

Internal Curing with Lightweight Aggregate: The Common Sense Contribution to Sustainable Concrete Pavements

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Abstract: Internal Curing (IC) has been used in concrete for more than 100 years in which the main usage of lightweight aggregate (LWA) was to decrease the density of the concrete. However, over the last decade, the research community has observed additional benefits of IC. This paper summarizes the main benefits obtained when using IC in normalweight concrete, with the final purpose of enhancing its durability by means of reducing shrinkage cracking and fluid transport properties while maintaining strength. At the same time it improves the aggregate-paste interface and the cement hydration, making more efficient use of the cement. More durable concrete infrastructures are expected, yielding more sustainable solutions. Lightweight aggregates are typically used for providing IC in concrete. Even though lightweight aggregates require energy to manufacture, when evaluated from a lifecycle perspective the overall economical and environmental impact of a pavement or structure is almost always lowered. The recent Auburn University and Purdue University research indicating reduced micro cracking and shrinkage, and increased 'reserve capacity' for temperature effects during construction will also be covered, with examples of how this research is being tested in real world concrete pavements and structures. Real projects will then be presented that show how internal curing improves concrete pavement performance.

Introduction

Internal curing (IC) is a re-emerging age-old technology that adds a common sense approach to the sustainability of concrete pavements. The use of wetted Expanded Shale Clay and Slate (ESCS) lightweight aggregate for IC helps to reduce early-age cracking and chloride ingress, and to increase the service life of concrete pavements. Increasing the service life is a key factor in providing sustainable structures; therefore IC can contribute positively to sustainability.

Internally cured concrete is not a new process; some might even say it is ancient since it can be considered to date back to concrete constructed during the Roman Empire. What is new, however, is a more complete understanding of how IC works and why IC increases the durability and service life of concrete in an economical and practical way.

While IC occurs automatically when wetted ESCS is used in conventional concrete to lower its density, it is only within the last decade that IC has been intentionally incorporated into normal weight concrete to improve its properties and performance (Hoff 2002, RILEM 2007, Bentz and Weiss 2010).

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Internal Curing

Internal Curing is a practical way of supplying additional curing water throughout the concrete mixture. This is done by using water absorbed in ESCS lightweight aggregate that replaces some of the conventional aggregate in the mixture. IC is often referred to as “curing concrete from the inside out”. This concept is illustrated in Figure 1, where conventional (external) curing can only provide water to a few mm of paste from the top surface (especially in high quality concrete), whereas IC enables the water to be distributed more equally.

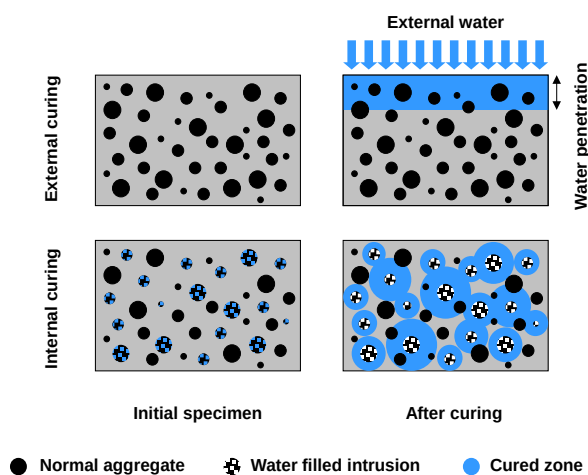


Fig 1. Conceptual difference between external and internal curing (Castro et al. 2010)

IC provides something that most concretes need and conventional curing cannot provide: additional curing water (without increasing the w/cm ratio) to help complete hydration of cementitious materials throughout the concrete. Although IC has shown benefits at water-to cementitious materials ratio (w/cm) up to 0.55, the need for IC increases as the w/cm is lowered, due to the smaller quantity of water present in the mixture and a tighter microstructure formed. Research shows that even in moderate w/cm (0.40 to 0.46) mixtures, the hydration and reaction are often not nearly complete, even after many months (Espinoza-Hijazin et al. 2010).

