

Evaluation of Internally Cured Concrete for Paving Applications

Chetana Rao¹, Michael I. Darter², John Ries³

ABSTRACT

This paper evaluates the use of Internally Cured Concrete (ICC) on Interstates, residential, industrial and other concrete pavement projects from the perspective of design, construction, longevity, curling, durability and life cycle cost. ICC is a concrete mixture in which a portion of the intermediate, and/or fine aggregates (for example, 30 percent of sand) is replaced with similar sized prewetted lightweight aggregate (LWA). Internal curing (IC) is a means to provide hydrating concrete adequate moisture from within the mixture (slab) to replace water lost due to chemical shrinkage. IC may also restore, at least partially, the moisture that escapes through evaporation. IC, which naturally takes place in LWA concrete, has been designed into conventional concrete to release moisture well after placement. ICC has also demonstrated good constructability on field. ICC has shown good durability results in reducing early age shrinkage and associated plastic shrinkage cracking as well as other random cracking on several bridge decks and a few concrete pavement projects. ICC has also demonstrated some benefits in material properties favorably impacting pavement performance that are presented in this paper.

INTRODUCTION

This paper is a condensed version of an extensive study titled *Evaluation of Internally Cured Concrete for Pavement Applications* (Rao, and Darter, 2013). Internally cured concrete (ICC) is defined in this report as a concrete mixture in which a small portion of the intermediate, and/or fine aggregates (for example, 30 percent of sand) is replaced with an equal volume of similar sized prewetted lightweight aggregate (LWA).

Internal curing, which naturally takes place in lightweight aggregate concrete (LWC), has been specifically designed into normal weight concrete to provide hydrating concrete adequate moisture from within the mixture to replace chemical shrinkage water well after placement and into the hydration process (Bentz and Weiss, 2011; Weiss et al., 2012). LWA may also be added to restore, at least partially, the moisture that escapes through evaporation.

It's important to note that:

¹ Chetana Rao, Ph.D.; Principal, Rao Research and Consulting, LLC; 60 Hazelwood Dr., Champaign, IL 61820; Email: cr Rao@raorc.com; Ph: (217) 369-6865.

² Michael I. Darter, Ph.D., P.E., Principal Engineer, Applied Research Associates, Inc., 100 Trade Center Dr., Champaign, IL 61820; Email: mdarter@ara.com; Ph: (217) 36-4500.

³ John Ries PE, FACI, Executive Director, Expanded Shale Clay and Slate Institute, 35 East Wacker Dr., Suite 850, Chicago, IL 60601; Email: jries@escsi.org; Ph: (801) 272-7070.

- ICC is not lightweight concrete. ICC exhibits only a slight reduction in unit weight.
- IC is intended to supplement, not replace, conventional curing practices.
- As described in ASTM C1761, there are several types of LWAs available. This paper focuses exclusively on expanded shale, clay, and slate (ESCS) LWA.
- ICC uses absorptive materials in the mixture that supplement the standard curing practices by supplying moisture to the interior of the concrete (ACI, 2013).

The objective of this research effort was to evaluate the use of ICC in concrete pavement for design, construction, performance, and life cycle costs.

Background

ICC has been used in several bridge decks in New York, Virginia, Indiana, Utah, North Carolina, Georgia, and Ohio with great success, reducing dramatically the amount of plastic shrinkage cracking and other random cracking (Streeter, Wolfe, and Vaughn, 2012; Schlitter et al., 2010; Ozyildirim, 2011; Delatte and Crowl, 2012; Henkensiefken et al. 2009).

However, ICC has only been used on a few concrete pavement projects. This paper covers those located in the general Dallas/Fort Worth, Texas area and include a major freeway, a large intermodal terminal, and many residential and collector streets. As of 2007, over 550,000 cubic yards of ICC had been placed in pavements in this region. Several of these projects were surveyed in February 2013. More pavement projects have been placed since then in Texas and other states.

