Impacts of Internal Curing on Concrete Properties

Literature Review
January 2015

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16. Abstract

Conventional concrete is typically cured using external methods. External curing prevents drying of the surface, allows the mixture to stay warm and moist, and results in continued cement hydration (Taylor 2014). Internal curing is a relatively recent technique that has been developed to prolong cement hydration by providing internal water reservoirs in a concrete mixture that do not adversely affect the concrete mixture's fresh or hardened physical properties. Internal curing grew out of the need for more durable structural concretes that were resistant to shrinkage cracking.

Joint spacing for concrete overlays can be increased if slab warping is reduced or eliminated. One of the most promising potential benefits from using internal curing for concrete overlays, then, is the reduced number of joints due to increased joint spacing (Wei and Hansen 2008).

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IMPACTS OF INTERNAL CURING ON CONCRETE PROPERTIES

Literature Review
January 2015

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BACKGROUND

Concrete curing is necessary for one reason: cement hydration. Cement hydration is a series of chemical reactions that require an adequate water supply and proper temperatures over an extended time period (Taylor 2014). Curing is defined as "action taken to maintain moisture and temperature conditions in a freshly placed cementitious mixture to allow hydraulic cement hydration and (if applicable) pozzolanic reactions to occur so that the potential properties of the mixture may develop" (ACI 2013).

Conventional concrete is typically cured using external methods. External curing prevents drying of the surface, allows the mixture to stay warm and moist, and results in continued cement hydration (Taylor 2014). Internal curing is a relatively recent technique that has been developed to prolong cement hydration by providing internal water reservoirs in a concrete mixture that do not adversely affect the concrete mixture's fresh or hardened physical properties. Internal curing grew out of the need for more durable structural concretes that were resistant to shrinkage cracking.

High-performance concrete mixtures were developed due to a growing focus on durability (Hoff 2002) and are created by the use of lower water-cementitious materials (w/cm) ratios, chemical admixtures, and supplementary cementitious materials (SCMs). However, achieving such performance can only be achieved if the cementitious system is well hydrated, meaning that it has to be well cured (Meeks et al. 1999).

If a concrete mixture is well cured, a benefit of using SCMs is decreased permeability (ACI [308-213]R-13 2013), especially at later ages. However, decreased permeability means that external curing is not as effective because the water cannot penetrate the system (Powers et al. 1959).

Low w/cm ratio concrete mixtures, those with w/cm ratios less than about 0.42, do not have enough water to fully hydrate the cement in the mixture (Neville 1996). According to Byard and Schindler (2010), as the cement in a concrete mixture hydrates, water in the capillary pores is consumed. This process decreases relative humidity in the mixture and increases internal stresses, resulting in an increased risk of drying shrinkage and cracking (ACI [308-213]R-13 2013).

To reduce the risk of drying shrinkage, it is necessary to mitigate the decrease in relative humidity in the mixture during hydration (Bentur et al. 2001). External curing does not meet this need because water cannot penetrate the full thickness of the element but is confined to a surface layer estimated to be about 1 in. thick at best. Moisture gradients can therefore develop in a concrete mixture as it hydrates (Mukhopadhyay et al. 2006), resulting in warping of pavements (Jeong and Zollinger 2004).

In the late 1950s and 1960s, the benefit of internal curing from absorbed moisture in lightweight aggregate (LWA) was identified by pre-stressed concrete researchers (Campbell and Tobin 1967, Jones and Stephenson 1957, Klieger 1957). The concept of internal curing resurfaced in the 1990s when Philleo (1991) proposed the use of saturated lightweight fine aggregate in concrete mixtures to provide water to replace that depleted during cement hydration (Philleo 1991).

Internal curing decreases the risk of cracking by providing additional water to a concrete mixture for the purpose of prolonged cement hydration without affecting the w/cm ratio (Delatte and Cleary 2008). Wei and Hansen (2008) have shown that warping in slabs on grade can be significantly reduced using internal curing (IC) concrete mixtures at w/cm ratios similar to those typically used for pavements.