IC has been shown to work well with supplementary cementitious materials (SCMs) such as fly ash or slag (De la Varga et al. 2012), especially at higher dosage levels since these materials have increased water demand during their reaction, compared to portland cement (Bentz and Weiss 2010).

The use of IC is not intended to replace conventional surface curing, but to work with it to provide more complete curing. IC can help in compensating for less than ideal weather conditions and poor conventional curing that is often seen in the real world.

The underlying theory and goal of Internal Curing

The need for IC emanates directly from the basic nature of cement hydration reactions. Chemical shrinkage occurs when cement reacts with water and the reacted products occupy a smaller volume than the initial constituents [Le Chatelier 1900]. In fluid systems (e.g., prior to set), this chemical shrinkage does not cause much concern as the entire system collapses on itself resulting in an externally measured volume change that is equal to the chemical shrinkage. However, after the concrete begins to harden, the structure of the cementitious matrix does not enable the externally measured volume change to be equal to the volume of chemical shrinkage [Sant et al.

2006]. As a result, vapor filled spaces are created within the matrix and stress begins to develop in the hardening paste [Jensen et al. 2001]. This is commonly referred to as self-desiccation (i.e., internal drying). This ‘internal drying’ cannot be completely mitigated through the use of additional water during external curing. IC provides readily available additional water throughout the concrete, allowing the pores to remain saturated, and minimizing stress and strain development. This reduces or eliminates early-age cracking of the concrete and promotes maximization of the hydration of cement, potentially contributing to increased strength and reduced transport coefficients. The goal of internal curing is to provide additional water in the proper amount at the proper time and with the proper spatial distribution so that the entire three-dimensional microstructure of hydrating cement paste remains saturated and autogenous stress free (Bentz and Weiss 2010).

The benefits of using internal curing

IC provides several benefits and some of them have already been mentioned. The next section briefly explains these benefits.

Increase in the hydration reaction

The main benefit of using IC is the provision of more available water for curing and further hydration. The fact that the curing water is provided from the inside makes it easier to achieve a better and more homogeneous curing throughout the matrix. Some techniques have been used to show how the curing water moves from the lightweight aggregate to the matrix (Trick et al. 2011, [Henkensiefken et al. 2009](#)). This effect will help to increase the degree of reaction (i.e. degree of hydration) of the cement particles (Castro 2011, De la Varga et al. 2012). Figure 2 shows the measurement of the degree of hydration via isothermal calorimetry in mortars containing fly ash with three levels of IC (0 %, 50 %, and 100 %). These levels refer to the volume of chemical shrinkage that is intended to be replaced with internal curing water. This is explained in more detail in the “Mixture Design” section. As mentioned above, IC can be used in mixtures containing supplementary cementitious materials, and, in fact, will be more beneficial since it provides water for longer times, and this is exactly what these “slower-reacting” materials need. It can be observed in Figure 2 how the extra hydration due to IC is apparent after 4 days and continues to increase throughout the 14-day testing period. “LWA” stands for lightweight aggregate.