Potential Benefits to Concrete Pavements

The primary benefits of IC are improved hydration, improved supplementary cementitious material (SCM) reaction, and reduced shrinkage. Additionally, many other small but collectively significant changes occur to several key mixture properties as have been documented in both laboratory and field studies (Bentz, Geiker, and Jensen, 2002; Hoff, 2002; Bentz, Lura, and Roberts, 2005; Thomas, 2006; Ozyildirim, 2011; Byard, Schindler, and Barnes, 2012; Maruyama and Teramoto, 2012; Varga, Castro, and Weiss, 2012; Weiss et al., 2012) and include the following:

- Reduction in unit weight by about 7 pcf.
- Reduction in elastic modulus by about 5 percent
- Reduction in zero-stress temperature by about 5 percent.
- Increase in strength by about 5 percent.
- Reduction in coefficient of thermal expansion (CTE) by about 5 percent.
- Reduction in shrinkage cracks.
- Reduction in permeability by about 10 percent.
- Reduction in shrinkage crack width in CRCP by 20 to 60 percent.
- Increase in flexural strength by about 5 percent.
- Increase in compressive strength by about 5 percent.
- Increase splitting tensile strength by about 5 percent.

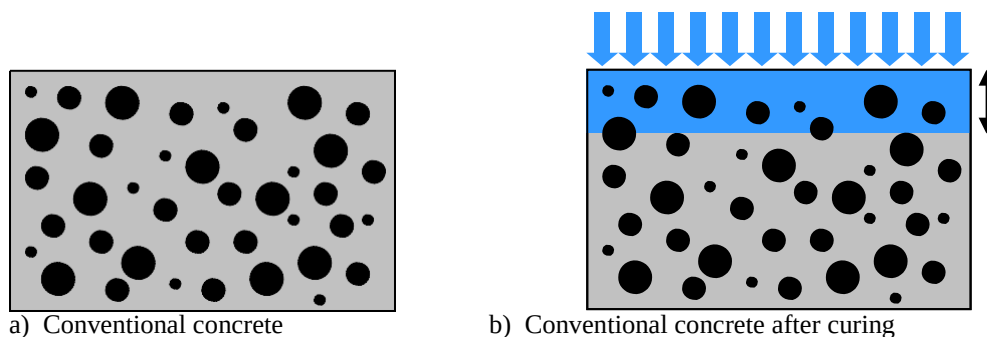
Each of these small changes is potentially beneficial to concrete pavement performance, however, the combined effect of all these changes can be substantial. Other beneficial effects that are possible but have not been fully documented to date, include:

- Reduction in joint and crack openings because of reduced zero-stress temperature and because of reduced long term drying shrinkage.
- Reduction in slab upward curling caused by a reduction in the moisture gradient. In a study conducted by Ya and Hansen (2008), prewetted fine LWA was found to be effective in reducing moisture warping (upward curling). This is very significant; it affects top-down and bottom-up cracking and joint faulting
- Reduction in permeability. This may lead to reduction in joint deterioration in harsh freeze-thaw climates.

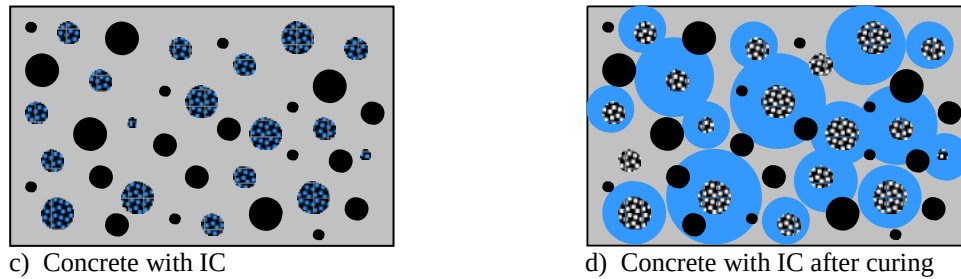
INTERNALLY CURED CONCRETE

The American Concrete Institute (ACI) defines IC as, “process by which the hydration of cement continues because of the availability of internal water that is not part of the mixing water” (ACI, 2014).

IC may be considered as providing moisture uniformly within the system, in contrast to traditional top-down curing methods, or with curing compound as in the case with pavements. As illustrated in Figure 1, prewetted LWAs provide moisture throughout the mass of the concrete. This alone can reduce shrinkage gradients in a slab. In case of pavements using a curing compound to control moisture loss, IC replenishes the moisture lost in chemical shrinkage, and the hydration process. The tendency toward a uniform moisture gradient may reduce slab curling.



CONVENTIONAL CURING



INTERNAL CURING

Figure 1. Volume of concrete that can be cured with IC vs. conventional concrete curing (Castro et al., 2010).

Internal Curing for Pavements

IC successes in bridge decks encouraged the pavement industry to explore its use in paving applications. A 1965 study investigated the mechanical properties and their effects on restrained and unrestrained volume changes for concrete pavement (Ledbetter et al., 1965). The study estimated lower curling stresses and deformations with lightweight concrete and recommended its use in paving, and the need for proper curing.

