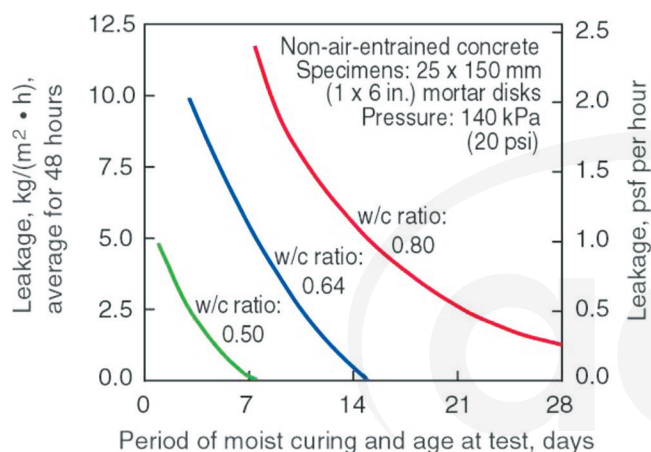


Fig. 1.3.1e—Influence of curing on water permeability of mortar specimens (Kosmatka and Wilson 2011).

until all of the cement has hydrated. When sufficient water is supplied, the former condition can be achieved for water-cementitious materials ratios (w/cm) of approximately 0.38 and less depending on cement type, mixing, and other physical and chemical properties (Powers and Brownard 1947).

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 Brownard 1947; Powers 1948). This is evident from the microperspective seen in Fig. 1.3.1b and from the macrobehavior illustrated in Fig. 1.3.1d and 1.3.1e, in which the continued pore filling that accompanies 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 w/cm .

The pore volume between cement particles seen in Fig. 1.3.1b (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/cm 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. 1.3.1e, which shows the combined effects of the duration of curing and w/cm . For the particular mortar specimens tested, a leakage rate of 0.5 lb/ft²/h (2.4 kg/m²/h) was achieved after 21 days of moist curing for a w/cm of 0.80. The same level of permeability and degree of pore-filling was reached after 10 days for $w/cm = 0.64$, and 2.5 days for $w/cm = 0.50$.

This interaction of mixing water and w/cm 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/cm . 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/cm 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/cm 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/cm and the availability of water (Mills 1966).

1.3.2 Need for curing—Even 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 still 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/cm 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. Concrete mixtures with a w/cm 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/cm less than 0.50.

A related issue in concrete with a low w/cm is that of self-desiccation, which is the internal drying of the concrete due to consumption of water by hydration (Neville 1996; Parrott et al. 1986; Patel et al. 1988; Spears 1983; Persson and Fagerlund 1997). As the cement hydrates, insufficient mixing water remains to sustain further hydration. Low- w/cm 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/cm of approximately 0.40 or less (Powers 1948; Mills 1966; Gholami 1994; Meeks and

Carino 1999) and is responsible for an almost negligible long-term strength gain in many low- w/cm mixtures. Self-desiccation also results in autogenous shrinkage due to the capillary stresses existing in partially-filled pores. In low- w/cm concretes, this autogenous deformation can be a primary cause of early-age cracking (ACI 231R). 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 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/cm , 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/cm mixtures prevents restoration of moisture lost in drying at the surface by migration of moisture from the interior. The surface of low- w/cm concrete can therefore dry quickly, calling attention to the critical need to rapidly provide curing water to the surface of low- w/cm concrete (Aitcin 1999). This also means that surface properties, such as abrasion resistance and scaling resistance, can be markedly improved by wet-curing low- w/cm concrete. Bulk properties, such as compressive strength, however, can be considerably less sensitive to surface moisture conditions (1.5 and 1.6). Philleo (1991) suggested that in satisfying the critical need for a way to get curing water into the interior of high-strength structural members, a partial replacement of fine aggregate with saturated lightweight fines might be a solution. For additional information on internally-cured concrete using preconditioned, absorptive, lightweight aggregates, refer to ACI (308-213)R-13.

1.3.3 Moisture 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 18°F (10°C) 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 (refer to ACI 305R). At temperatures above approximately 158°F (70°C), ettringite phases can become unstable, leading to potential damage due to so-called delayed ettringite formation (Thomas 2001). Curing measures directed primarily toward the maintenance of satisfactory concrete temperature under specific environmental conditions are addressed in greater detail by ACI 305R, ACI 306R, ACI 301, and ACI 318.

1.4—Deliberate curing procedures

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 cementi-

tious 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, concrete mixture, and 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 1.4 and in Chapters 3 through 5. 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 favorable 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 sometime 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 any time 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 (Cordon and Thorpe 1965). This is covered in more detail in 3.3.

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 of water, or the use of spray-applied, liquid membrane-forming curing compounds.