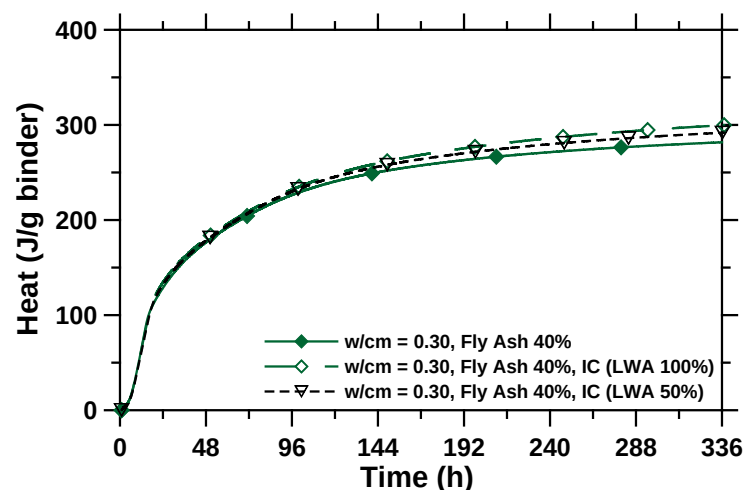


Fig 2. Effect of changing IC replacement level on the degree of hydration (De la Varga et al. 2012)

This further cement hydration contributes to a better (or more optimized) use of the cement, allowing it to maintain (and sometime increase, as it can be observed in Figure 3) the strength values despite of using a lower density material.

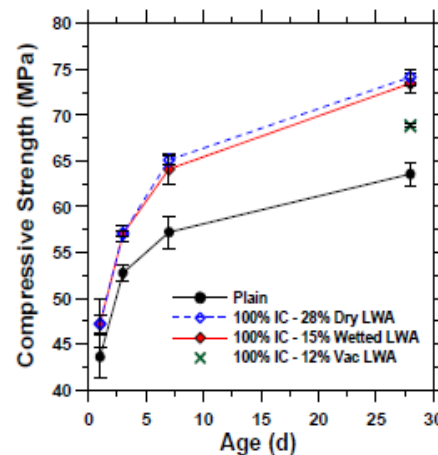


Fig 3. Effect of providing IC on the strength development of mortar mixtures (Golias 2010)

Less cracking and lower transport properties

The additional and more uniformly distributed curing water provided by IC will minimize the internal autogenous stresses due to self-desiccation, resulting in less early-age shrinkage (i.e. less early-age cracking) and lower fluid transport properties. Figure 4 shows how the autogenous shrinkage is considerably decreased when IC is included (the samples even depict net expansion).

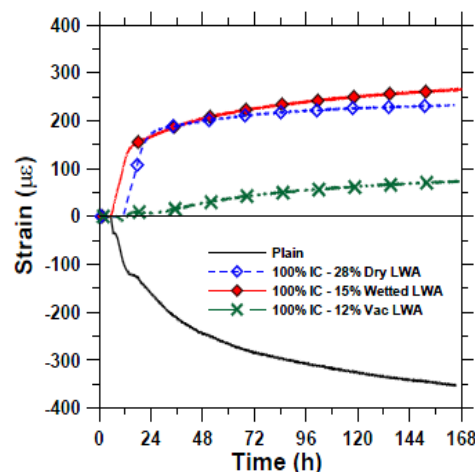


Fig 4. Autogenous shrinkage measurements in internally-cured mortars containing different types of lightweight aggregates (Golias 2010)

Byard and Schindler (2010) studied the effect of using lightweight aggregate on the cracking tendency of bridge deck concrete by cracking frame testing techniques. Cracking frames measure the development of stresses due to thermal and autogenous shrinkage effects from setting until the onset of cracking. In this study, ESCS coarse and fine aggregates were used to provide IC. Both sand-lightweight and all-lightweight concretes were prepared to compare their behavior relative to a normal weight concrete in a bridge deck application. Specimens were tested under isothermal

curing conditions and match-cured conditions that simulate summer and fall placement scenarios (see Figures 5 and 6) (Byard and Schindler, 2010).

The results showed that increasing the amount of pre-wetted lightweight aggregate in the concrete systematically decreases the density, modulus of elasticity, coefficient of thermal expansion, and thermal diffusivity of the concrete. The use of pre-wetted lightweight aggregates in concrete can reduce or eliminate the stress development caused by autogenous shrinkage (Figure 6). The decrease in autogenous stresses is due to internal curing, because water is desorbed from the lightweight aggregates to fill capillary voids formed by chemical shrinkage. When compared to a normalweight control concrete, the use of lightweight aggregates delays the occurrence of cracking at early ages in bridge deck applications (Figure 5).