The use of IC for mixtures with SCMs like fly ash or slag has the potential to offer additional benefits. IC can meet the additional water demand of the SCMs usually created from their delayed hydration and set time past the normal curing period of conventional cement. This enhanced curing makes it possible to fully realize the durability benefits offered by SCMs in concrete mix designs.

A few pavement projects were constructed during the last decade in the Dallas-Fort Worth area (Villareal and Crocker, 2007; Friggle and Reeves, 2008). ICC mix designs were used for both JPCP and CRCP designs. ICC was also used in a high early strength paving project, where traffic was opened in 12 hours. The high early strength mix used Type III cement and a non-chlorine accelerator. ICC reduced shrinkage cracks, and therefore has the potential to reduce durability problems associated with high permeability issues. Also, the reduced modulus of elasticity are expected to reduce stresses.

Designing an Internal Cured Concrete Mixture

The following quote from the Expanded Shale Clay and Slate Institute (ESCSI) publication (2012) describes the design of an ICC mixture:

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. The same amount of water concentrated only in coarse ESCS aggregate can leave part of the cementitious paste "un-protected" by IC. This is because the water only travels a limited distance

(on the order of 2 to 20 mm) depending on age and w/cm. In some mixtures, intermediate size aggregate may be used to optimize total aggregate grading, as well as provide IC.

The amount of wetted ESCS aggregate needed is based on the absorption and desorption of the aggregate being used. For most practical concrete applications, 7 lbs. IC water/100 lbs. cementitious material provides an appropriate value for the amount of IC moisture needed. However, the amount of IC water may be increased to accommodate evaporation or to satisfy the higher water demand in mixtures with SCMs.

Knowing the target amount of IC water needed and the aggregate's absorption and desorption, the amount of prewetted ESCS aggregate can be determined through the use of ESCSI's "Guide for calculating the Quantity of Prewetted ESCS Lightweight Aggregate for Internal Curing http://www.escsi.org/ContentPage.aspx?id=698&ekmense1=1b7c39fc_6174_698_6 or by contacting the ESCS lightweight aggregate supplier.

IC and Concrete Pavement Sustainability

The potential of ICC for increased durability and longer life would be a major component of sustainability. State highway agencies' interest in "long life pavement programs" have increased design lives from 20 years to 30, 40, 50, and 60 in several States, with one study examining 100 years catching the attention of environmental, and natural resource groups. This trend will continue as traffic congestion increases and sustainability gains more importance.

Cusson et al. (2010) compared the service lives of high-performance concrete bridge decks with and without internal curing. Based on their assumptions, service life estimates of 22 years for conventional concrete, 40 years for high-performance concrete without internal curing, and 63 years for high-performance concrete with internal curing were reached. In this case, internal curing should produce a bridge deck with an increased service life and a significantly reduced life cycle cost (ACI 213R-14). Although this was done for bridge decks, it indicates the possible potential for concrete pavements.

ICC's ability to provide good curing throughout the concrete slab thickness, supports thorough hydration and a low-permeability cement matrix. Reduced permeability mitigates durability related problems like alkali silica reaction, sulfate problems, corrosion, freeze-thaw damage, and D-cracking.

AASHTOWARE PAVEMENT ME DESIGN PROCEDURE AND PERFORMANCE PREDICTION FOR ICC

The AASHTOWare Pavement ME (AASHTO ME) design procedure is based on mechanistic-empirical design concepts. The design procedure calculates pavement responses such as stresses, strains, and deflections under design traffic and climatic conditions and then

accumulates the damage over the analysis period. The procedure then empirically relates calculated damage over time to pavement distresses and smoothness based on performance.

AASHTO ME design uses a number of algorithms and models to (1) characterize new or existing pavement foundation, structure, layer materials (e.g., concrete slab), traffic, and climate; (2) calculate stresses/strains/deflections due to the interactions between materials properties, applied traffic load, and climate; and (3) estimating the resulting damage manifested as distress (cracking, faulting, punchouts) and smoothness loss over the design life of a pavement.

Design Inputs and Models Affected by ICC

A review of the AASHTO ME design models and algorithms with ICC material property inputs does not indicate there are any potential problems to designing or analyzing either JPCP or CRCP that incorporate ICC. With increased strength, reduced modulus, reduced shrinkage, reduced unit weight, and reduced CTE the designs result in improved pavement performance.