According to Byard and Schindler (2010), internal curing can be provided by highly absorptive materials that will readily desorb water into the cement pore structure. This will reduce capillary stresses and provide additional water for cement hydration. Materials that may be used for internal curing include LWA, super absorbent particles (SAP), perlite, and wood pulp. SAP, perlite, and wood pulp do not provide structural capacity to the concrete mixture, while LWA does (Byard and Schindler 2010).

HOW INTERNAL CURING WORKS

Internal curing is affected by three key items: the volume of water needed from the LWA, the desorption properties of the LWA, and the spacing of the LWA within the mixture (Henkensiefken 2009).

Volume of Water Needed for Internal Curing

The amount of water that is needed from the LWA for internal curing is dictated by two measurable elements: chemical shrinkage and autogenous shrinkage (Henkensiefken et al. 2009).

Chemical Shrinkage

Chemical shrinkage can be described as the change in total internal volume as cement hydrates (Jensen and Hansen 2001). Chemical shrinkage is considered to be caused by two mechanisms: one is that the volume of hydration products is less than the volume of reagents, and the other is due to desiccation as water is consumed in the hydration process. Self-desiccation leaves behind pores filled with vapor rather than water (Bentz and Snyder 1999). The drying pores left behind by self-desiccation set up shrinkage stresses and slow down and/or hinder hydration (Persson 1997). According to Streeter et al. (2012), water in the capillary pores that was consumed by self-desiccation can be replaced by water absorbed from moist external curing. However, low-permeability mixtures do not allow external water to be transported through the system.

Autogenous Shrinkage

Autogenous shrinkage can be described as the measurable change in external volume of a concrete mixture due to chemical shrinkage (Jensen and Hansen 2001). The difference between chemical shrinkage and measured autogenous shrinkage is a result of the formation of microcracking within the system.

The volume of chemical shrinkage and autogenous shrinkage are equal prior to set. After set, the volumes differ significantly. Once a mixture has set, the external volume is restrained and cannot change equivalently with the chemical shrinkage (Henkensiefken et al. 2009). According to Henkensiefken et al. (2009), the amount of additional curing water necessary is that represented by the difference between the chemical and autogenous shrinkage (Henkensiefken et al. 2009).

Desorption Capability of the LWA

As the cement paste hydrates and self-desiccates, a decrease in pressure occurs in the capillary pores. This decrease in pressure creates suction that pulls water out of the saturated LWA into the cement paste. The majority of the water in the saturated LWA should be released at a relative humidity of 96%. Almost all of the water should be released when the relative humidity reaches 92% (Henkensiefken et al. 2009). Figure 1 illustrates the desorption process.