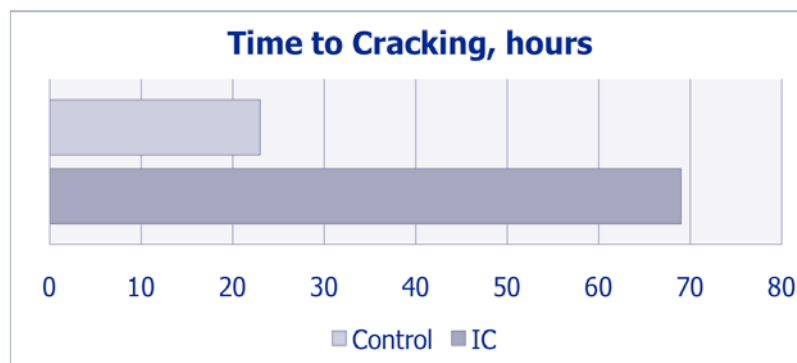


Fig 5, Summer curing temperature profile for IC mixture compared to control at 0.42 w/c. (Byard and Schindler 2010)

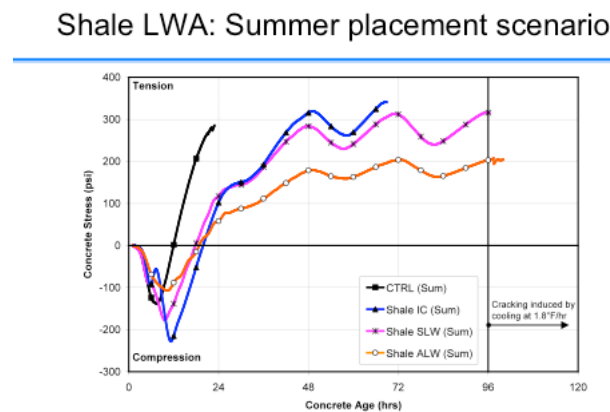


Fig 6. Restrained stress development for IC and control mixture for the Summer placement scenario (Byard and Schindler 2010)

The effect on fluid transport properties can be shown by measuring the electrical conductivity through the concrete. Figure 7 shows the reduced conductivity at 1-year for non-sealed ('real world') conditions. Both the 0.30 and 0.42 w/c mixtures show that IC results in a reduction of the measured conductivity (Henkensiefken et al. 2009a). This effect is also explained by the fact that more hydration products are formed (see previous section) yielding a finer and less conductive microstructure.

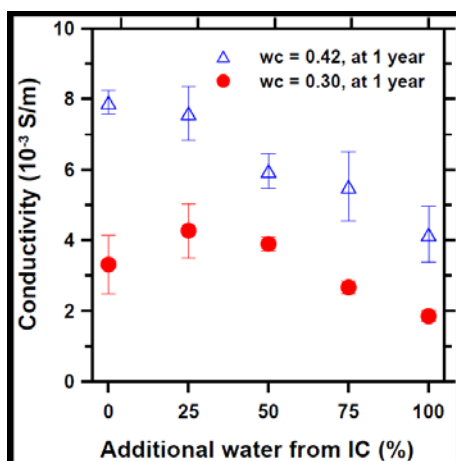


Fig 7. The improved hydration shown by the reduced conductivity at 1 year for real world conditions. (Henkensiefken et al. 2009a)

Permeability investigations conducted on lightweight and normalweight concrete exposed to the same testing criteria have been reported by numerous researchers, Nishi et al. (1980), Keeton (1970), Bamforth (1987), and Bremner et al. (1992). It is of interest that, in every case, despite wide variations in concrete strengths, testing media (water, gas, and oil), and testing techniques (specimen size, media pressure, and equipment), lightweight concrete had equal or significantly lower permeability than its normalweight counterpart. Khokrin (1973) further reported that the lower permeability of lightweight concrete was attributed to the elastic compatibility of the constituents and the enhanced bond between the lightweight aggregate and the mortar matrix.