In addition, ICC can reduce concrete shrinkage, which may alter the built-in temperature gradient and thus slab stresses and deformation; ICC can also alter the crack spacing patterns and crack opening magnitudes in CRCP, reduce tensile stresses and decrease fatigue damage accumulation at the top of the slab.

INTERNALLY CURED CONCRETE (ICC) PAVEMENTS

The following five ICC pavements were visited in the Dallas-Fort Worth region in February, 2013 to determine the performance of ICC pavement projects:

- A. State Highway 121 (SH 121) southbound lanes between I-75 and Dallas North Tollway, north of Dallas: This CRCP project, built 2006, contains a 1,400-ft-long ICC segment on the outer lane and shoulder. The rest of the project used conventional concrete.
- B. I-635 off ramp near I-80, Dallas: This project used ICC in a high-strength concrete mixture designed for early opening, placed 2012.
- C. Union Pacific Intermodal Terminal: This project, built in 2005, is located 12 miles from Dallas, within the city of Hutchins and Wilmer.
- D. Windsor Park South: This is a residential subdivision in Fort Worth constructed during 2006-2007.
- E. Alexandria Meadows North: This is a residential subdivision north Fort Worth, constructed 2006-2007, containing both ICC and conventional concrete.

The AASHTO ME design software was used to model sites A, C, and E using ICC and conventional concrete properties to compare pavement performance. The analyses were performed in a conservative manner using the national calibration factors, which allow the use of laboratory-measured PCC properties (ARA, 2011). The CRCP crack width coefficient

was reduced from 1.0 to 0.8 for the ICC section to simulate the tighter crack width measured in the field.

A) State Highway 121 North of Dallas

The North Texas Tollway Authority (NTTA) controls this section of SH 121. This CRCP project used a conventional limestone mixture and a 1400 ft outer lane and shoulder built with ICC. A view of the CRCP lanes is shown in Figure 2 along with a picture of core showing steel and inclusion of LWA (dark particles). The pavement has an excellent ride quality after 7 years with no distress occurrence.



Figure 2. ICC pavement in outer traffic lane and shoulder on Texas SH 121 (top) and view of the core removed from CRCP slab.

CRCP design details are as follows (Friggle, 2013):

- 13-in. CRCP with 0.7 percent longitudinal reinforcement placed at mid-depth.
- 4-in. asphalt concrete base layer.
- 10-in. lime stabilized subgrade.
- Natural subgrade is AASHTO classification A-7-6.

The project was tested and monitored by the Center for Transportation Research (CTR). The pavement was constructed in November with 38°F to 57°F daily temperature swings. The ICC concrete was delivered to the job site in a ready mix truck instead of the normally used

dump truck. The slump was adjusted, allowing the paving operation to function efficiently. Kim and Won (2008) report that the bleed water was not excessive and aided good finishing and the shrinkage strain over 28 days indicating 10 to 15 percent less shrinkage for ICC.

Additionally, Friggle and Reeves (2008) reported mix design, construction, and crack survey details. The ICC mixture used 300 lb/yd³ of intermediate LWA and the ICC strengths well exceeded design criteria ranging from 1750 psi at 1 day to 6000 psi at 28 days. A crack survey performed at 76 days after construction reported to have developed shrinkage cracks at an average spacing of 31 feet for the ICC. Additional surveys were performed and are shown in Table 1. In addition, the crack width on the ICC section was reported to be significantly less.

Table 1. CRCP crack spacing measurements by CTR on SH 121 in Texas.

Measurement Year	Conventional Concrete Inside Lane (3 rd lane from shoulder) Mean Crack Spacing, ft	Conventional Concrete Lane Adjacent to ICC Lane (2 nd lane from shoulder) Mean Crack Spacing, ft	ICC Lane (adjacent to shoulder) Mean Crack Spacing, ft
2006	Construction		
2007 [#]	9.4	9.4	22.7
2009 ^{##}	7.4	7.2	8.6
2010 ^{##}	6.5	7.0	8.9
2011 ^{##}	6.9	7.6	7.7
2012 ^{##}	5.7	6.1	6.4
AASHTO prediction	5.6	5.6	6.3
[#] Field measurements reported by Friggle and Reeves (2008)			
^{##} Measurement from digital photos taken by ARA for NTTA			
NOTE: This study was performed in 2013 and data were available up to 2012.			

The SH 121 project was modeled using the AASHTO ME design procedure to compare the ICC with the conventional concrete pavement. For details see full report *Evaluation of Internally Cured Concrete for Paving Applications* (Rao and Darter, 2013).

