CONCRETE CURING AND ITS PRACTICE IN SOUTH AFRICA: A LITERATURE REVIEW

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Abstract

Concrete curing is the most important and final step in concrete construction though it is also one of the most ignored procedure. Curing of concrete is a pre- requisite for the hydration of the cement content. For a given concrete, the amount and rate of hydration and furthermore the physical make-up of the hydration products are dependent on the time-moisture-temperature history. Concrete curing is specially neglected procedure in South Africa. This paper presents detailed literature review on the relevance of concrete curing in the world. Furthermore, the paper presents the South African practice on concrete curing and makes aware the civil construction industry about the problem and recommends the accepted engineering concrete curing practice.

Key words: Concrete, concrete curing, compressive strength, concrete curing methods

1. Introduction

According to Cather [1994], curing is the creation of an environment in which hydration reactions can proceed to help fulfil the aim of producing concrete of adequately low porosity. Curing is adequate when the resulting concrete achieves the expected service performance. ACI [1998] defines Curing as the process by which portland cement concrete matures and develops over time as a result of the continued hydration of the cement grains in the presence of sufficient water and heat. The maintenance of a satisfactory moisture content and temperature in concrete during its early stages so that desired properties may develop.

Curing plays an important role on strength development and durability of concrete. Curing takes place immediately after concrete placing and finishing, and involves maintenance of desired moisture and temperature conditions, both at depth and near the surface, for extended periods of time [Meeks and Carino, 1999]. Properly cured concrete has an adequate amount of moisture for continued hydration and development of strength, volume stability, resistance to freezing and thawing, and abrasion and scaling resistance [Poole, 2005].

ACI [1998] states that adequate curing is essential to obtain the desired structural and durability properties of concrete. Proper curing of concrete is one of the most important requirements for optimum performance in any environment or application. Historically, curing has not received the attention it deserves. Poor curing practices adversely affect the desirable properties of high-performance concrete, just as they do any concrete. Proper curing of concrete is essential to obtain maximum durability, especially if the concrete is exposed to severe conditions where the surface will be subjected to excessive wear, aggressive solutions, or severe environmental conditions (such as cyclic freezing and thawing). Likewise, proper curing is necessary to assure that design strengths are attained.

Even when good quality concrete is placed on the job site, curing is necessary to ensure the concrete provides good service over the life of the structure. Good concrete can be ruined by the lack of proper curing practices [Neville 1996]. Curing has a major impact on the permeability of a given concrete. The surface zone will be seriously weakened by increased permeability due to poor curing. The importance of adequate curing is very evident in its effect on the permeability of the "skin" (surface) of the concrete.

In the United States and other countries, contractors tend to either short cut curing requirements in the field or ignore them almost completely. One survey conducted in the United States in 1979 estimated that 24 % of concrete used in non residential construction was not cured at all, and only 26 % was cured in accordance with project specifications [Senbetta, 1994]. This situation has improved very much since then by the contribution of ACI.

A common feature in the recent research literature on concrete curing is the development of comparative data, which are useful in evaluating option, but often the data are difficult to use for actually designing guidance. For example, research will commonly compare effects among types of cementitious materials, among different mixture proportions, among different curing materials and practices [ACI, 1992]. The design and intent of the research was not to determine optimum curing times or application rates of curing materials; thus, it is sometimes difficult to extract from this research recommendations for specific guidance on how to specify curing practices [Al-Fadhala and Hover, 2001]. However, the literature was reviewed with a particular focus on trying to get this kind of information from it.

Early research and guidance focused on effects of curing on properties of cement paste and on strength of concretes and mortars as the basic performance property [Okamoto and Whiting, 1994]. Guidance on curing is still largely based around strength and durability. Strength is properly identified as the performance property of interest when determining when concrete can be load bearing. Durability against one or more of the degradation processes that affect concrete is also sometimes strongly affected by curing. Some degradation processes are affected by the state of hydration of the entire section of concrete, such as strength. However, other curing related problems are more affected by the properties of the concrete at or near the surface than by the strength of the entire section of concrete. Examples include cracking resulting from near-surface drying strains, rate of penetration of water and waterborne salts from the concrete surface, and abrasion resistance [ACI, 1996]. Obtaining adequate curing of the near-surface zone is more likely to be disrupted by inadequate choice of materials and practices. Research on the relationship between curing and development of physical properties has tended to recognize both the strength aspect and the surface properties aspect of the problem [ACI, 1998].