Aggregate-Paste interface/Elastic Compatibility

It is well recognized that cracks initiate at 'weak points' within the matrix. The aggregate-paste interface is one of these points due to stress concentrations resulting from the difference in modulus of elasticity between the two phases. Furthermore, these regions are normally more porous due to the presence of Ca(OH)_2 , a porous cement hydration product that does not contribute to strength development (Mindess 1981).

The aggregate-paste interface is commonly referred as Interfacial Transition Zone (ITZ). One principal difference between ESCS lightweight aggregate and normal weight aggregate is the positive influence on the ITZ that lightweight aggregate provides. The ITZ with the ESCS is an interface between two porous media: the lightweight aggregate particle and the hydrating cementitious binder, and has been demonstrated to be significantly superior to that of normal weight aggregate (see Figure 8, ESCSI July 2006). This improvement in the microstructure of the ITZ results in reduced microcracking at the aggregate-cement interface because of the similarity of the modulus of elasticity of the ESCS aggregate and the surrounding cementitious matrix (Zhang 1990). Additionally, the ITZ is less porous due to the presence of more water (water provided by the lightweight aggregate) than in other regions. This enhances the formation of hydration products from the reaction of the silicates present on the surface of the fired ceramic ESCS aggregate with the Ca(OH)_2 formed from the cement hydration and deposited on the aggregate surface (Holm 1984). Peled et al. (2010) used an Atomic Force Microscope (AFM) to measure the type of ITZ present when IC is included. They concluded that less porosity is observed in these regions due to more complete hydration.

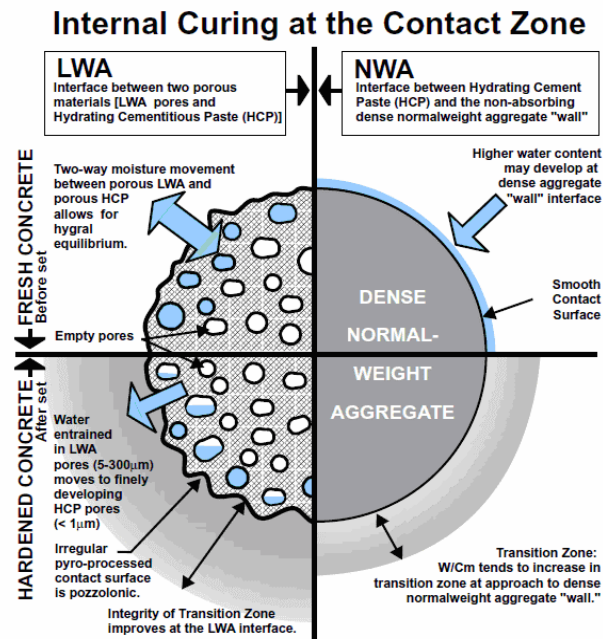


Fig 8. Internal Curing at the Contact Zone or ITZ (ESCSI July 2006)

It is well known that lightweight aggregate concretes exhibit lower elastic moduli than normal aggregate concretes, which yields a higher strength/moduli ratio (Holm 1984, Raoufi et al.). This means that a higher ultimate strain capacity (the strain at which disruptive dilation of concrete starts) is also provided by lightweight concrete.

The improved ITZ and strain compatibility are key factors in the freeze-thaw durability of lightweight aggregate concrete that has been demonstrated at the Treat Island facility (Thomas et al, 2011).

IC Mixture Design

The aggregate size used for IC is normally a fine grading that replaces a portion of the normal weight mixture's sand fraction. The fine grading provides a more even distribution of the IC water throughout the cementitious paste (Bentz and Weiss 2010). The same amount of water concentrated only in coarse ESCS aggregate can leave part of the cementitious paste "unavailable" for IC since the water will only travel several millimeters during hydration. Depending on the total aggregate grading, intermediate size aggregate may be used to optimize aggregate grading as well as provide IC.