Performance Prediction

The 13-inch CRCP sections with ICC and conventional concrete were predicted to have excellent performance throughout the 30-year design life. The two performance criteria used in CRCP designs—punchouts and International Roughness Index (IRI)—were predicted to remain well below the threshold levels, indicating very conservative designs. Extending the

analysis period beyond 30 years, the analysis suggests that the designs will not fail up to 50 and 70 years for the conventional and ICC concrete sections, respectively.

The projects were reanalyzed to optimize the design thicknesses using the AASHTO ME design procedure at 97 percent reliability, which yielded design thicknesses of 11 inches for conventional and 10 inches ICC. The resulting performances are almost identical.

ICC CRCP has longer crack spacing (76 versus 66 inches) and narrower crack openings. The crack openings remain much smaller in the ICC section because of the lower shrinkage and reduced crack width calibration factor. The maximum crack openings at 30 years are estimated to be 17 mils for the conventional and 11 mils for the ICC sections. Tighter transverse cracks are very beneficial to long-term performance. In addition, longer mean crack spacing implies fewer shorter cluster cracks for punchout development, and tighter cracks result in a lower chance of breakdown of load transfer.

The analyses of the SH 121 project suggest that ICC presents significant benefits and can reduce the design thickness by 1 inch while providing similar performance and reliability.

B) High Early Strength ICC Off Ramp of I-635

A short section of an off ramp was constructed in 2012 with a specially designed mixture for high early strength using ICC. This off ramp is located on I-635 (Lyndon Johnson Freeway) south of US Highway 80 in Mesquite.

The contractor was given the opportunity to design the mixture to achieve an early opening of 400 psi flexural strength in 12 hours. The ICC mix was designed with Type III cement, a gap-graded aggregate blend with intermediate size LWA, and a non-chloride accelerator, water reducer, and slump retention admixture. The inclusion of prewetted LWA, while having no detrimental effect on early strength development, was valuable for providing the necessary curing water to reduce shrinkage cracking, so common in high early strength concrete pavement slabs.

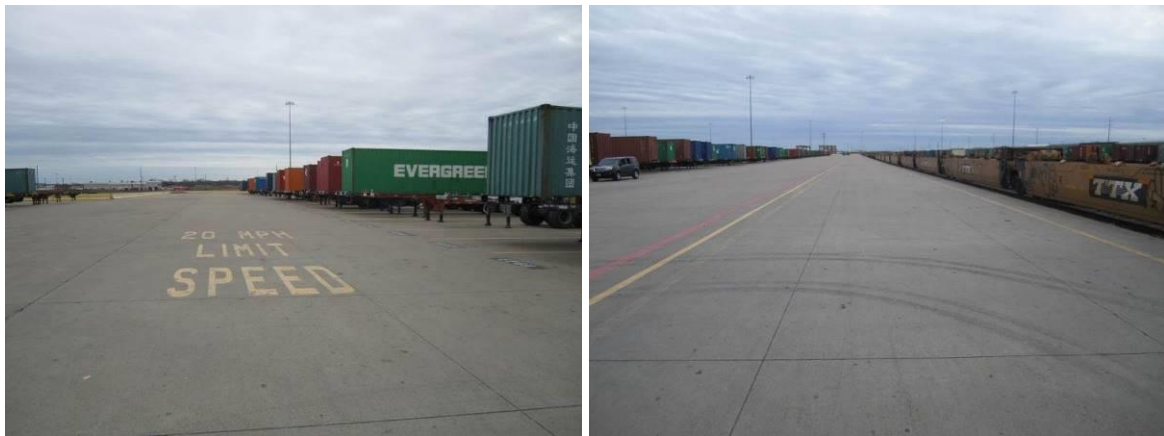
During the 2013 survey it was impossible to get close enough to determine the crack spacing and crack widths; however observations indicated both the ICC and control sections were in excellent condition with no early age distresses detected.

C) Union Pacific Intermodal Terminal

The 360-acre Union Pacific (UP) Intermodal Terminal is located within the city limits of Hutchins and Wilmer. The terminal features 365,000 pounds lift capacity and 4,000 parking stalls operating 24-7 with four loading tracks. A picture of the facility is shown in Figure 3. The facility has a short section of the roadway that carried literally every truck entering and leaving the facility as shown in Figure 4.

