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Curing of High-Performance Concrete for Strength—What is Sufficient?

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Synopsis: This paper reports the results of an exploratory study on the effects of curing duration on the variation of mortar strength with distance from the drying surface. A novel, notched cylindrical test specimen was adopted for measuring tensile strength at different depths. Two mortar mixtures with *w/c* of 0.30 and 0.45 were used; the former was assumed to be representative of the paste system in a high-performance concrete. Specimens were moist cured for (1, 3, or 7) d and then exposed to air at 25 °C and 50 % or 70 % RH. The cylinders were sealed to simulate one-dimensional drying in a large member. Tensile strengths were measured at 28 d. Relationships between tensile strength and depth were compared with those of specimens continuously moist cured. The data tended to show that 1 d of moist curing might be sufficient to ensure adequate strength development at a depth of 25 mm from the exposed surface. The phenomenon of increasing strength with drying may have confounded the results, and recommendations for additional studies are provided.

Keywords: curing; drying; high-performance concrete; mortar; tensile strength

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BACKGROUND

Motivation for Study

In 1990, the National Institute of Standards and Technology (NIST) organized an international workshop to:

- Identify ongoing and planned research programs on high-performance concrete;
- Identify potential applications where high-performance concrete could be used on a routine basis;
- Identify technical barriers to widespread use of high-performance concrete;
- Identify institutional barriers and deficiencies in standards which hinder the use of high-performance concrete;
- Develop a listing of critical research to overcome the technical barriers and provide a sound basis for the needed standards.

The workshop, co-sponsored by the American Concrete Institute, was attended by prominent international experts in various aspects of concrete technology. The workshop proceedings (Carino and Clifton 1990) adopted the following definition of high-performance concrete:

Concrete having desired properties and uniformity which cannot be obtained routinely using only conventional constituents and normal mixing, placing, and curing practice. As examples, these properties may include:

- *Ease of placement and compaction without segregation*
- *Enhanced long-term mechanical properties*
- *High early-age strength*
- *High toughness*
- *Volume stability*
- *Long life in severe environments*

The above definition was modified and adopted in 1998 as the ACI definition of high-performance concrete, as follows (Russell 1999):

> *Concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices.*

Examples of desired characteristics were included in a "commentary" to the ACI-definition. The above definitions have been criticized as being too broad and not practical for specification purposes. Consequently, others (Zia et al. 1991; Goodspeed et al. 1996) have defined different classes of high-performance concrete with specific properties. In general, the majority of high-performance concretes used in North America can be characterized as concretes with water-cementitious materials ratios (*w/cm*) lower than about 0.4. The term "water-cementitious materials ratio" is used instead of "water-cement ratio" because other cementitious materials (pozzolans or ground slag) besides portland cement are typically used to produce high-performance concrete. Thus high-performance concrete typically has high compressive strength and high resistance to fluid penetration.

The proceedings of the NIST/ACI workshop provided an outline of primary and secondary research needs within the following general areas:

- Materials and proportioning
- Processing and curing
- Mechanical properties and test methods
- Durability and test methods
- Structural performance and design
- Standards and acceptance criteria

The outline of research needs has provided a roadmap for a multi-faceted, long-term research program on high-performance concrete at the National Institute of Standards and Technology. The following research needs related specifically to curing were identified (Carino and Clifton 1990):

- Evaluate the effectiveness of moist curing considering the completeness of hydration as a function of time;
- Seek an understanding of interactions between ambient exposure conditions, mixture rheology, and needed evaporation control measures;
- Develop a more comprehensive understanding of the effects of internal curing temperature, and develop guidelines for curing high-performance concrete based on sound technical knowledge.

One of the first curing-related studies in the NIST program established the applicability of the maturity method to high-performance concrete (Carino et al. 1992). The study that is reported in this paper represents the initial experimental effort to establish the basis for the duration of the moist curing period for high-performance concrete. Prior to initiating the experimental program, the authors prepared a report on the state-of-the-art related to curing of high-performance concrete (Meeks and Carino 1999). That report covered the following topics:

- Review of the characteristics of high-performance concrete;

- Review of the physical and chemical properties of cement paste related to curing;
- Historical review of the ACI building code requirements for curing;
- Review of other curing recommendations, standards, and criteria;
- Review of recent research on curing requirements;
- Recommended research needs.