The amount of wetted ESCS aggregate needed is based on the volume of chemical shrinkage created by self-desiccation that is intended to be filled with water. For most practical concrete applications, it has been observed that 7 lbs IC water/ 100 lbs cementitious provides an appropriate value for the amount of IC moisture needed (Bentz et al 2011, ESCSI 2011). Since SCMs like fly ash and slag are known to have higher water demand during their reaction, additional IC water may be required for mixtures containing high volumes of SCM.

Bentz et al [2005] developed an equation for calculating the amount of lightweight aggregate needed to provide the required amount of IC water, based on the aggregate properties, the cement content and the w/cm ratio. In some applications it may be reasonable to do trial mixes with varying dosages of IC aggregate above and below the 7 lb value to determine a three-point curve for optimum performance.

Another reference for practical calculation of the amount of ESCS aggregate

needed is the *Guide for Concrete Mixture Designs using Prewetted ESCS Lightweight Aggregates for Internal Curing* (ESCSI 2011).

ESCS lightweight aggregate

ESCS is a manufactured ceramic aggregate produced by expanding and vitrifying shale, clay or slate in a rotary kiln. The process produces a porous, low density yet strong durable aggregate that is dimensionally stable over time. ESCS contain a uniformly distributed system of pores that have a size range of approximately 5 to 300 μ m, developed in a continuous, relatively crack-free, high-strength vitreous phase. Pores close to the surface are readily permeable and can be filled with water within the first few hours to a few days of exposure to moisture. Interior pores, however, are filled extremely slowly, with many months of submersion required to approach saturation. Interior pores are essentially non-interconnected and a small fraction remains unfilled after years of immersion (ACI 213R-03).

The IC performance of a lightweight aggregate is determined not only by its absorption properties, but also by its desorption behavior. Desorption is a measure of how readily the lightweight aggregate will release its pre-absorbed water into the cement paste. The size of the pores of an ESCS particle, while very small, is much larger than the pores within the cement paste. As a result, research has shown that ESCS will release over 85% of its absorbed water at internal relative humidity of 94% or higher (Castro et al. 2011). Figure 9 shows this effect comparing the ESCS (desirable behavior) with non-ESCS lightweight aggregate exhibiting ‘undesirable-desorption’ properties.

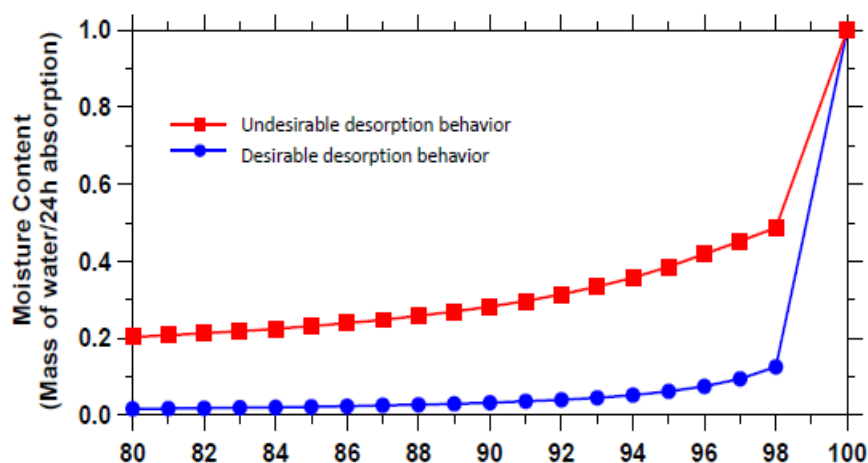


Fig 9. Desirable and undesirable aggregate behavior (Castro et al. 2011)

How internal curing contributes to sustainability

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 lb of ESCS generates about 18 lbs of CO₂ (ESCSI 2006), which is roughly equivalent to the amount of CO₂ to manufacture 18 lbs of portland cement.