2. Literature Review

The importance of concrete curing has never been given emphasis in Africa. Even engineers and users neglected that the adverse effect of not practicing concrete curing cost a lot. This paper review the existing knowledge and concepts on concrete curing. The effect of curing on concrete durability was recognized in some of the earliest literature, particularly the effects of curing on surface features such as abrasion resistance. Lack of adequate curing continues to be considered one of the most important causes of poor durability. The well known work on the effects of cement hydration, and hence curing, on cement microstructure was shown by Powers and Brownyard [1946-47]. Furthermore, Senbetta (1994), Taylor (1997), and Meeks and Carino [1999] have done remarkable works on effects of concrete curing. In practical terms, several major themes emerge, as described by Neville [1996a].

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

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

The concrete near the surface of a concrete structure has been recognized as potentially different from concrete interior to the structure because of the potential for exposure to different environmental conditions, either during curing or during service. Curing deficiencies will likely have their strongest effect on this part of the concrete. A poorly cured near-surface zone is likely to be less durable than a well cured one because of the possibility of a less dense microstructure and the possible presence of some level of cracking. This truth has been known for a long time, as indicated by Gonnerman's [1930] study, of the effect of curing on strength and abrasion resistance. Recent literature further investigates this [Dhir, Hewlett, and Chan, 1989 and 199; Parrott, 1995; and McCarter and Watson, 1997]. Much of the research on curing in the last 10 years involves the near-surface zone in one way or another, mostly as it affects durability; development of test methods that measure near-surface properties have dominated the literature on curing test methods. This is discussed in a later section. This thickness of the near-surface zone or curing-affected zone varies from a few millimeters to about 50 mm, depending on the composition of the concrete and on the climatic conditions [Cather, 1994].

There has been some research effort in the past 20 years to develop a better understanding of the physics of water movement and evaporative loss from concrete. This research is driven by two needs. One is to better understand properties required of curing compounds and evaporation retardants. The other is to estimate time required to dry concrete.

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

Research on the drying process, contributes indirectly to understanding of curing concrete. This research mostly focuses on moisture movements in concretes that contain only water vapor and the relationship between concrete properties and rate at which this vapor can be reduced to below about 80 percent and lower.

Ravina and Shalon [1968] conducted laboratory tests to investigate the effects of water-cement ratio, cement content, evaporation conditions, and tensile strength of fresh mortar on development of plastic shrinkage cracks. The range of mixture proportions covered overlapped with paving mixtures only a little, but two important things pertinent to concrete paving were evident. One was that mixtures that developed high tensile strengths, like paving mixtures, did not crack under the experimental conditions used. Second, cracking in higher water-cement ratio mixtures usually occurred after evaporation of 2-3 kg/m^2 of mixing water. These cracks developed 0.5 to 2 h after all bleed water had disappeared. The authors concluded that tensile strength was a major variable determining susceptibility to plastic shrinkage cracking.

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

The following references represent recent work in this area and provide good descriptions of the physics of moisture movement and sorption [Radocea, 1994]. The rate with which water moves into concrete can have important implications for some kinds of curing practices. Low water-cement ratio concretes (<0.40) are known to sometimes consume all of the mixing water during hydration so that, if additional hydration is needed, water must be added to the concrete during curing. But the capillary continuity among pores and with the surface of concrete tends to decrease rapidly in low water-cement ratio concretes, so that introducing appreciable water into the concrete may be difficult [Meeks and Carino 1999, Cather 1994].

Radocea (1994) models shrinkage due to drying during the plastic phase, but does not attempt to include the tensile properties of the concrete and so the model does not extend to predicting cracking. Wang, Shah, and Phuaksuk [2001] investigated effects of fly ash and fibers on plastic shrinkage cracking. Mora et al. [2001] investigated the effect of fibers and shrinkage-reducing admixtures on plastic shrinkage cracking. Again, fibers reduced the amount of shrinkage cracking. Shrinkage-reducing admixtures are principally intended to reduce amounts of drying shrinkage, but were also found to reduce plastic shrinkage. Holt [2000] quantitatively measures evaporation, shrinkage, and development of cracking in laboratory concretes and describes the relationships among them.