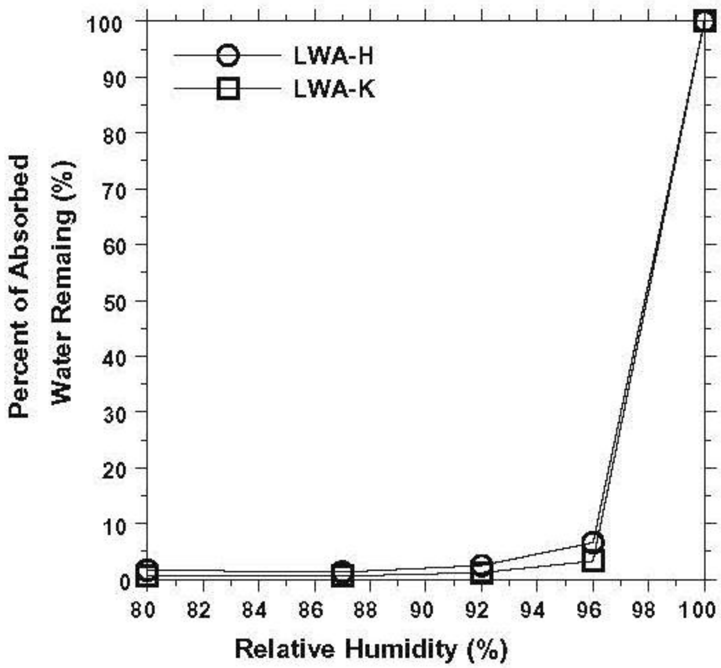


Figure 1. Desorption isotherm of two different lightweight aggregates

Spacing of the LWA

Even if an adequate amount of water is supplied by the saturated LWA, it must be well distributed in the mixture to protect all of the paste. The required spacing of the LWA is determined by the ability of water to travel through the hydrating mixture. Henkensiefken et al. (2009) used the hard core/soft shell model developed by the National Institute of Standards and Technology to simulate the effect of varying LWA replacement volumes on protected paste volume. Their results showed that by using low LWA replacement volumes, most of the paste could be protected if the available water in the LWA could travel 1.0 mm. Their simulations also showed that higher LWA replacement rates could provide protected paste within 0.20 mm of the LWA. Therefore, if a mixture is highly impermeable, a higher LWA replacement volume is necessary to achieve proper spacing and provide adequate water to the mixture.

EFFECTS OF INTERNAL CURING

Strength

Compressive Strength

One of the factors designers, contractors, and owners are concerned about is the compressive strength of the mixture. Test data from Cusson and Hoogeveen (2008) showed that internally cured concrete using varying amounts of saturated LWA significantly reduced autogenous shrinkage without affecting the strength or elastic modulus of the concrete. This was accomplished using a total w/cm ratio of 0.34 for all four mixtures and reducing the amount of mix water by the amount of water supplied by the LWA to reduce the effective w/cm ratio.

The New York State Department of Transportation (NYSDOT) constructed a series of bridges from 2009 to 2011 using LWA for internal curing (Streeter et al. 2012). The mix designs for the bridges specified a 30% LWA replacement (by volume) and a w/cm ratio of 0.40. Table 1, using data from the report by Streeter et al. (2012), shows that internal curing either had a negligible effect on strength or resulted in higher strengths.

Table 1. Concrete properties for NYSDOT bridges

		7-Day Strength (psi)		**28-Day Strength (psi)**		**56-Day Strength (psi)**	
Highway	**Feature Spanned**	**Control**	**IC**	**Control**	**IC**	**Control**	**IC**
I-81	East Hill Road	3720	3335	5040	5273	5900	5853
I-290 Ramp D	I-290	3040	3500	4677	4683	5343	5417
Court Street	I-81	4727	4859	6309	6976	nd	nd

Note: nd = no data

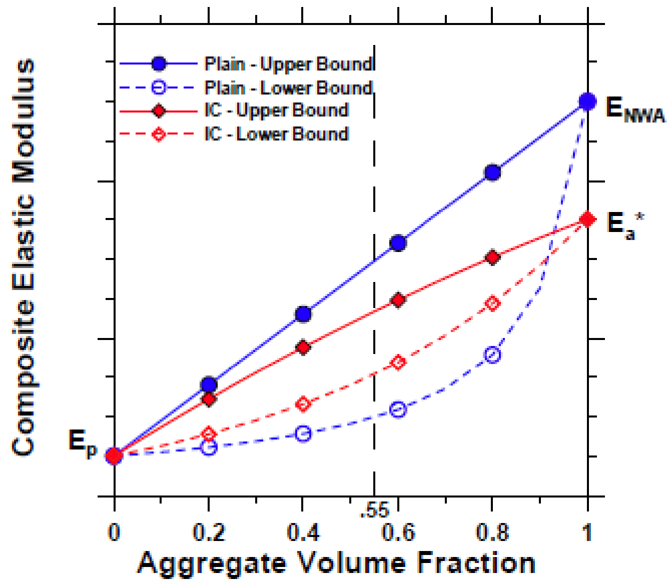
Byard and Schindler (2010) used different LWAs (i.e., shale, clay, and slate) to produce internally cured concrete mixtures that exhibited similar or higher compressive strengths when compared to normal concrete. These results were produced using a w/cm ratio of 0.42 (Byard and Schindler 2010).

Flexural Strength

Roberts (2004, 2005) showed an improvement in 3-day and 28-day flexural strength results in internally cured concrete compared to control mixtures. The studies used a w/cm ratio of 0.44 for both mixtures and 100 lb./yd.^{3} saturated LWA substitution for the internally cured mixture.