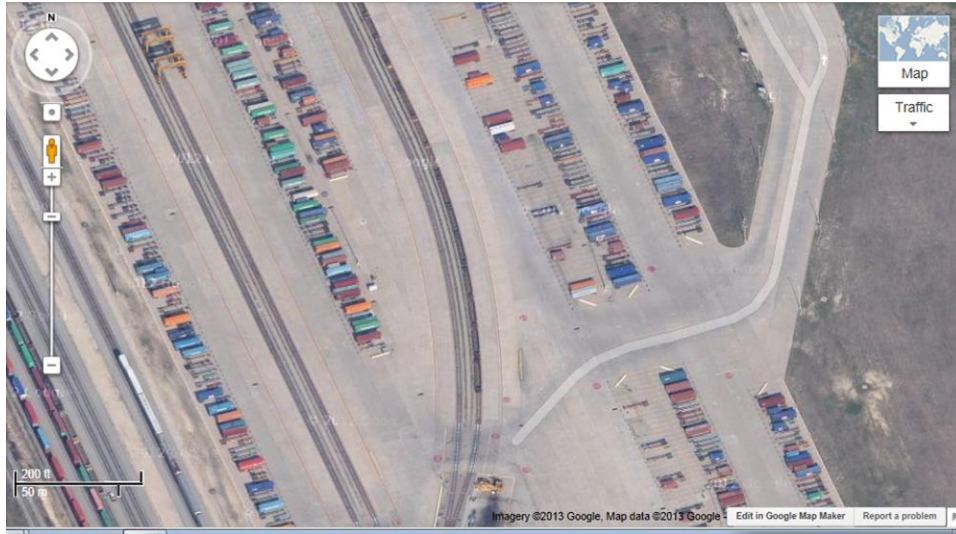


a) Aerial view of the UP intermodal facility



b) Pictures showing the ICC JPCP slabs at the UP intermodal facility

Figure 3. Aerial view (top) and pictures (bottom) of the UP Intermodal facility



a) Aerial view.



b) Picture of the ICC JPCP slabs at the entrance to, and exit from the facility.

Figure 4. Maximum traffic zone of the UP intermodal facility.

Pavement Design, Materials, and Construction

The following summarize the key design, materials, and construction information that impact pavement performance:

- Constructed throughout 2005 under a range of weather conditions typical of the Dallas-Fort Worth area.
- JPCP design with 15 x12 ft slabs, 8.5 inches thick, doweled transverse joints, untreated 12-inch aggregate base on AASHTO A-7-6 subgrade.
- The ICC mix design used a partial substitution of intermediate size LWA replacing an equal volume of normal weight aggregate.
- The average compressive strength was improved by 1000 psi as reported by Villarreal and Crocker (2007) and it was attributed, at least in part, to improved hydration.
- Villarreal and Crocker (2007) also reported the mitigation and elimination of plastic and drying shrinkage cracking.
- ICC mixture also demonstrated enhanced workability and better consolidation due to an improved total grading provided by the use of an intermediate aggregate. Contractors reported that it reduced the total placing time

In 2013 (8 years in service) walking surveys and windshield surveys were conducted to cover a majority of the large project. There were virtually no shrinkage or plastic shrinkage cracks, spalls, or transverse and longitudinal cracks observed in the project. It was in excellent condition as shown in Figure 3 and Figure 4, with only a few small areas of spalling along joints.

The upward curl in the slabs (between diagonal corners) were measured on at least 20 slabs around the facility (see Figure 5); no measurable upward curl existed on the project. This is important as significant upward curling can lead to top-down transverse and longitudinal cracking over time with continued truck loading.



Figure 5. Curl measurement in the UP intermodal facility slabs

The as-built ICC pavement was analyzed using the AASHTO ME design procedure. Also, a control design was considered with conventional concrete using the same thickness and other design inputs. The ICC JPCP analysis indicated a long life of 60 years can be expected. In comparison, the conventional concrete pavement with the same design thicknesses did not have equivalent performance. The AASHTO ME design procedure analysis showed that the inbound and outbound JPCP lanes would fail at 40 years due to excessive transverse fatigue cracking. JPCP slab thickness for the conventional concrete, clearly, is inadequate to carry the 60 years of traffic. IRI and faulting performance were acceptable, however.

Next, the conventional concrete JPCP design was optimized to determine the required design thickness according to the AASHTO ME design procedure. The analysis established a minimum design thickness of 9.0 inches is required over 60 years. Therefore, ½-inch increase in thickness was needed to achieve the performance levels of 8.5 inches of ICC.

