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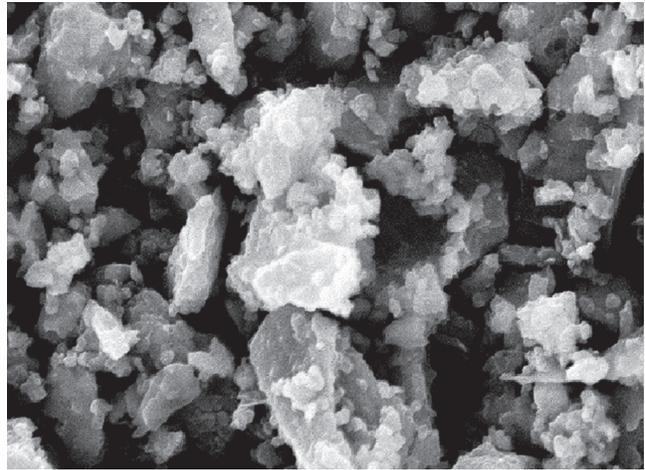
Fig. 1.3.1a—Unhydrated particles of portland cement—magnification 2000× (Soroos 1994).

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,
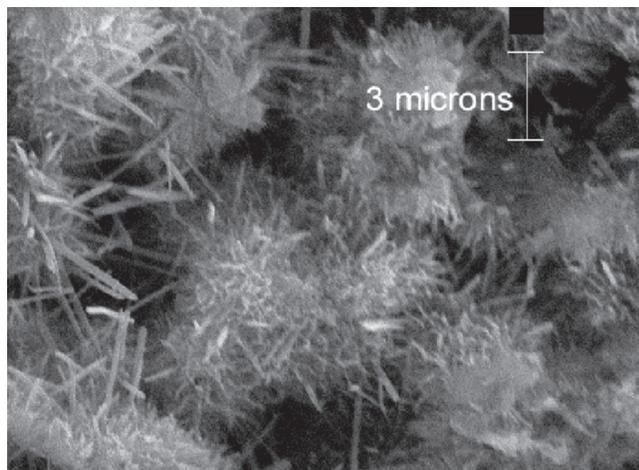
Fig 1.3.1b—Multiple particles of partially hydrated portland cement—magnification 4000× (Soroos 1994).

Fig 1.3.1c—Close-up of single particle of hydrated cement—magnification 11,000× (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
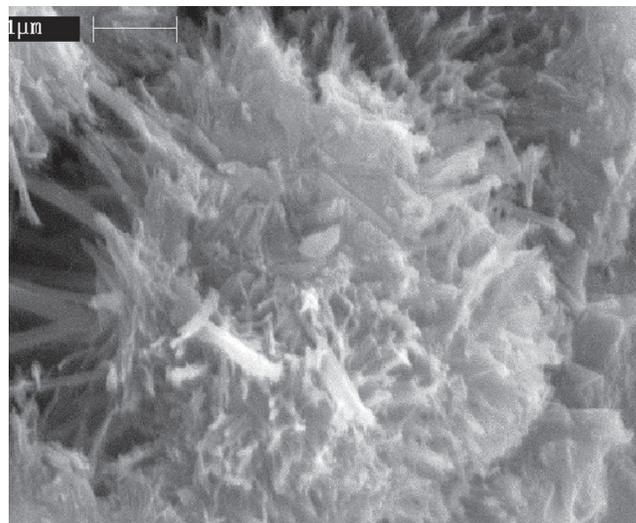
oriented mass. Besides the hydrate water, additional water is adsorbed onto the surfaces and in the interlayer spaces of the layered gel structure during the hydration process. This is known as physically bound water, or gel water. Gel water is typically present in all concrete in service, even under 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 or
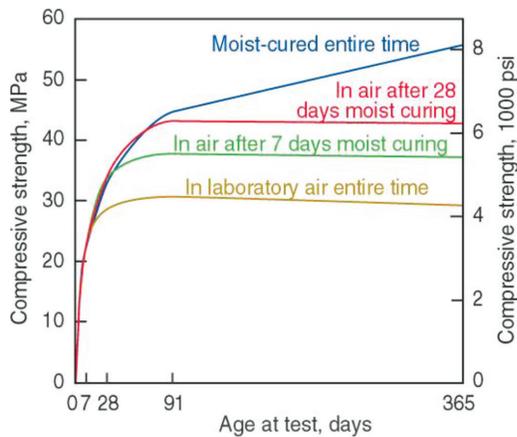
Fig. 1.3.1d—Compressive strength of 6 x 12 in. (150 x 300 mm) cylinders as a function of age for a variety of curing conditions (Kosmatka and Wilson 2011).
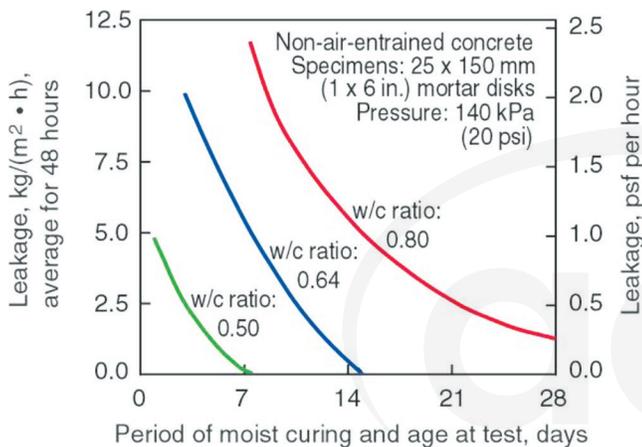
Fig. 1.3.1e—Influence of curing on water permeability of mortar specimens (Kosmatka and Wilson 2011).

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 Brownyard 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 Brownyard 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; Cather 1994; Meeks and