Modulus of Elasticity

The stiffness of the aggregates in concrete mixture directly impact its modulus of elasticity (Mehta and Monteiro 2006). The effects of IC on elastic modulus is shown in Figure 2 (Golias 2010). A study by Golias (2010) used control and IC mixtures with w/cm ratios of 0.30 and 0.50 and respective fine aggregate replacement rates of 28% and 25%. These test results showed an elastic modulus reduction when compared to the control mixtures. This may be beneficial because it will lead to reduced stresses under shrinkage strains (Shah and Weiss 2000).



Source: Golias 2010

Figure 2. Effect of internal curing on predicted modulus of elasticity

Byard and Schindler (2010) also tested IC concrete mixtures using different LWAs. These test results also showed an elastic modulus reduction for IC mixtures.

The reduction of the elastic modulus is due to the use of LWA, which has a lower stiffness than the normal weight aggregate due to its increased porosity (Byard and Schindler 2010). Equation (1) (ACI 318 2008) estimates modulus of elasticity using known densities and compressive strengths. Equation (1) also shows that increased LWA replacement will reduce the modulus of elasticity.

$$E_c = 33 w_c^{1.5} \sqrt{f_c} \quad \textbf{(1)}$$

where,

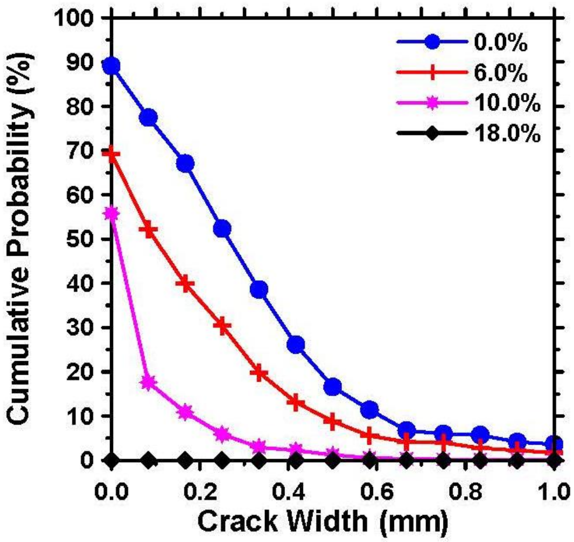
- E_c = modulus of elasticity (lb./in.^{2}),
- w_c = density of normal concrete or equilibrium density of lightweight concrete (lb./ft.^{3}), and
- f_c = concrete compressive strength (psi).

The results of the Golias (2010) study also imply that a reduction in w/cm ratio will yield a greater effect of the aggregate stiffness on the overall stiffness of the mixture.

Shrinkage

Plastic Shrinkage

Internally cured mortar mixtures using saturated LWA can significantly reduce or eliminate plastic shrinkage. As shown in Figure 3 (Schlitter et al. 2010), the probability of plastic shrinkage cracking decreases as the volume of LWA replacement increases. Plastic shrinkage cracks can be eliminated if an adequate LWA replacement quantity is used.



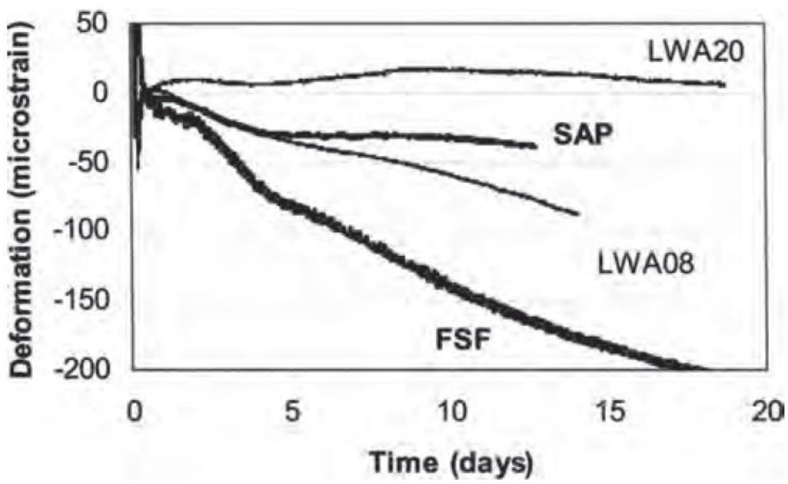
Source: Schlitter et al. 2010

Figure 3. Cumulative distribution of crack width occurrences in concrete with different replacement volumes of LWA