D & E) Windsor Park, and Alexandria Meadows Subdivision

These sections were constructed as jointed plain concrete slabs with no dowel bars. The slabs are 7" thick, 12' wide with 15' joint spacing and placed directly on compacted sub grade consisting of soft fine-grained soil. The paving was done by slip form pavers for two lanes width. The curbs were also paved in the same operation. Pictures of the ICC pavements in the two subdivisions are shown in Figure 6.



a) ICC slabs in residential area



b) ICC slabs along horizontal curve



c) Sawed surface of ICC along curbs



d) ICC pavement surface

Figure 6. ICC pavement in low traffic residential area.

Walking surveys were conducted on several ICC and conventional streets in the subdivision. No significant longitudinal or transverse cracking, plastic shrinking cracking, spalling, or other defects were noted. In general, the 8-year-old pavement was in excellent condition. Diagonal corner-to-corner curling was measured on several ICC slabs and zero upward curling was observed.

Traffic includes light autos and pickups plus heavy trash hauling vehicles once per week, along with a few moving vans and other trucks. The pavements were also loaded with construction traffic during construction of homes. For the AASHTO ME design analysis, a traffic level of 400,000 trucks over a 60-year period in one direction was used.

The AASHTO ME design analysis indicated that the ICC project would have good structural performance for at least 40 years. Cracking, joint faulting, and IRI are below the design performance criteria up to 40, 45, and 55 years after construction. The performance was evaluated at a reliability level of 95 percent.

In comparison the conventional concrete meets all performance requirements for only a period of 25 years, before transverse cracking exceeds the design performance criterion. The results show that for these identically designed residential pavements, the ICC pavement life extends the pavement life 15 years (from 25 to 40 years). This increase by 60 percent is significant.

EVALUATION OF ICC FOR OTHER PROJECTS USING AASHTO ME DESIGN

Five additional projects with different climate zones, traffic levels and designs were also analyzed using AASHTO ME design analysis for both ICC and conventional concrete.

- JPCP site on I-45 adjacent to the UP terminal
- Four FHWA Long-Term Pavement Performance (LTPP) Specific Pavement Study 2 (SPS-2) sites: Test sections were selected from Iowa, North Carolina, Colorado, and Arizona to represent Wet-freeze, Wet no-freeze, Dry freeze, and Dry-no freeze climate zones respectively.

JPCP for I-45 near UP Terminal

The JPCP site on I-45 is just east of the UP Intermodal Terminal. This simulated project was modeled after the intermodal facility for all inputs except traffic, which was based on TxDOT traffic counts. Cumulative truck traffic of 40 million trucks over the design 60 yr design life was used.

Optimizing the design thickness produced a required thickness of 11.5 inches for the conventional concrete and 10.5 inches for the ICC pavement. Results of the design and the predicted performance are summarized in Table 2.

Table 2. Summary of I-45 JPCP designs using conventional concrete and ICC for 30-year design at 97 percent reliability.

Design Results	Conventional JPCP	ICC JPCP	Design Criterion
Optimized thickness, inch	11.5	10.5	Meets performance criterion for cracking, faulting, and IRI
Slab dimensions, ft	15 x12		
Dowel diameter, inch	1.50		
Shoulder type	Tied concrete shoulder		
Base course	12-in. crushed stone layer		Selected base course and subgrade at project site
Subgrade	A-7-6		
Percent slabs cracked at 30 years [#]	4.4	4.8	5.0 percent slabs
Joint faulting at 30 years [#]	0.11	0.12	0.15 inches
IRI at 30 years [#]	144	151	160 inches/mile
[#] Performance reported at 97 percent reliability			

The results demonstrate that ICC produces a more economical design and can result in a reduction of up to 1 inch in JPCP thickness. This project was also used in the life cycle cost analysis.

LTPP SPS-2 Sites AASHTO ME Design Analysis

The inputs were obtained from the LTPP database, and are provided in Table 3. The ICC inputs are shown in bold and were estimated by adjusting the conventional inputs based on laboratory test results for ICC mixtures (Byard and Schindler, 2012). Table 4 presents a summary of the predicted performance.

