High Performance Concrete
Enhancement Through Internal Curing

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Introduction

Currently, there are several driving forces toward making good concrete better. These are: recognition that durability results from a choice of materials and procedures; the embrace of the concept of high performance concrete (HPC) and the enhancement of these by the innovative concept of the internal curing of concrete. These concepts are simultaneously coming together in 2004 and 2005. They will assure that 50, 75, 100 or 150 year concrete is a valid expectation. Internal curing (IC) in place of, or as an adjunct to, external curing can assure that results contemplated through HPC will be achieved and improved. Problems resulting from low water-cement (w/c) ratio concretes, such as autogenous shrinkage, have been identified, and research and field experience show us how IC will resolve them. Recognizing that external curing is less effective in certain situations, ACI Committee 308 is rewriting the Curing Guide 308R to include Internal Curing as an alternate process to that of external curing of concrete so that the potential properties of the mixture may develop [1]. The result is that the design engineer and the ready mixed concrete (RMC) producer will assume more of the responsibility for curing instead of leaving it to the contractor or his agent to cure the concrete, sometimes under adverse conditions.

High Performance Concrete (HPC)

Recently, the number of projects using HPC has substantially increased because engineers and state departments of transportation have seen that the mechanical and durability properties such as high strength, low permeability, resistance to freeze thaw and resistance to chemical attack are enhanced. Enhanced, yes, but not completely satisfied. Although, through the use of HPC, drying shrinkage is reduced, autogenous shrinkage and self-desiccation, consequences of low water/cement (w/c) ratios, result in cracking not being eliminated, particularly at early ages. Without sufficient water, the cement does not hydrate soon enough, with the result that micro-cracking and autogenous shrinkage occur.

The purpose of HPC is to obtain long term strength, early age strength, low permeability, density and longer life in a severe environment [2]. Internal curing is used for the same purposes and end-results, including durability [3]. It even improves the durability of higher fly-ash concretes [4]. The two concepts have a synergistic effect, and internal curing enhances each of the desired characteristics of HPC and importantly durability.

Internal Curing (IC)

Concrete can be improved by the substitution, for a small amount of natural sand in the mixture, of an equal volume of crushed structural grade absorbent lightweight aggregate sand (LWAS). Most expanded shale lightweight aggregates have the ability to absorb 15% or more by weight of water and this absorbed water is immediately available to hydrate the cement particles deprived of mixing water in low w/c ratio concretes. This occurs through prompt release of the water as the concrete cures and the mixing water is used up [5].

For the past 50 years coarse lightweight aggregate (usually 3/4 inch) has been used, not for the purpose of supplying the extra water in the mix, but for the economy of its saving weight in bridge decks and multistory buildings. It was observed that its absorbed water supplied the function of internally curing the concrete, with the result that there was a great reduction in expected cracking.

It has been found, in the last five years, that the replacement for natural sand in the mix of as little as 100 lbs. per cubic yard of saturated lightweight aggregate sand will supply the water needed to properly hydrate the cement at a w/c ratio of 0.43 [6]. The water, which is not included in the water cement ratio calculation, needs to be within capillary distance of the cement particles thirsty for water. This is the process of Internal Curing (IC).

The lower we go from a water-cement (w/c) ratio of 0.43 the autogenous shrinkage problem becomes more noticeable. At 0.43 the problem is measurable and correctable; at 0.40 it becomes a definite concern; at lower numbers its resolution becomes a must. At 0.35, external curing is not effective [7]. The use of strong, crushed LWAS as a replacement of some of the natural sand in the mixture is effective [3, 5, 8, 9].

Mechanics of Internal Curing

The time it takes to release absorbed water from saturated surface dry (SSD) lightweight aggregate is a reflection of the time it takes to absorb water into the pores of dry aggregate and the capillary force of the passageways to the unhydrated cement. The crushed LWAS absorbs much of its water in the first 30 minutes. If the capillaries are sufficiently large, this water becomes immediately available when the aggregate and cement are incorporated in the mixture and as the concrete gains its initial set. As the skeleton is formed during the initial hydration of the cement, localized areas become deficient of water. The absorbed water either replaces the conventional mixing water or it directly hydrates cement particles thirsty for water. The "back-up" absorbed water is drawn by capillary force and gravity from the aggregate into the pores formed by the space where the mixing water was. As that water is used up by the further hydration of the cement, it is replaced. Because water is so fluid, capillary action so strong and the thirst of the cement particles so intense, all these actions take place simultaneously [8]. The key is to have the water available and used before the voids, where the mixing water was, become clogged with products of hydration.

Readily available internal water that is within capillary distance of the cement particles hydrates those particles not otherwise hydrated by the mixing water. This provides increased early age (0-72h) strength, eliminates almost all the autogenous shrinkage [6, 9] and further enhances the concrete by reducing the permeability of the concrete. With later age (3-28 days), the absorbed water continues to hydrate the cement (the c of cm) and starts to react with the cementitious material (the m of cm) thus providing increasing strength and other beneficial characteristics. In still later ages (28 days on) the retained water provides higher internal relative humidity and consequently eliminates self-desiccation.

Advantages of Internal Curing

A mixture, with a w/c of 0.434 which contains 100 lbs. of lightweight aggregate sand as a replacement for an equal volume of natural sand, provides 7 day flexural strength in 3 days [9]; improves the 84 day permeability (Coulombs) 25%; the 28 day compressive strength 10%; the 28 day tensile strength 6% and the durability factor 2% or more [3, 5, 6]. At a lower w/c ratio more LWAS will be needed; at a range of 0.38 to 0.40 about 200 lbs. per cubic yard are required [9].