Curing Requirements in the ACI Building Code

A review of the predecessors to ACI 318-95 revealed that the general requirements for curing of concrete have changed very little since the first standard regulations were proposed in 1909 (Meeks and Carino 1999). The basic requirement has been to cure concrete made with normal portland cement for a period of at least 7 d and to cure high-early-strength concrete for at least 3 d.

Tests reported by Price (1951) indicated that normal strength concrete that is moist cured for 7 d and then stored in air will attain approximately the same 28-day strength as if it had been continuously moist cured. These tests provide validation of the 7-day criterion in the ACI Code. Since high-early-strength concrete will gain strength more rapidly, the Code permits a 3-day curing period.

In the 1971 Code, a requirement was added to maintain the concrete temperature above 10 °C during the curing period. This addition is to ensure that sufficient strength development will occur during the prescribed minimum curing periods. In addition, a new provision was added for checking the adequacy of curing procedures based on strength tests of field-cured cylinders. Both requirements were carried over to the 1995 version of ACI 318.

The ACI Code, however, makes no distinction between strength and durability considerations with regard to curing requirements. Since ACI 318 deals primarily with structural safety, the provisions are intended primarily to ensure adequate structural capacity. The only explicit mention of durability in relation to curing is contained in the provisions (originally added in 1971) dealing with accelerated curing.

The ACI Code also does not address curing requirements for concretes made with other cementitious materials besides portland cement. Since the nature of the cementitious system affects early-age strength development characteristics, this omission may be a major deficiency in the current Code.

Applicability of Curing Practices to High-Performance Concrete

Carino and Meeks (1999) concluded that current curing practices and standards are based on studies related primarily to strength development characteristics of conventional (ordinary) concretes. Most high-performance concretes, however, are fundamentally different from conventional concrete, because they typically have a low water-cementitious materials ratio (*w/cm*) and one or more admixtures. In addition, supplementary cementitious materials, such as silica fume, fly ash, and ground slag, are commonly used in practicable mixtures to achieve high strength, low permeability, reduced temperature rise, and economy. High range water-reducing admixtures are used typically to provide workability. Since the composition of high-performance concrete differs from conventional mixtures, early-age characteristics of the hydrating paste will also differ. Therefore, existing curing practices may not be optimal for high-performance concrete. A better understanding is needed of the role of an external supply of moisture and of the adequacy of membrane-forming compounds when a low *w/cm* is involved.

The effects of *self-desiccation* are also important considerations in high-performance concretes with low *w/cm*. Self-desiccation refers to the process by which concrete dries itself from the inside. Moisture in the paste is consumed by the hydration reactions, and the internal relative humidity may decrease to the point where there is not enough remaining free water to sustain hydration. Consequently, hydration will terminate at an early age if additional moisture is not provided. To prevent early-age self-desiccation, water that is consumed by hydration needs to be replaced by the ingress of external moisture. Therefore, the common practice of sealing concrete with a membrane-forming compound may not be a appropriate curing practice for low *w/cm* concrete. However, for how long is moist-curing effective? As hydration proceeds, capillary pores in the paste become discontinuous, thereby hindering the ingress of additional water into the concrete. When this state is reached, additional moist curing may be of little, or no, benefit, because the water may not be able to penetrate to the interior quickly enough to maintain saturation of the capillaries and sustain hydration. Current curing requirements, based on research on conventional concrete, do not consider these factors.

One of the most controversial topics that emerged from the literature review by Meeks and Carino (1999) concerns the sensitivity of various properties of high-performance concrete to different curing conditions. Some researchers have reported that high-performance concrete is more sensitive to the details of curing than normal concrete; whereas, others have found the opposite to be true, at least for some properties. These differences may be attributed to the different experimental procedures that have been used. For example, Hasni et al. (1994) reported that the use of silica fume makes high-performance concrete more sensitive to different curing methods when considering both strength and durability properties. In addition, they reported that high-performance concrete with silica fume is more sensitive to different curing methods than is normal concrete for characteristics such as compressive and flexural strength, depth of carbonation, and microcracking. Comparison of high-performance concrete without silica fume with normal concrete showed that normal concrete was more sensitive to the curing method for these same properties. With respect to resistance to penetration of chloride ions, results showed that high-performance concretes with and without silica fume, as well as normal concrete, were insensitive to the curing method.