The energy required to produce:

- Crushed stone is about 70,000 Btu/ton (Nisbet et al, 2000)
- Sand and gravel is about 40,000 Btu/ton (Nisbet et al, 2000)
- ESCS is about 2.16 MBtu/ton or 1.34 MBtu/cy. One ton of ESCS is about twice the volume of one ton of normal weight aggregate(ESCSI 2006).

Considering the significant potential to increase the service life of the concrete, reduce the amount of cement, and increase the potential for the use of SCM, internal curing is a practical way to increase the sustainability of concrete. However the carbon footprint for each mixture must be individually evaluated based on the balance of CO₂ from cement reduction, increased SCM use, and the potential increase in service life.

Cusson, Lounis, and Daigle studied the impact of internal curing on the service life of three bridge deck designs in severe environmental conditions using analytical models. A normal concrete deck, a HPC deck with SCM, and a HPC deck with SCM and IC were compared. It was found that the HPC with SCM and IC extend the service life by more than 20 years when compared with the HPC with SCM mixture and by more than 40 years when compared with the normal concrete. This was mainly due to a significant reduction in the rate of penetration of chlorides as a result of reduced early-age shrinkage cracking and reduced chloride diffusion. Life-cycle cost reductions of 40% and 63% were estimated when conventional HPC with SCM and internally cured HPC with SCM were used in bridge decks instead of normal concrete, respectively. This life-cycle cost savings is realized despite the fact that the in place unit cost of internally-cured HPC is 4% higher than that of conventionally cured HPC with SCM and over 30% higher than normal concrete decks (Cusson 2010).

According to Henkensiefken et al. (2009), IC has the potential to contribute to a more sustainable infrastructure in a variety of ways. For example, IC with blends of LWA and Crushed Concrete Aggregate may provide cost-effective sustainable materials with significant reductions in autogenous shrinkage and early-age cracking, without sacrificing strength. IC not only contributes to a more efficient cement hydration, but also promotes enhanced performance of SCMs such as fly ash and slag, both seen as major material sources for “greener” more sustainable concretes. The use of IC can substantially reduce transport properties such as diffusion and sorptivity, thereby increasing the service life of concrete structures. In addition, the enhanced hydration and increased strengths provided by IC may allow for small but significant reductions in cement content in many concrete mixtures.

Recent projects where IC has been used

Although the concept of IC maybe new to many in the concrete industry, it is an automatic side benefit anytime prewetted ESCS is incorporated in a concrete mixture. IC has been included in thousands of projects over the last 90 years. Since 2003 over 2,000,000 CY of internally cured normal weight concrete mixture with 1.3 million in low slump pavements have been placed (ESCSI 2012).

Some of the benefits reported from contractors in Texas, Indiana, and New York are that IC helps compensate for poor jobsite curing as well as supporting proper curing. IC mixtures can tolerate higher curing temperatures without cracking or losing strength. Lower concrete density may reduce design loads and transportation costs. Also improved workability and finishability has been noticed because the additional IC water helps to eliminate some of the ‘sticky’ properties commonly found in concrete’s utilizing SCMs.

Some of the more recent projects that have incorporated wetted ESCS into a normal weight concrete mixture for the specific purpose of internal curing are:

The Union Pacific Intermodal, Hutchins, TX facility started in 2005 and incorporated over 250,000 yd³ (190,000 m³) of internally cured concrete. The mixture used 5 ft³

(loose) per yd^3 of concrete, of an ESCS intermediate grading (3/8 in. to No. 8) that replaced a portion of both the normal weight coarse and fine aggregate to enhance the cementitious hydration as well as the total aggregate grading of the mixture. The average strength gain was about 1000 psi with a 200 lbs/yd^3 reduction in density, which translates to 2000 lbs per 10 yd^3 load of concrete. (Villarreal et al. 2007) In contrast to conventional paving mixtures, cracking was extremely minimal and a visual inspection after 6 months in service only found one crack. (Villarreal 2008)

