Optimizing the Sustainability of Concrete Through Internal Curing

by: Benjamin E. Byard and John Ries

Abstract: The internal curing process is often referred to as "curing concrete from the inside out". This process is accomplished by using materials that absorb water, such as lightweight aggregate, to replace some of the normalweight aggregate in the freshly placed concrete mixture. This absorbed water can then be released from the aggregate into the paste fraction as the paste begins to desiccate. By doing this the hydration reactions of cement and supplementary cementitious materials are enhanced, and capillary stresses are reduced as the water is readily released from the absorbent materials.

This paper gives a general overview of internal curing, and will show how internal curing plays a practical and economical role in today's move toward sustainable concrete. The paper will explain how internal curing works, why internal curing is used, summarize the modern history of internal curing, and how it affects the carbon footprint of a concrete mixture. In addition, how to adjust the concrete mixture to provide appropriate amount of internal curing, and reduce the life-cycle costs of the concrete. Examples of real projects that have used internally cured concrete will then be highlighted.

Keywords: Internal curing, life-cycle cost, lightweight aggregate, mixture proportioning, performance, sustainability,

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INTRODUCTION

The internal curing (IC) process is often referred to as "curing concrete from the inside out". This process is accomplished by using materials that absorb water, such as lightweight aggregate (LWA) or supper absorbent polymer, to replace some of the aggregate in the freshly placed concrete mixture. This absorbed water can then be released from the aggregate into the paste fraction as the paste begins to desiccate. By doing this the hydration reactions of cement and supplementary cementitious materials (SCM) are enhanced, and capillary stresses are reduced as the water is readily released from the absorbent materials.

Internal curing is not a new process, and occurs naturally in conventional lightweight concrete; which has been used since 3000 B.C. when the Sumerians used LWA concrete to build Babylon[1]. In addition, Romans used LWA concrete in building their empire including the Pantheon and the aqueducts[1]. What is new, however, is a better understanding of the internal curing process. This better understanding has resulted in IC being intentionally incorporated into normalweight concrete to improve its properties and performance in an economical and practical way.

How internal curing works

The reaction products formed from cement hydration occupy a smaller volume than the initial components[2]. The reduction of the volume of the reactants due to hydration is chemical shrinkage. Before setting, this phenomenon results in a volumetric change but generates no stress because the concrete is still plastic[3]. At setting, enough hydration products have formed to provide a self-supporting skeletal framework in the paste. Within the framework of solids are water-filled capillary voids. As water is consumed by the ongoing hydration process, the voids desiccate and capillary tensile stresses are generated, which results in a volumetric shrinkage. The concrete volume change that occurs without moisture transfer to the environment or temperature change is called autogenous shrinkage. When wetted LWA is introduced into the mixture, it can desorb water from its pores into the paste maintaining high moisture levels, limiting capillary stresses and increasing the ultimate degree of hydration[4].

To date, in North America almost all IC research and construction projects use expanded shale, clay or slate (ESCS), which is a porous, low density, strong and durable lightweight aggregate. The pore structure of this aggregate will allow it to absorb water, and readily release it to the hydrating cementitious paste. Research by Castro et al. [5] has shown that ESCS will release over 85% of its absorbed water at relative humidity of 94%. This has been found to be the optimal level of desorption for IC to occur. To be most beneficial the internal curing water needs to be released from the aggregate at high relativity humidity, like that of the paste fraction in concrete at early-ages[5]. The performance of other absorbent materials is not covered in this paper as they are still in various stages of research and development.

Why internal curing is used

Durability - Internal curing increases the performance of concrete by increasing the amount of cement hydration[6, 7, 8]. The improvement in degree of hydration is seen even at higher w/cm of 0.45, as the illustrated in Figure 1. This increase in hydration is attributed to the additional moisture provided by the lightweight aggregate. Increased degree of hydration improves the microstructure of the paste fraction; which, increases paste density and strength[9]. This increased degree of hydration and strength has also been shown with mixtures containing SCM[10]. The SCM reactions generally require more time than ordinary cement reactions. Thus, the increased strength of internally cured SCM mixtures has been attributed to the longer periods of high moisture allowing for their long-term hydration and pozzolanic reactions to take place[4]. In addition, internal curing has been shown to provide a denser and more homogeneous interfacial transition zone (ITZ) between LWA particles and paste, when compared to the ITZ of normalweight aggregate particle[11]. Generally, the ITZ region is less dense than the bulk hydrated cement paste, and provides a preferential pathway for the ingress of potentially deleterious chloride ions[12]. The improved ITZ, provided by LWA, greatly reduces the transport properties at the LWA[4].