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

Beltzung and Wittmann [2001] develop the theoretical aspects of autogenous volume changes and measure effects at very early ages (from time of adding water until just past time of setting). There is significant shrinkage associated with the earliest reactions that has practical significance in concretes with high cement contents. Sule and van Breugel [2001] investigated the interaction between autogenous shrinkage and cracks formed around reinforcing steel in very low water-cement ratio concretes (0.33). Reinforcement tends to distribute strains, resulting in longer times to cracking and the formation of many small cracks rather than a few large ones. van Breugel [2001] discusses some autogenous shrinkage modeling efforts and shows how these are able to separate and analyze the many components of this phenomenon. Bjontegaard and Sellevold [2001] investigated the combined effects of strains due to early changes in temperature associated with hydration and autogenous shrinkage.

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

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

Kettle and Sadegzadeh [1987] reported the effects of different curing methods on abrasion resistance of concrete. The principal variable was method of finishing, but adequate curing was also found to be important. Both plastic sheeting and curing compounds were effective in giving good abrasion resistance. Malchow and Senbetta [1987] demonstrated quantitatively the effect of good curing on abrasion resistance, scaling resistance, and corrosion of steel, chloride penetration, shrinkage, and water absorptivity. Curing was continuous, either by sealing the surface of specimens with wax or curing compound, or by storage in a fog room, so no information on length of early curing could be derived.

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

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

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

Meeks and Carino [1999] completed a comprehensive review of information on curing of high-performance concrete. Their description on curing high-performance concrete is pertinent to this project. The long-term goal of the proposed research is to provide the basis for modifying current ACI standards related to curing so that structures in service will perform as required. Curing requirements should consider economy of construction and not place undue demands on the construction team. On the other hand, curing requirements should assure the owner that the potential properties of the concrete in the structure are realized. To achieve these goals, emphasis should be placed on developing a system to verify the adequacy of curing on the job.

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

- Evaluation of curing methods should be done on full-scale models that accurately simulate field concrete in dimensions, exposure conditions, and temperature history.
- The idea that low water-cement ratio concretes will benefit from added-water types of curing should be investigated. There is a concern that added water may not penetrate into the concrete to any appreciable degree, so the effort may be wasted.
- In-place test methods should be developed.
- Curing requirements should be revised to better reflect the particular performance requirements of high-performance concrete (HPC).

A common feature of HPC design is development of high strength. Mixture proportions commonly involve low water-cement ratios. As has been mentioned elsewhere, water-cement ratios less than 0.40 are generally thought to create a condition where the concrete will internally desiccate due to consumption of all of the mixing water by hydration, and that if additional hydration is necessary, then water must be added during curing. But since low water-cement ratio concretes tend to be relatively impermeable, there is some question about how effective externally added water will be in penetrating the concrete. Persson [1997)] studied relative humidity depth profiles in concrete at various water-cement ratios, with and without silica fume in the concrete.

Information on bridge deck curing practices comes mostly from State Department of Transports and from several papers on current practice that has appeared recently. The principal concern with the concrete in bridge decks is usually that it not be excessively permeable to chemical compounds that promote corrosion of reinforcing steel, such as carbon dioxide and particularly chloride, and that they do not crack appreciably.

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

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

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

Healy and Lawrie [1998] investigated cracking in highway bridge decks in Maryland, U.S; two large bridges had almost 100 percent of surface area cracked. The authors investigated mechanical causes, but determined that shrinkage cracking was the principal cause and that curing practices were deficient.

Fast-track paving is a technology by which road pavements are placed and opened to traffic quickly, usually within 24 to 48 h. Strength gain of most conventional concrete mixtures is too slow to allow this. One technique that has been used in fast-track paving is to take advantage of the heat of hydration of the cementitious materials to create an elevated curing temperature, thus accelerating strength gain. A more common approach is to proportion the concrete with a high cement content and low water-cement ratio (<0.40).