Autogenous Shrinkage

One of the original uses investigated for internal curing was the reduction of autogenous shrinkage in low w/cm ratio concrete mixtures. Bentur et al. demonstrated that a 25% substitution of saturated LWA was able to eliminate autogenous shrinkage (Bentur et al. 2001).

Figure 4 shows the autogenous shrinkage for mortars containing different prewetted absorbent materials (Geiker et al. 2004). A 20% substitution of saturated LWA was effective in eliminating autogenous shrinkage.



Source: Geiker et al. 2004

Figure 4. Autogenous shrinkage for mortars containing different prewetted absorbent materials, all cured at 86°F (30°C)

Warping

Warping is the deflection of a concrete slab due to a moisture gradient between the top and bottom of the slab. These moisture gradients are largely caused by drying shrinkage and create uplift at joints and slab edges (Wei 2008) (Jeong and Zollinger 2004).

A decrease in warping can be achieved by providing a uniform relative humidity through the thickness of a slab. This can be achieved by allowing desorption of water from saturated LWA. In a study conducted by Wei and Hansen (2008), internally cured concrete mixtures reduced warping by 70%. The mixes used a 0.45 w/cm ratio and were dried for 16 days (Wei and Hansen 2008).

Permeability

Permeability is of particular interest because of its ability to indicate potential durability (El-Dieb and Hooton 1995). Using mortar samples made with 0.08 units of internal curing water per mass of cement and a w/cm ratio of 0.4, Bentz (2009) was able to show a reduction in the chloride diffusion coefficient of 25% to 45% compared to the control samples. This reduction was due to the decrease in the amount of percolated paste (Bentz 2009).

A similar study by Cusson and Margeson (2010) used concrete samples with a w/cm ratio of 0.5 and 0.075 units of internal curing water per mass of cement. This study showed that chloride permeability decreased by 25% and water permeability decreased by 19%. It was also shown that the internally cured concrete had a 20% higher C-S-H content (determined at 28 days using thermal gravimetric analysis), indicating an increase in cement hydration. The results of this study are shown in Table 2 (Cusson and Margeson 2010).

Table 2. Selected test results on impact of internal curing properties of high-performance concrete

Property	Reference concrete (w/c = 0.35)	Internally cured concrete (w/c = 0.35)	Relative improvement (%)
w/c_{ic} (kg/kg)	0	0.075	
C–S–H content at 28 days (%)	10.2	12.3	21
Compressive strength at 7 days (MPa)	45	50	11
Compressive strength at 28 days (MPa)	60	65	8
Water permeability (m/s)	2.1 × 10−11	1.7 × 10−11	19
Chloride permeability (Coulomb)	553	415	25
Freeze–thaw resistance, mass loss (%)	0.6	0.26	
Salt scaling resistance, mass loss (%)	0.46	0.3	

Source: Cusson and Margeson 2010

Freeze-Thaw Resistance

Freeze-thaw resistance is the ability of the concrete to accommodate expansive pressures induced by freezing water contained in the capillary pores. When the water provided for IC leaves the LWA and is used for hydration, the remaining air voids should aid in freeze-thaw resistance (Bentz and Snyder 1999). Cusson and Margeson (2010) subjected concrete samples to 300 rapid freeze-thaw cycles in water and 50 slow freeze-thaw cycles in a 4% CaCl solution. The results of the study (Table 2) showed that the internally cured concrete performed better than the reference concrete.