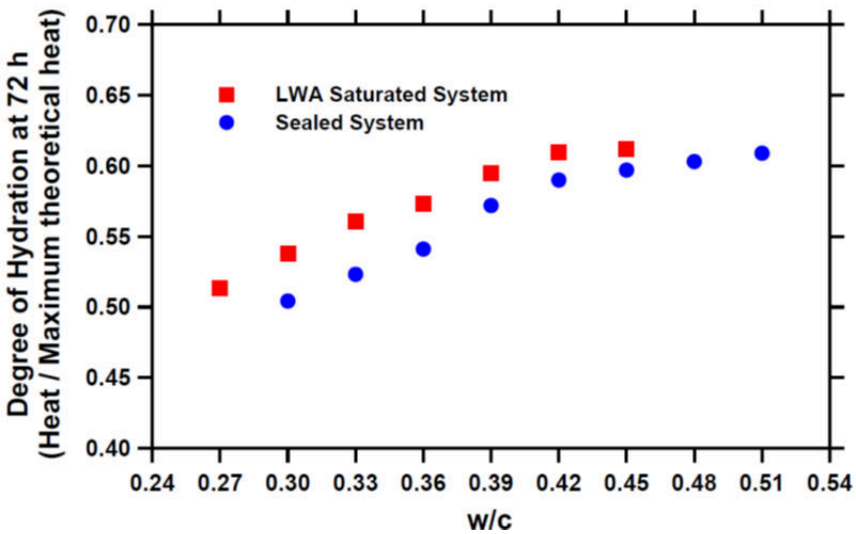

Figure 1 — Degree of hydration of sealed specimen[6]

Stress development - The additional water provided by IC minimizes the internal autogenous stresses caused by self-desiccation[4, 13, 14]. This reduced autogenous stress reduces the total state of stress, and can improve the cracking performance[14]. Internally cured concrete also benefits from reduced modulus of elasticity and coefficient of thermal expansion (CTE) when compared to non-internally cured concrete, all of which lower stresses within the concrete, and improve the cracking performance of the concrete. The increased cracking performance of the internally cured concrete compared to non-internally cured is illustrated in Figure 2. The combined effect of the reduced CTE, modulus of elasticity, and autogenous stress results in an increased time to cracking of the internally cured sample. In field placements, this increased cracking performance may be in the form of increased crack spacing, decreased crack widths or fewer cracks.

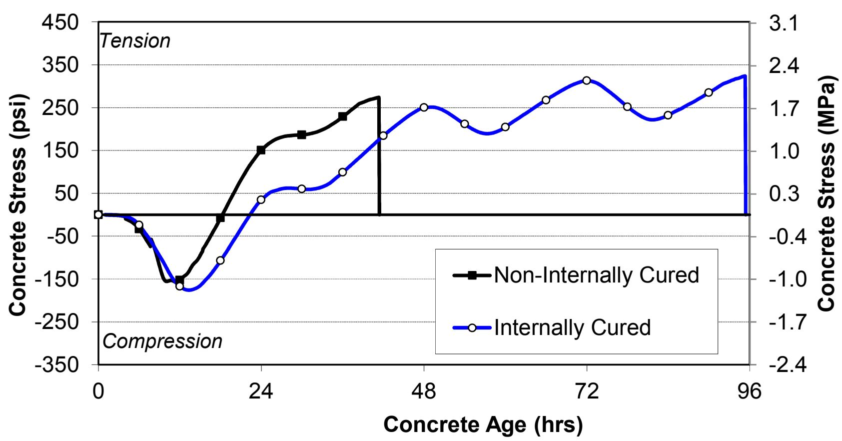

Figure 2 — Stress development of bridge deck concrete[14]

Surface curing may only penetrate the concrete 0.08 to 0.79 inches (2 to 20 mm), and may be insufficient to maintain adequate moisture throughout the cross section[13]. Properly proportioned internally cured concrete can provide an even distribution of internal curing water throughout the thickness of the concrete section, which can reduce internal stresses due to warping[15].

Internal curing has also been shown to works well with SCM[16]. SCM have increased chemical and autogenous shrinkage[10, 13]; consequently, they have been found to have increased demand for internal curing water compared to concrete with ordinary portland cement[16]. Internal curing has been shown to significantly reduce the increased self-desiccation associated with concrete mixtures containing SCM[16].

Construction - Internal curing was recently described as a way to make conventional concrete more robust for field construction due to its ability to perform well under a wide range of site conditions[17]. During construction, internally cured concretes have available water to reduce plastic and drying shrinkage cracking that can occur in higher temperature and lower humidity placements[17]. In addition, their decreased CTE and modulus which reduce thermal stresses, and allow for more early-age robustness with respect to thermal shock from form removal, cooling, or diurnal temperature changes[17, 14].

Concrete finishers have reported improved workability and finishability, because the additional IC water helps to eliminate some of the stickiness commonly found in concrete utilizing SCM, such as silica fume.