In its "Specification of materials and methods to be used", the Department of Public Works, Republic of South Africa [1993] stated that concrete surfaces should be kept continuously damp for at least 10 days by methods as may be approved by the consultant. Unfortunately, its practicality is out of question.

3. Conclusions and Recommendations

In this literature review the basic concepts related to curing of concrete are elaborated. It has been made clear that curing is a complex process, and there are many factors that effect the duration of curing to ensure that the concrete will develop a sufficient level of its potential properties to perform as planned. A review has been presented of various curing requirements, including those from other countries, for comparison with the ACI 318 Code. The following recommendations are drawn from this literature review work:

- ✓ The concrete industry must do a better job of educating contractors, engineers, superintendents, and quality control personnel of the importance of good curing practices in the field. This is especially true for high-performance concrete since it has been found to be even more sensitive to curing conditions than ordinary concrete, particularly at early ages. It has been suggested that one way to highlight the importance of curing is to make it a separately billed item in the schedule of prices for the project [Cather 1994].
- ✓ Contract specifications usually contain curing requirements; however, they are rarely adhered to in the field [Neville 1996]. Similar to the batching and mixing operation for concrete, curing needs to be closely supervised and controlled. As a construction project progresses, it is extremely difficult to prove whether proper curing has been applied. Although specifications may be adequate and complete, one of the biggest obstacles to ensuring proper curing in the field is the lack of standard methods to verify curing adequacy. Various penetrability methods have been proposed [Kropp and Hilsdorf 1995], but none has yet to be standardized for use. Without approved testing methods, it will continue to be difficult to verify desired levels of curing in the field.
- ✓ Proper curing involves maintaining suitable moisture content in the paste. This can be accomplished using many different curing methods, or combinations of various methods. All these methods, however, involve two basic concepts. Either the surface of the concrete is kept moist by supplying an external supply of water (water curing), or the loss of moisture is controlled by the use of impervious coatings, membranes, coverings, or by the concrete formwork.
- ✓ The concrete temperature should be maintained above freezing at a relatively constant value throughout the period of curing. The concrete must also be protected from high temperatures. Controlling the temperature can be a difficult matter since there are three potential sources of heat-the surrounding environment, absorption of solar heat, and the heat generated from the hydration reactions.
- ✓ Preservation of reasonably uniform temperature throughout the concrete body is essential. The ACI committee recommended that any drop in temperature during the first 24 h after curing not exceed 16.7 °C (30 °F) for mass concrete or 27.8 °C (50 °F) for thin sections. This is to reduce the chance of cracking due to temperature gradients. This addition is to ensure that sufficient strength development will occur during the prescribed minimum curing periods. Furthermore, a provision was added for checking the adequacy of curing procedures on the basis of strength tests of field-cured cylinders. Both requirements have been carried over to the current ACI Code.

- ✓ Any new concrete structure must be protected from heavy loads, large stresses, shock, and excessive vibration as the concrete gains strength during early curing. Concrete progresses to its hardened state as determined by the rate of hydration in the paste. This progress can be hampered if the concrete undergoes significant mechanical disturbances during the critical early-age period when the microstructure is beginning to develop. Damage at early age may prevent the concrete from attaining the desired strength and durability to perform satisfactorily.
- ✓ There must be enough time allowed for hydration to progress sufficiently to produce concrete having adequate properties for its intended use. The amount of time needed depends on a number of variables-curing temperatures, type of cement, and moisture content of the paste. The basic requirement has been to cure concrete made with normal portland cement for a period of at least 7 days and to cure high-early-strength concrete for at least 3 days [ACI, 1998].
- ✓ Tests reported by ACI [1998] indicated that normal strength concrete that is moist cured for 7 days and then cured in air will attain approximately the same 28-day strength as if it had been continuously moist cured. These tests confirm the validity of the 7-day criterion in the ACI Code.
- ✓ Keeping formwork in newly poured concrete structures for at least 5 days will positively impact quality, strength and durability of concrete
- ✓ Curing practices in which water is added will provide the supply of moisture needed to sustain hydration and pozzolanic reactions.

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