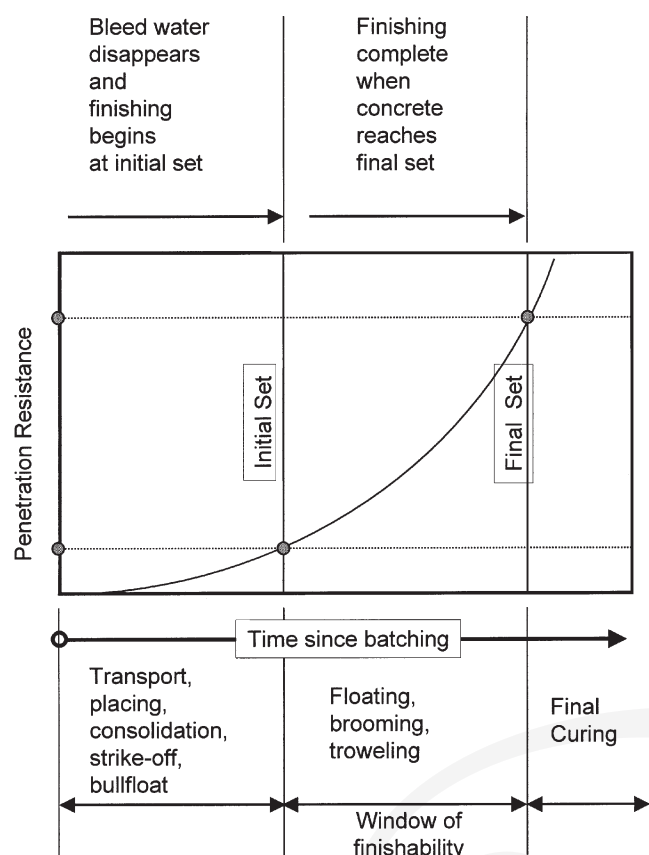


Fig. 1.4.2.1—Conventional construction operations under ideal conditions. Initial set coincides with the cessation of bleeding and final set coincides with the completion of finishing. Finishing can be initiated immediately after all bleed water has just evaporated. Final curing can begin immediately after concrete has reached the final set.

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 bullfloating 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 C403/C403M) for mortar sieved from concrete (Kosmatka 1994; Dodson 1994). This concept is illustrated in Fig. 1.4.2.1 (ACI 302.1R; Suprenant and Malisch 1998a,b,e; Abel and Hover 2000).

Surface finishing beyond bull floating should not be initiated before initial set or before the bleed water has disappeared from the concrete surface. Before initial set, the concrete is not stiff enough to hold a texture or support

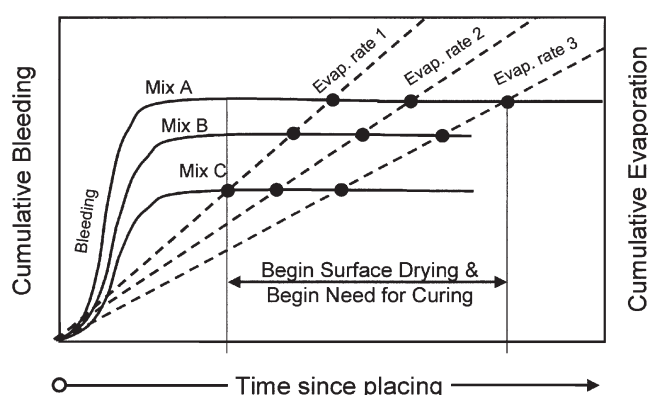


Fig. 1.4.2.2—Schematic illustration showing the combined influence of bleeding characteristics and evaporation in determining the time at which the surface of concrete begins to dry.

the weight of a finisher or finishing machine. Furthermore, bleeding of the concrete also controls the timing of finishing operations. Bleed water appears at 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 (refer to 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 C232/C232M (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, 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 C403/C403M) 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 refers to the term “window of finishability” to iden-

tify the time period between initial and final set (Fig. 1.4.2.1) (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. 1.4.2.2. 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. For structural concrete and slipformed concrete, the initial bleed rate may often be less than the evaporation rate, giving further urgency for the application of early curing measures (Wojakowski 1999).