Other Benefits

The use of 5 $ft.^3/yd.^3$ of LWA reduces the weight of a cubic yard of concrete by approximately 200 lb. A typical 10 $yd.^3$ load will lose 2000 lb. in total weight, which could increase a typical load by 0.5 $yd.^3$ assuming the vehicle has sufficient capacity. This would result in increased fuel savings and production and a decrease in equipment wear (Villarreal and Crocker 2007).

CONSTRUCTION OF INTERNALLY CURED CONCRETE PAVEMENTS

Mix Proportioning

The amount of saturated LWA necessary for internal curing is a function of the type and size of the LWA, the amount of moisture in the LWA, the type and amount of cementitious materials in the mixture, the w/cm ratio at the time of mixing, and the amount and duration of external moist curing provided to the concrete mixture (Hoff 2002).

Bentz and Snyder (1999) developed an equation (2) for determining the quantity of LWA necessary to provide the water for internal curing:

$$M_{LWA} = \frac{C_f \times CS \times \alpha_{max}}{S \times \phi_{LWA}} \quad \textbf{(2)}$$

where,

- M_{LWA} = mass of (dry) fine LWA needed per unit volume of concrete (kg/m^3 or lb./yd.^{3}),
- C_f = cement factor (content) for concrete mixture (kg/m^3 or lb./yd.^{3}),
- CS = chemical shrinkage of cement (g of water/g of cement or lb./lb.),
- α_{max} = maximum expected degree of hydration of cement,
- S = degree of saturation of aggregate (0 to 1), and
- ϕ_{LWA} = absorption of lightweight aggregate (kg water/kg dry LWA or lb./lb.).

For the purpose of initial estimates, the value for the chemical shrinkage coefficient (CS) to be used is 0.07 lb. of water per pound of cement. The maximum expected degree of hydration of cement can be approximated as 1 at w/cm ratios greater than 0.36, and as ([w/cm]/0.36) for w/cm ratios less than 0.36 (Bentz et al. 2005).

Applying equation 2 to a concrete mixture with a cement factor of lb./yd.^{3}, a chemical shrinkage factor of 0.07 lb. water/lb. cement, and an aggregate absorption of 18% at complete saturation would require 143 and 155 lb. of dry LWA for w/cm ratios of 0.33 and 0.40, respectively.

Equation 2 provides an initial estimate of the amount of LWA required for internal curing, but it does not account for all of the varying effects causing autogenous shrinkage in concrete. The American Concrete Institute recommends collecting data for developing a three-point curve to obtain actual mix proportions. The data from the three-point curve regarding the property(s) in question can be used to determine the adequate LWA replacement (ACI [308-213]R-13 2013).

Stockpile Management

Proper saturation of the LWA is required to ensure proper performance of internally cured concrete. Many of the desired effects of internal curing may be adversely affected by insufficient saturation of the LWA. ASTM C128-12 testing can be conducted to ensure the LWA is in a saturate surface-dry (SSD) state. NYSDOT requires continuous and uniform spraying of the LWA stockpile for a minimum of 24 hours followed by a 12 to 15 hour period to drain the stockpile (NYSDOT 2010).

Batching, Transport, Finishing, Curing

The batching, transport, placement, finishing, and curing of internally cured concrete is similar to that of conventional concrete. The LWA should be evaluated for proper saturation prior to batching.

The provision of internal curing does not remove the need to provide adequate surface curing using conventional means in order to reduce the rates of drying from the surface.

INTERNAL CURING FOR CONCRETE OVERLAYS

Concrete overlays are a system applied to existing pavements of all types in order to repair premature damage or to extend working life. Most overlays are debonded from the existing system by means of a thin asphalt or geotextile interlayer. Because the existing pavement provides a stiff foundation, the concrete thickness in an overlay may be somewhat less than in a full-depth slab. Because the need to provide sawn joints in the slab is a function of slab thickness, overlays tend to use closer joint spacing, which can prove challenging when seeking to keep the joints out of the wheel path. Joint spacing guidelines from Harrington (2008) are shown in Table 3.