While internal curing does not replace conventional surface curing, it can help compensate for higher temperature, low relative humidity weather conditions and poor conventional curing that is often seen in the real world.

THE HISTORY OF INTERNAL CURING

The first modern awareness of internal curing dates back to the mid 1950's when Paul Klieger[18] wrote, "*Lightweight aggregates absorb considerable water during mixing which apparently can transfer to the paste during hydration.*" Campbell and Tobin[19] confirmed this with a comprehensive program that showed the availability of absorbed moisture in lightweight aggregate will produce a more forgiving concrete that was less sensitive to poor field curing conditions.

In the early 1990s, the benefits of internal curing came to the concrete industry forefront. Robert Philleo[20] stated, "*Either the basic nature of Portland cement must be changed so that self-desiccation is reduced, or a way must be found to get curing water into the interior of high-strength structural members. The latter is possible through the use of saturated lightweight aggregate. However, people striving for high strengths are not eager to use lightweight aggregate. A partial replacement of fine aggregate with saturated lightweight fines might offer a promising solution.*"

Structural lightweight aggregate was used on the Hibernia Offshore Platform in Newfoundland, Canada, to improve buoyancy by replacing 50% of the coarse aggregate with wetted ESCS aggregate. The benefits of internal curing quickly became apparent on this innovative use of high-strength lightweight concrete, which spawned new research on the subject in the mid-1990s. [21]

Around 2000, the National Institute of Science and Technology (NIST) started an extensive investigation of IC. Since then, IC has been widely investigated with well over 100 papers published to date. One recent significant report, "Internal Curing: A 2010 State-of-the-Art Review," by Bentz and Weiss[4] covers the subject in depth.

INTERNAL CURING MIXTURE DESIGN

Generally, autogenous stress development is not considered a concern at w/cm above 0.42[9]. However, internally cured concrete has shown decreased chloride permeability at w/cm up to 0.55[22], and has shown to have increased degree of hydration results in mixtures with w/cm up to 0.45[6].

The IC mixture design is quite simple; typically, a fine LWA replaces a portion of the normalweight mixture's sand fraction. The finer grading provides a more even distribution of IC water than the same amount of water in coarse ESCS aggregate. In hardened concrete, water only travels a limited distance depending on age and w/cm; therefore, it's important the IC water is distributed as evenly as possible. Henkensiefken[23] showed that water from LWA can move 0.07 inches (1.8 mm) into the paste surrounding an aggregate particle. However, more recent research has shown that water from lightweight aggregates travels at least 0.12 inches (3.0 mm) into the paste[24]. In some mixtures, intermediate size aggregate may optimize total aggregate grading, as well as provide IC[14].

For most practical concrete applications, 7 lbs IC water/100 lbs cementing material (7 kg IC water / 100 kg cementing material) provides an appropriate value for the amount of IC moisture needed. This value is based on the work of Geiker et al. [25] who showed most cement have a chemical shrinkage of 7 ml / g of cement. However, the amount of IC water may be increased to accommodate evaporation, or to satisfy the higher internal curing water demand in mixtures with SCMs. The amount of wetted ESCS aggregate needed is based on the absorption and desorption properties of the aggregate being used, and the desired proportion of IC water.

Knowing the target amount of IC water needed and the aggregate's absorption and desorption, the amount of wetted ESCS aggregate can be determined through the use of ESCSI's "Guide for Concrete Mixture Designs using Wetted ESCS Lightweight Aggregates for Internal Curing,"[26] or "Mixture Proportioning for Internal Curing"[27].

INTERNAL CURING HELPS THE "SUSTAINABILITY" OF CONCRETE

Cusson et al.[28] studied the impact of internal curing on the service life of high-performance concrete (HPC) bridge decks by using deterministic analysis of analytical models to predict the times to onset of corrosion, onset of corrosion-induced damage, and failure of bridge decks. Three bridge deck designs were compared in severe environmental conditions: (1) normal concrete deck with 0.40 w/c; (2) HPC deck with SCM and 0.35 w/cm; and (3) HPC deck with SCM and internal curing at 0.35 w/cm. It was found that the use of HPC with SCM extended the service life 18 years compared to normal concrete and that HPC with SCM incorporating internal curing extended the service life of normal concrete bridge decks 41 years. The significant increase in service life using IC is mainly due to a significant reduction in the penetration rate of chlorides in concrete as a result of reduced early-age shrinkage cracking and reduced chloride diffusion.

When compared to normal concrete in bridge decks, Cusson et al. [28] estimated life-cycle cost reductions of 40% with conventional HPC and 63% reduction with internally cured HPC. This lower life-cycle cost is despite the fact that the in-place unit cost of internally cured HPC can be 4% higher than that of conventionally cured HPC, which in turn can be up to 33% higher than that of normal concrete. The lower cost is due to a longer predicted service life and less frequent maintenance activities, because the internally cured HPC bridge deck's lower permeability and fewer cracks.