1.4.2.2.1 Evaporation—The rate of evaporation is influenced by air and concrete temperatures, relative humidity, wind speed, 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 exacerbated in hot, dry weather as the concrete temperature rises. Wind speed becomes a factor as well, because wind moves water vapor away from the surface as it evaporates. In still air, evaporation slows 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 the early 1800s (Dalton 1802). 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 et al. (1955) for hydrological purposes, as reported by Veihmeyer (1964) and Uno (1998). Most well-known is the evaporation rate nomograph that was refor-

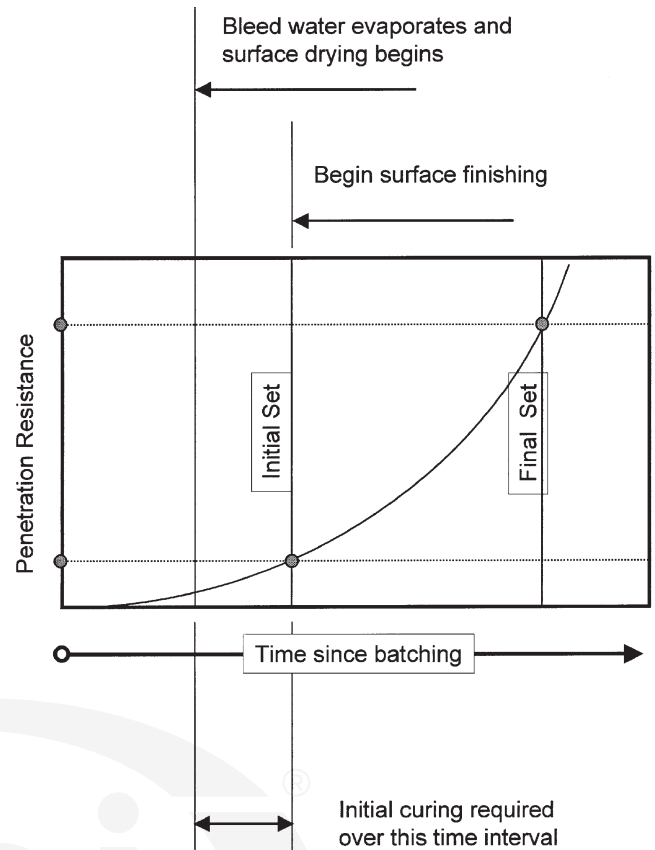


Fig. 1.4.2.2.3—Bleed water disappears and surface drying commences at some time before beginning finishing. Initial curing is required to minimize moisture loss before and during finishing operations.

matted from Menzel's earlier version in 1960 by the National Ready Mixed Concrete Association (NRMCA 1960) (Fig. 5.2.1). The use, limitations, and accuracy of this tool for estimating rate of evaporation are discussed in detail in 5.2.1.1.

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 and may experience plastic shrinkage cracking. 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, aggressively evaporative environments,

or both, surface drying can begin well before initial set and initiation of finishing operations, as indicated in Fig. 1.4.2.2.3. 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 (refer to 3.3). 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. 1.4.2.1, final curing should be 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

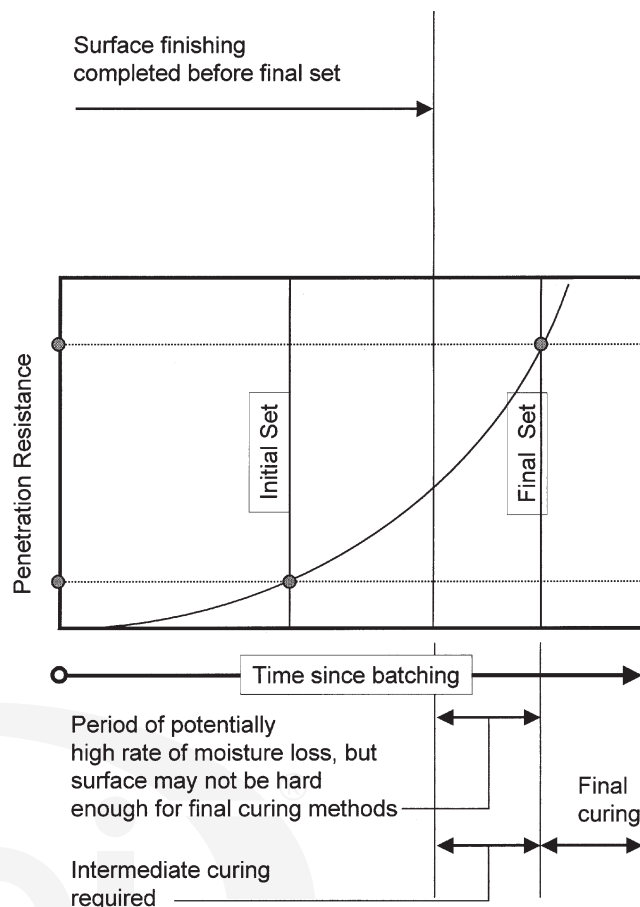


Fig. 1.4.2.2.5—Surface finishing has been completed before concrete surface has reached final set.

can be deleterious. These conditions are described in the following section.

1.4.2.2.5 Conditions under which intermediate curing is recommended—Intermediate curing measures are performed whenever the concrete surface has been finished and before final curing can be initiated.