Internal Curing can provide several advantages, depending on the time (hours-days-months) that it takes to provide the reaction with cement or puzzolans. In order to prevent micro-cracking or autogenous shrinkage, the cement needs to be hydrated in the early hours after the water and cement are commingled. Early age (<3 days) is the crucial time for strength gains to be achieved to enable the concrete to be strong enough not to be cracked by the internal and external strains applied to it. This is the period that micro-cracking and autogenous cracking occur. IC is vital to keep that from occurring. A 20% sand replacement with LWAS enables the almost complete elimination of autogenous shrinkage and reduces the risk of cracking 50% [10].

Eliminate the Risk of Autogenous Cracking

Practitioners (engineers, architects, owners) will decide the margin they feel their particular application can risk against cracking, against corrosion of the reinforcing steel and against all those deficiencies of concrete that can occur because of improper curing. The effects of different amounts of LWAS on autogenous shrinkage were investigated at the National Research Council Canada [10, 11] on large prismatic concrete specimens under fully-restrained autogenous shrinkage (specimens were sealed against external drying). The concrete had a water-cement ratio of 0.34 and a cement-sand-stone ratio of 1:2:2. The sand replacement ratios used in the studies that have been published were 0% (control), 6% and 20%. It was shown that the specimen with 6% LWAS developed slightly less shrinkage and comparable creep than the control specimen. Both the control and 6% LWAS specimens failed after 1.5 days of testing, reflecting a decrease of internal relative humidity (RH) after initially hydrating cement and then absorbing other water from the matrix. The specimen with 20% LWAS, however, demonstrated (i) less internal drying (i.e. enhanced internal curing), (ii) a clear reduction of autogenous shrinkage and (iii) a much reduced tensile stress to strength ratio not higher than 0.5 (i.e. a minimum safety factor of 2). It was also shown that LWAS in the amounts tested in the study did not adversely affect the air content, strength or modulus of elasticity of the concrete.

With cracking eliminated, or largely so, and with permeability reduced, water, salt and other deleterious substances which could adversely affect the reinforcing steel are hindered from entering the concrete. Together, HPC and IC enable the concrete to withstand the attacks, with the result that bridges, pavements, parking structures and walls are essentially repair free for a significant period. The pay off is that they are able to reach service lives of 50, 75, 100 or 150 years.

Internal Curing Saves Dollars

Moreover, external curing costs money and is subject to procedures not being followed. The most important part of good concreting practice is often the most abused and overlooked in the field. The cost of external, after-the-fact, curing, repair cost and earlier replacement of the concrete exceed the relatively low initial cost of IC. The value added properties provide the RMC producer with an additional promotion tool. In addition, there is the obvious advantage of eliminating much of the uncertainty of external curing.

The cost of the IC agent (the lightweight aggregate sand used) that is incorporated in the concrete depends on the amount needed.

Not only is the cost of the IC agent (LWAS) of interest to the designer who uses it to reduce cracking but also the characteristics of the aggregate itself are important: its absorption, its particle strength, particle shape, gradation and its ability to not detract from mixing, placing and finishing. Consequently, it is well to make comparative tests, using ASTM C 109/C 109 M [3, 6], to test the LWAS to be sure the mortar compressive strength is not compromised.

How Much LWAS to Use

The February 2005 issue of ***Concrete International*** had an article authored by Bentz, Lura and Roberts on how much IC agent to use [12, 13]. The rationale is based on the chemical shrinkage (autogenous shrinkage) and the desorption of the readily available water as it migrates to the hydrating cement. The maximum expected degree of hydration of the cement depends on the water available. The rate depends on the ability of the lightweight aggregate to desorb the water quickly.

A less than optimum lightweight aggregate will have inadequacy of water or desorb it at a lower rate such that the maximum amount of hydration of the cement is not achieved. The ASTM C128 test for absorption has a time of 24 hours and this test is an indicator of the water available internally for the hydration of the cement not hydrated by the mixing water. Since desorption is especially important in the initial and final setting stages, an absorption at 30 minutes has been accepted as a measure of early availability of absorbed water. As far as the absorption of the lightweight aggregate is concerned, each shale, clay or slate out of which the aggregate is made has its own characteristic expansion with resulting void or pore configuration. Some voids are large, some infinitesimally small, some are interconnecting, some are not. The result is that 24 hour absorptions vary from 5% or less to 25% or more. Consequently, with different lightweight aggregates, the same mass of lightweight aggregate might have widely varying ability to provide water for the hydration of the cement.

The formula is designed for computing the amount of LWAS to use by knowing the degree of saturation of the water in the aggregate, the w/c ratio, the degree of hydration of the cement and the amount of cement [9].

Procedure for Using LWAS

The procedure for best results is within standard practices of ready mixed concrete plants. In addition to replacing some of the natural sand with an equal volume of structural grade LWAS, care should be exercised to batch the LWAS saturated surface dry (SSD). Your lightweight aggregate supplier can provide you with specific procedures.

Summary

There are many opportunities to make good concrete better through the use of HPC and IC. Applications needing the benefits have been identified. In the case of bridges, Anthony E. Fiorato, past president of ACI said, "Durability is a driving force on the choice of materials in bridge construction." He said we could "… accomplish this through materials, selection and design." Concrete in the 21st Century is being improved through choice of ingredients and engineered systems and practices, rather than relying on methods that are affected by on-the-job practices and the weather. Instead of external curing with water after-the-fact, water will be engineered into the concrete through the use of water absorbent materials.

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