Texas State Highway SH 121 incorporated 1300 yd^3 of internally cured concrete on one side of a 5 mile section near Dallas, Texas in November 2006. A 500 ft long section of continuously reinforced concrete pavement was evaluated for cracks on February 1 and September 11, of 2007. The side with IC showed 21 cracks, in comparison to the normal weight control on the other side of the road that showed 52 cracks. In addition the crack width was considerable smaller on the side with the IC concrete. The concrete incorporated 300 lb/yd^3 (178 kg/m^3) of pre-wetted intermediate size ESCS. The concrete was Class P (3500 psi or 570 psi flex at 7 days).

New York State has incorporated the use of prewetted lightweight ESCS fines into numerous bridge decks throughout the state. Thousands of yards of internally cured concrete (ICC) 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 sever climate.

In general the field evaluation of the New York State ICC when compared to similar HP bridges has shown to reduce cracking associated with concrete shrinkage but has not eliminated all deck cracking. The ICC presented no problems to concrete suppliers when batching concrete or to contractors placing and finishing concrete on bridges.

Some of the bridges were compared with similar HP bridges without IC constructed by the same contractor at about the same time in the same general area using the same materials. The ICC used about 250 pounds of wetted ESCS at 22% moisture. The ICC had equal to higher strengths even though it had about a 5 lbs/cf lower density and on some occasions higher air content and higher slump.

The recent history and development of internal curing

The fact that absorbed moisture in the ESCS is available for internal curing has been known for more than five decades. The first documentation of improved long term strength gains ,was reported in 1957 by Paul Klieger, who wrote "*Lightweight aggregates absorb considerable water during mixing which apparently can transfer to the paste during hydration*". (Klieger, 1957). In addition, he commented in detail on the role of absorbed water in lightweight aggregates for extended internal curing. This was confirmed in 1967 by a comprehensive program (Campbell and Tobin) that showed the availability of absorbed moisture in lightweight aggregate produced a more forgiving concrete that was less sensitive to poor field curing conditions.

In the early 1990's the benefits of internal curing came to the concrete industry forefront with Robert Philleo stating, "*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” (Philleo, 1991).

Structural lightweight aggregate was used on the Hibernia Offshore Platform in Newfoundland, Canada, to improve buoyancy by replacing 50% of the coarse aggregate with prewetted ESCS. The benefits of internal curing quickly became apparent on this high profile project (10,000psi+), which spawned new research on the subject in the mid 1990's. Around the year 2000 the National Institute of Science and Technology (NIST) started investigating the subject.

Since then internal curing has been widely investigated with well over 100 published papers to date. One recent significant report, *Internal Curing: A 2010 State-of-the-Art Review* by Bentz and Weiss covers the subject in depth. (Bentz 2010)

Conclusion

Research shows that the use of wetted ESCS for IC can contribute to sustainable development by substantially improving the performance of normalweight concrete. IC improves cement hydration and SCM reactions. Internally cured concrete pavements and bridge decks benefit from reduced cracking, reduced chloride ingress and increased service life. These benefits have been shown in this paper using studies performed at Auburn University and Purdue University.

Internal curing is a helpful tool however it cannot be expected to replace or make up for deficiencies in sound structural design and good construction practices. It should be used in combination with other techniques such as gradation optimization and the use of SCMs to improve concrete. Internally cured concrete does not replace surface curing but it may be especially helpful in concrete that is exposed to poor curing conditions such as concrete pavements.

The better understanding of how IC works has made possible its acceptance as a new technology that holds promise for producing concrete with enhanced durability and longer service life, thereby providing a positive contribution to increasing the sustainability of our nation's infrastructure.

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