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. 1.4.2.2.5.

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 this reason, the earlier that 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 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 as measured by ASTM C403/C403M, 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 C309 or C1315 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, to keep it continuously wet, 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 C309 and C1315 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 wet 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; Meeks and Carino 1999).

1.4.2.3 Preparation for placing 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 (3.7) 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. Refer to ACI 301, 302.1R, 305R, and 306R for additional information on preparedness.

1.4.3 Curing of 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. As soon as the forms can be loosened without damage to the concrete, water should be applied to the top of the form and allowed to run down the interface between the form and new concrete until forms are fully removed. After form removal, formed surfaces can benefit from curing. The use of permeable formwork in placing and curing concrete has been extensively reviewed by Malone (1999). Controlled permeability formwork systems have also been presented and evaluated in numerous reports (Price and Widdows 1991; Basheer et al. 1993, 1995; Long et al. 1995; Sousa-Coutinho 1999; Price 2000). The use of permeable formwork can enhance the curing process while the forms are in place; however, recommended curing procedures for formed surfaces should be followed after removing the permeable formwork.

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 water loss 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 achieving the desired properties of the concrete should be given first consideration in such decisions (refer to 3.6 and 3.7 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/cm to an equivalent permeability varied from 3 days for low w/cm to 1 year for high w/cm (Powers et al. 1959). The duration of curing is sensitive to the w/cm of the pastes because a lower w/cm 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 assurance that the desired concrete properties will be achieved

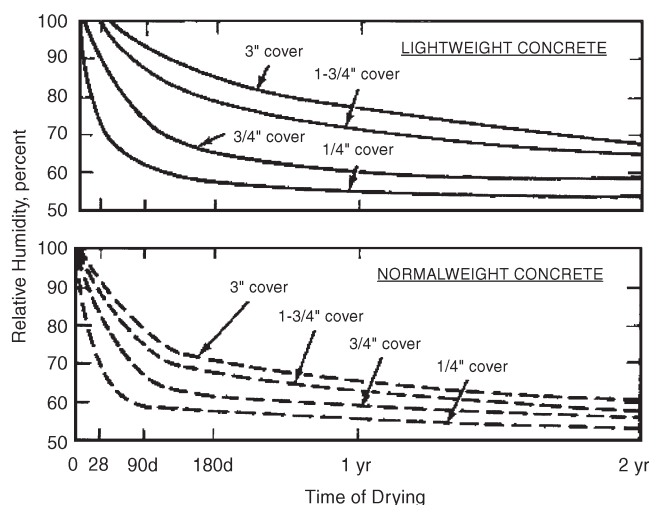


Fig. 1.5—Example of variation of internal relative humidity with depth from surface of concrete cylinder (Hanson 1968). (Note: 1 in. = 25.4 mm.)

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 1.3.1d shows the compressive strength of 6 x 12 in. (150 x 300 mm) 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 property development should be considered in approving the termination of curing any time 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 percent of the specified strength. This is a reasonable practice if the anticipated post-curing conditions allow the concrete to continue to develop to 100 percent of the specified strength within the required time period. When post-curing 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 concrete properties if curing is insufficient. Refer to 3.8 for details on recommended duration of curing.

1.5—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 1.5 shows an example of how internal relative humidity (RH) varies with depth from the surface for a 6 x 12 in. (150 x 300 mm) concrete cylinder (Hanson 1968). Concrete with an internal RH of 70 percent, for example, would gain or lose no moisture when placed in air at an RH of 70 percent. The cylinder specimens had been moist cured for 7 days and then dried at 73°F (23°C) and 50 percent RH. For the specimen cast with normalweight aggregate, the humidity at 1/4 in. (6.4 mm) depth was approximately 70 percent at an age of 28 days, whereas the humidity was approximately 95 percent at the center of the cylinder. At 28 days, the cement in the outer 1/4 in. (6.4 mm) would have ceased to hydrate, whereas that in the center of the cylinder would have continued to hydrate (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 1/4 to 3/4 in. (5 to 20 mm), 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, whereas 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, whereas interior or bulk properties may develop more fully.

Surface hardness, abrasion resistance, scaling resistance, surface permeability and absorption, 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 5). 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. Whereas tests of compressive strength have traditionally been used to demonstrate the effects of curing (Fig. 1.3.1d), such tests are actually not as representative of curing effectiveness as tests of the aforementioned surface properties. This is because the curing-affected zone is not critical with regard to the compressive strength of cylinders or cores, 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 1/2 in. (12 mm) or so of the core sample (Montgomery et al. 1992). In a typical core test, the concrete in the curing-affected zone is covered or reinforced with neoprene caps or capping compound, the ground smooth, or cut off altogether. Core tests, therefore,