Results of work in Norway that was summarized by Gjørv (1991) generally agree with the findings by Hasni et al. (1994). Gjørv reported that the use of silica fume makes concrete more sensitive to proper curing compared with normal concrete. Silica-fume concrete is more vulnerable to plastic shrinkage cracking than normal concrete, which necessitates good, early-age, curing practices to control this tendency. Another reason cited by Gjørv for why silica-fume concrete is more sensitive to proper curing is related to the effects of drying on strength properties. Good curing practices must be used to prevent early drying, which can reduce tensile and flexural strengths of silica-fume concrete more than for normal concrete.

Torii and Kawamura (1994) also reported on the effects of curing on mechanical and durability-related properties of concrete, and some of their results do not agree with those summarized in the previous paragraphs. Their results indicated that the detrimental effects of poor curing practices on pore structure are more significant in normal-strength concrete than in high-strength concrete with silica fume. In their studies, high-strength concrete in which 8 % of the mass of cement was replaced by silica fume apparently developed a dense pore structure at early ages regardless of curing method. This independence of the curing method is attributed to the use of a low *w/cm* (0.30) and the rapid early-age pozzolanic reactions of the silica fume. Tests for resistance to chloride ion penetration and carbonation depth also showed that high-strength concrete, both with and without silica fume, was less affected by poor curing conditions than normal concrete. This can be attributed to the fact that concrete with a low *w/cm* may attain a low porosity paste at a lower degree of hydration than concrete with a higher *w/cm*. Comparisons between high-strength concretes, with and without silica fume, revealed that the silica-fume concrete was less affected by changes in curing method, when considering resistance to chloride ion penetration and carbonation. Carino and Meeks (1999) conclude that additional studies are needed to reconcile these conflicting conclusions regarding the sensitivity of low *w/cm* concrete to the curing method.

Duration of Curing Period

Hilsdorf and co-workers (Hilsdorf and Burieke 1992; Hilsdorf 1995) have presented informative work on concrete curing. Their efforts include experimental and theoretical studies in the search for rational curing requirements. Although their work was not directed specifically to high-performance concrete, the underlying approaches are applicable to all types of concrete.

According to Hilsdorf and Burieke (1992), concretes can be distinguished by their *curing sensitivity*, which refers to the curing duration needed to reach some specified level of durability or strength. The long-term properties of concrete with low curing sensitivity would not be affected significantly by the duration of the curing period. Curing sensitivity is affected by the characteristics of the cementitious materials, mixture proportions, and the environment to which the concrete is exposed after curing has been terminated. The latter factor affects the rate of moisture loss from exposed surfaces. The *w/cm* of a particular concrete has a significant influence on the curing sensitivity. Concretes with low *w/cm* will gain strength faster and become impermeable sooner than those with higher *w/cm*. This is an important characteristic since it may mean that curing duration can be reduced in accordance with the *w/cm*.

Based on the above considerations, Hilsdorf summarized the four factors that must be considered in establishing minimum curing durations (Hilsdorf 1995):

- Curing sensitivity of the concrete as influenced primarily by the cementitious system;
- Concrete temperature as it affects the rate of hydration (and, therefore, rate of strength development and reduction in porosity);
- Ambient conditions during and after curing as these affect the rate of strength development and severity of drying of the surface layer;
- Exposure conditions of the structure in service as these affect the required "skin" properties for adequate service life.