Some additional cost, energy, and emissions will be associated with manufacturing ESCS lightweight aggregate, but these are lower than the savings realized due to its use. In general, 100 lbs (45kg) of ESCS generates about 18 lbs (8kg) of CO_2[29], which is roughly equivalent to the amount of CO_2 created by manufacturing 18 lbs (8kg) of portland cement. To determine the carbon footprint, each mixture needs to be individually evaluated based on the balance of CO_2 from cement reduction, increased SCM use and the potential increase in service life.

Through the use of IC, users of concrete structures as well as owners and the overall society will benefit for years to come with a more durable concrete that can have a longer service life[28]. This helps the economy by lowering the life-cycle cost of structures. The environment benefits from a more efficient use of cementing material and the potential for reducing the carbon footprint of a concrete mixture.

INTERNAL CURING PROJECTS

Since 2003, over 2 million yd^3 (1.5 million m^3) of internally cured normalweight concrete have been placed, including 1.3 million yd^3 (1.0 million m^3) of low slump pavements[30]. Some of the more recent projects that have incorporated wetted ESCS aggregates into a normalweight concrete mixture for the specific purpose of internal curing are provided below.

The Union Pacific Intermodal Terminal, Hutchins, TX[31]

The union pacific intermodal terminal project in Hutchins Texas, started in 2005, and incorporated over 250,000 yd^3 (190,000 m^3) of internally cured concrete. The mixture used 5 ft^3 (0.15 m^3) bulk volume of an ESCS intermediate grading (3/8 in. to No. 8) in each cubic yard of concrete to replace a portion of both the normalweight coarse and fine aggregate. This enhanced both the cementitious hydration and overall aggregate grading of the mixture, which resulted in the mitigation or elimination of plastic and drying shrinkage cracking. The average compressive strength gain was about 1000 psi (7 MPa) with a 200 lbs/yd^3 (120 kg /m^3) reduction in unit weight, which translates to 2000 lbs (900 kg) less weight per 10 yd^3 (7.6 m^3) load of concrete.

Texas State Highway SH 121[30]

Texas State Highway SH 121 incorporated 1300 yd^3 (1000 m^3)of internally cured concrete on one side of a 5 mile (8 km) section near Dallas in November 2006. A 500 ft (150 m) long section of continuously reinforced concrete pavement was evaluated for cracks on February 1, 2007, and again on September 11, 2007. The side with IC showed

21 cracks. In comparison, the normalweight control on the other side of the road showed 52 cracks. In addition, the crack width was considerably smaller on the side with the internally cured concrete.

New York State[30]

New York State has incorporated the use of wetted ESCS LWA fines into numerous bridge decks throughout the state. Thousands of yards of internally cured concrete were specified to reduce cracking associated with low permeability concrete that incorporated SCMs into the mixture. These structures are exposed to high traffic volumes and have high exposures to de-icing chemicals because of the severe climate.

The State of Indiana [30]

Indiana began their transition from IC laboratory research to the field testing with two bridge decks near Bloomington, cast in September 2010. The placement of the internally cured bridge deck is shown in Figure 3. The bridges had similar design and were constructed with the same methods and materials supplied from the same ready mix company. One of the bridge decks used non-internally cured, conventional, bridge deck concrete; while the other internally cured bridge deck had approximately 55% of the fine aggregate replaced with wetted lightweight aggregate. One finisher noted that the IC mixture was less "sticky" and easier to work with.

Test results showed similar compressive strengths at 10 days, and at 3 months the internally cured concrete was 20% stronger. Rapid chloride permeability results for the IC mixture was 10% lower at 28 days, and nearly 40% lower after 3 months. The internally cured mixture also showed lower drying shrinkage. It was also notable that cracks developed in the conventional deck after the first few months of service as illustrated in Figure 4, while at nearly one year after placement, the internally cured concrete has no visible cracking as illustrated in Figure 5.

Figure 3—Placement of internally cured bridge deck concrete near Bloomington IN[30]

Figure 4—Cracking in conventional concrete bridge deck after 3 months of service[30]

Figure 5—Internall cured bridge deck with no observed cracks after 1 year of service[30]

SUMMARY

The goal of internal curing is to provide additional curing water with a proper spatial distribution, so that the entire three-dimensional microstructure of hydrating cementitious paste remains saturated and autogenous stress free[4]. Internal curing reduces or eliminates early-age cracking of the concrete and promotes increased of hydration of cementing materials, contributing to increased strength, and reduced transport coefficients. All of which helps concrete achieve its maximum potential as a sustainable building material by extending its service life and improving the economical, environmental, and social aspects of the concrete industry.

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