Table 3. Joint spacing guidelines

Unbonded Resurfacing Thickness	**Maximum Transverse Joint Spacing**
< 5 in (125 mm)	6 x 6 ft. (1.8 m x 1.8 m) panels
5 – 7 in. (125-175 mm)	Spacing in ft. = 2 times thickness in in.
>7 in (175 mm)	15 ft. (4.6m)

Source: Harrington 2008

In addition, the stiff support system means that any warping is accentuated because there is no give in the foundation. This leads to rocking and faulting along with increased stresses and thus potential premature failure of the slabs. (Jeong and Zollinger 2004).

Joint spacing for concrete overlays can be increased if slab warping is reduced or eliminated. One of the most promising potential benefits from using internal curing for concrete overlays, then, is the reduced number of joints due to increased joint spacing (Wei and Hansen 2008).

While the immediate benefit is decreased costs due to reduced sawing time, equipment, and personnel, the long-term benefit would be the potential to reduce the need for patching due to joint failures. If it is possible to increase transverse joint spacing by a factor of two, the number of potential failures should decrease by a factor of two. If it is also possible to eliminate a quarter-point longitudinal joint using longer transverse joint spacing, the number of potential failures can be decreased by a factor of four.

EXISTING INTERNALLY CURED CONCRETE PAVEMENTS

State Highway 121 North of Dallas, Texas

A section of SH 121, operated by the North Texas Tollway Authority, north of Dallas, Texas, was constructed using internal curing. The project was a 13 in. continuously reinforced concrete pavement (CRCP) using a conventional mixture and limestone aggregates. A 1,400 ft. long test section using LWA for internal curing was built for the project. A 10 to 15 percent reduction in shrinkage was observed on the project over 28 days in the test section. The internally cured section also produced a larger crack spacing (22.7 ft.) when to compared to the conventional section (9.4 ft.). More importantly, the cracks on the internally cured section were tighter than on the conventional section. (Rao and Darter 2013).

High Early Strength ICC Off Ramp of I-635 in Mesquite, Texas

In 2012 a section of an off ramp on I-635 in Mesquite, Texas, was constructed with a high early strength mixture that utilized internal curing. The mixture used a Type III cement, a gap-graded aggregate blend with intermediate LWA, a non-chloride accelerator, water reducer, and slump-retention admixture. The use of internal curing had no adverse effect on early strength and was able to reducing shrinkage cracking by providing additional curing water (Rao and Darter 2013).

Dallas Intermodal Terminal

In 2005 Union Pacific Railroad constructed a 360 acre intermodal transfer facility using internally cured concrete pavement. This project was constructed using an 8.5 in. JPCP on a 12 in. aggregate base. The following statement is from the original technical paper for the project:

> Actual field conditions have demonstrated the improved hydration of the cementitious materials. This improvement can be quantified as demonstrated by the average compressive strength increase of about 1000 psi (7 MPa) shown herein. The slow release of moisture from the lightweight aggregate to the concrete matrix has resulted in the mitigation or elimination of plastic and drying shrinkage cracking, as well as limiting the effects of self-desiccation. Enhanced workability and better consolidation due to an improved total grading provided by the use of an intermediate aggregate was also evident, as the contractors reported that it reduced the total placing time. (Villarreal and Crocker 2007)

This project is one of the most widely recognized internal curing paving projects, using 250,000 $yd.^3$ of concrete, which would be equivalent to 150 lane miles of 8.5 in. internally cured concrete pavement. After 8 years of service, this pavement showed almost no cracking. This pavement also showed no measurable curl in a random sampling of 20 slabs on the project (Rao and Darter 2013).

Kansas US 54 Expansion

In 2014 the Kansas DOT reconstructed a five-mile section of US 54 near Iola, Kansas. Two 500 ft. test sections were constructed for the project. One section was constructed with internally cured concrete. The other section was constructed as a control using the same concrete mixture as the rest of the project. The pavement design utilized a 9 in. concrete pavement with 15 ft. joint spacing on 4 in. of granular subbase.

Instrumentation was placed in two panels of the test section and one panel of the control section. The panels surrounding the instrumented panels were measured for deflection during the initial curing window.

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