To establish minimum curing durations, Hilsdorf emphasized that attainment of compressive strength is not the only criterion that must be considered; other possible criteria include the following:

- Depth of carbonation
- Permeability
- Maturity or degree of hydration

The depth of carbonation must be controlled to ensure that the reinforcing steel is surrounded by an alkaline environment and remains in a passive state. The minimum duration of curing for adequate resistance to carbonation depends on the depth of cover, the desired service life, the relationship between time and depth of carbonation, and the relationship between concrete permeability and carbonation. Given this information, additional relationships between permeability, water-cement ratio, and time can be used to estimate the minimum duration of curing (see Meeks and Carino [1999] for a summary). It should be noted that carbonation is not a pervasive problem in North America compared with other regions. This can be attributed, in general, to the deeper cover over reinforcing steel and overall better quality of the concrete in North America.

The permeability criterion is a more general form of the carbonation criterion. In this case, the minimum curing duration is based on achieving a certain level of impermeability as measured by a specific test method. One difficulty in using the permeability criterion is the selection of the critical level of impermeability because there is insufficient knowledge of the relationships between measured permeability values and long-term durability.

In the degree of hydration or maturity criterion, the minimum duration of curing is based on the concrete reaching a specified degree of hydration or maturity. Once the required degree of hydration is defined, empirical relationships between time, temperature, and degree of hydration (or maturity) can be used to estimate the minimum curing duration. The empirical relationships are expected to be affected by the characteristics of the cementitious system in the concrete. As is the case with the permeability criterion, there is insufficient knowledge to relate the minimum degree of hydration (or maturity) at the end of the curing period with long-term performance.

A compressive strength criterion may involve one of two approaches:

1. *R1-Concept*: The concrete is cured until it attains a specified minimum strength. As an example, a suggested minimum strength is the strength after 7 d of moist curing that would be obtained by a reference concrete with a water-cement ratio of 0.6 and made with the same materials as the concrete to be cured (Hilsdorf 1995). A water-cement ratio of 0.6 corresponds closely to the highest value for which capillary pores can become segmented with good curing.
2. *R2-Concept*: The concrete is cured until the in-place compressive strength reaches a prescribed fraction of the 28-day specified compressive strength so that at 28 d the concrete at a prescribed depth will attain the specified strength.

The R1-Concept offers the advantage that the use of mixtures with low water-cement ratios or having rapid early strength development can reduce the curing period. This criterion may be applicable when durability is of concern, because it has been established that, for a given concrete, there is a "reasonably reliable" correlation between compressive strength and other durability-related characteristics (Hilsdorf and Burieke 1992; Ho and Lewis 1988).

In the R2-Concept, the curing duration is independent of the water-cement ratio, but it would depend on the rate of strength development. The R2-Concept is appropriate when structural strength is of concern. The basic notion is that the concrete should be cured long enough so that the in-place strength at some depth below the surface attains the specified strength used to design the structure. This is illustrated schematically in Fig. 1, where the solid curve represents strength development of the concrete under standard curing and the dashed curve represents in-place strength development at some prescribed distance from the exposed surface. When curing is terminated, drying of the surface occurs and hydration ceases when the moisture content in the surface layer falls below a critical value. However, it will take time for the drying front to penetrate into the concrete. As result, the interior concrete continues to gain strength after curing is terminated. When the drying front reaches the prescribed depth, two things happen: (1) the strength increases due to drying and (2) the rate of hydration is reduced. Later, the concrete at the prescribed depth dries below a critical level and strength development ceases. The objective is to ensure that the two strength development curves cross at an age of 28 d or later.

The question that has to be answered to implement the R2-Concept is as follows: What fraction of the standard-cured strength has to be attained at the end of the curing period to ensure that the design strength is attained in the interior of the member? ACI Committee 308 (1998) specifies that the strength at the end of the curing period should be at least 0.7 of the design strength. Hilsdorf (1995) notes that this value is based on data obtained in the early 1950s, and those results may not be applicable to modern concretes. Hilsdorf suggests that a value of 0.7 may be conservative, and that research is needed to understand the dynamics of internal drying and strength development after curing is terminated for different types of modern concretes.

Hilsdorf (1995) suggested that the curing period should be long enough so that at 28 d (or other applicable age) the concrete strength at the depth of the first layer of reinforcement will equal the design strength. The rationale for this requirement is to ensure that the bond strength (or development length) of the reinforcing steel will attain the value assumed in the structural design. Hilsdorf used analytical models to estimate the required curing duration. Diffusion theory was used to model the drying of the concrete from the exposed surface. It was assumed that the rate of hydration was not affected until the moisture content dropped below the value that is in equilibrium with a relative humidity of 90 %. The calculations were carried out for a concrete with a 28-day strength of 40 MPa, for cements with different hardening rates, and for different values of ambient relative humidity (ambient temperature was 20 °C). The cover depth was taken conservatively as 25 mm. The results of the calculations are summarized in Fig. 2.

The vertical axis in Fig. 2 represents the fraction of the standard-cured, 28-day strength when curing is terminated. The horizontal axis represents the 28-day strength at a depth of 25 mm expressed as a fraction of the 28-day design strength. The effects of different cement types were minor (see Hilsdorf 1995), and so the results of the calculations are shown as three curves, each representing a different ambient relative humidity. Based on these calculations, for an ambient relative humidity of 60 %, curing may be terminated when the concrete has attained 0.6 of the standard-cured, 28-day strength. If the ambient relative humidity is 50 %, curing has to be maintained until 0.85 of the standard-cured strength is attained. On the other hand, if the ambient relative humidity is 80 %, only about 0.4 of the standard-cured strength has to be attained. The time required to achieve these fractional strengths at a specific temperature can be estimated from the strength development characteristics of the cement.

In summary, Hilsdorf and co-workers presented a rational approach to establish the curing duration. A key factor affecting this duration is the controlling criterion for adequate long-term performance. Hilsdorf's studies showed that, in most cases, the critical curing duration was controlled by compressive strength criteria (Hilsdorf and Burieke 1992; Hilsdorf 1995). This is an important finding because it tends to affirm that strength-based criteria may be the most practical approaches to evaluate the adequacy of curing, possibly even when durability is a primary concern. If preliminary testing of the specific concrete mixture to be used in construction results in a reliable correlation between strength and durability, in-place strength measurements would be a suitable method for assessing the adequacy of curing in the field.

OBJECTIVE AND SCOPE

The exploratory study summarized in this paper examines the influence of the duration of moist curing on the variation of strength with distance from the drying surface. The strength at an age of 28 d was used as the basis for comparison. To simplify testing, mortar was used instead of concrete and only portland cement was used as the cementitious material. While these simplifications may limit the direct applicability of the results, it was felt that correct trends would be revealed.

Two mortar mixtures with water-cement ratios of 0.30 and 0.45 were used; the former is intended to be representative of the hydration and drying behavior of a high-performance concrete with a low *w/cm*. Three moist curing periods were used: (1, 3, or 7) d. At the end of the moist-curing period, the specimens were sealed and allowed to dry at 25 °C at either 50 % or 70 % relative humidity (RH). Reference specimens were continuously moist cured by storing them in a limewater bath.

Tensile strength was measured at 28 d as a function of distance from the drying surface using cylindrical test specimens with circular notches cast at various depths. The notches created reduced cross sections that forced failures to occur at predetermined distances from the drying surface. The estimated average tensile strength at a depth of 25 mm was used as the basis for evaluating the influence of the different curing procedures. The objective was to determine the minimum duration of moist-curing so that the 28-day strength at 25 mm was not lower than the case of continuous moist-curing.

Six curing treatments, in addition to continuous moist curing, were investigated for each water-cement ratio. Four notch depths were used for each treatment. Three replicate specimens were tested for each notch depth. For the continuously moist-cured specimens, two runs were used to establish the reproducibility of the results. Additional details of the experimental program may be found in the doctoral dissertation of the second author (Meeks 1997) and a summary report by Carino and Meeks (2000).

EXPERIMENTAL PROCEDURE

Table 1 lists the mixture proportions of the two mortars used to prepare the cylindrical specimens. The two mixtures were proportioned so that they had approximately the same volume fraction of paste. The water in the high-range water reducer was included as part of the mixing water. The sand was a graded silica sand that conformed to ASTM C 778. The portland cement was a sample of cement 116 issued by the ASTM Cement and Concrete Reference Laboratory (CCRL) in its proficiency sample program. Table 2 lists the degree of hydration versus age for curing of CCRL cement 116 under saturated conditions. These