Table 3. Summary as-built SPS-2 inputs for the conventional concrete obtained from LTPP database. **Adjusted ICC inputs in bold**

Design Input	Iowa 19-0213 Wet freeze	N Carolina 37_0203 Wet no- freeze	Colorado 08_0213 Dry freeze	Arizona 04_0213 Dry no- freeze
Design life, years	30	30	30	30
PCC thickness, inches	8.5	8.5	8.6	7.9
Slab width, feet	12	12	12	14
Unit weight, pcf (7 pcf less)	138 (131)	145.5 (138.5)	148 (141)	143 (136)
PCC CTE, $\times 10^{-6}$ in./in./°F (5 percent less)	4.4 (4.18)	4.06 (3.857)	4.8 (4.56)	4.8 (4.56)
Zero-stress temperature, °F	95	100.7	74.5	118
Flexural strength, psi (5 percent more)	525 (5.62)	714 (764)	588 (629)	666 (713)
Modulus of elasticity, psi (ICC 5 percent less)	3,100,000 2,945,000	4,380,000 4,161,000	3,600,000 3,420,000	4,500,000 4,275,000
Ultimate shrinkage, $\times 10^{-6}$ in./in. (Default with ICC properties)	569.3 (560)	775 (758.2)	618.9 (607.9)	500.2 (491.7)
Aggregate type	Limestone	Granite	Granite	Granite
w/c ratio	0.61	0.7	0.59	0.58
Initial AADTT	500	734	3000	2400
Cumulative truck traffic	9.5 million	12.7 million	41 million	85 million

Table 4. Predicted performance of ICC and control LTPP SPS-2 sections.

SPS-2 Site	Years to 15% Cracking @90% Reliability		Transverse Cracking at Year 30 @ 90% Reliability, percent		IRI at Year 30 @ 90% Reliability, inch/mile	
	Control	ICC	Control	ICC	Control	ICC
Iowa	9	30	68	4	235	115
North Carolina	7	21	80	24	195	146
Colorado	22	30	18	7	155	149
Arizona	8	22	97	25	182	107

The results of the analyses indicate that a JPCP designed with ICC for an Interstate highway (major freight route) was 1 inch thinner than a conventional concrete design for the same performance requirements. The analysis of the four SPS-2 sections indicates that for the same structural design over a 30-year design life, ICC pavements show improved structural

performance and can offer an average more than 10 years of service before exceeding performance criteria.

EVALUATION OF LIFE CYCLE COSTS OF INTERNALLY CURED PAVEMENTS

Two projects, previously analyzed were used for the LCCA. The optimized designs for a design life of 30 years with both conventional and ICC alternatives were used in the LCCA for an analysis period of 60 years. Maintenance and rehabilitation (M&R) activities and schedules were established based on AASHTO ME design performance predictions for both the alternatives. The results are as follows:

- The SH 121 CRCP project with 1 inch less thickness for ICC:
 - 5 percent reduction in initial construction cost.
 - 21 percent reduction in M&R costs.
 - 7.6 percent reduction in overall life cycle cost.
- The SH 121 CRCP with same thickness for ICC and conventional:
 - 4.3 percent increase in initial construction cost.
 - 24 percent reduction in M&R costs.
 - 1.3 percent reduction in overall life cycle cost.
- The I-45 JPCP project with 1 inch less thickness for ICC:
 - 1.7 percent reduction in initial construction cost.
 - 6.7 percent increase in M&R costs.
 - 0.9 percent reduction in overall life cycle cost.
- The JPCP project when analyzed for the Midwest climate with same traffic levels and 1-inch thickness reduction for ICC and assuming less slab repairs due to freeze-thaw and joint spalling:
 - 1.4 percent reduction in initial construction cost.
 - 15.8 percent reduction in M&R costs.
 - 2.6 percent reduction in overall life cycle cost.

Thus, the small changes (< 5 percent) in several PCC inputs, brought about by internal curing of the PCC, can result in a significant difference in design thickness leading to reduced LCC.

SUMMARY AND CONCLUSIONS

The two key benefits determined for ICC in concrete pavement are structural longevity and durability. Structural longevity is improved with ICC due to its small reduction in unit weight, elastic modulus and coefficient of expansion and a small increase in strength. These small effects, when combined, amount to a significant positive impact on slab fatigue damage and associated slab cracking in jointed concrete pavements analyzed. Likewise, ICC leads to reduced crack openings and reduced punchout failures in CRCP.

Several case studies were analyzed using the AASHTOWare ME design procedure, and the results indicate improved performance and longer lives of ICC projects. Life cycle cost analyses for these projects showed generally lower costs in ICC as compared to conventional concrete.

ICC also provides durability benefits through moisture loss control and improved hydration, including that of SCMs from extended moisture supply. ICC shows reduction in early age shrinkage and associated plastic shrinkage cracking. Reduction in permeability and improved interfacial transition zone between aggregate and cement paste may also control joint disintegration in pavements that are subjected to freeze-thaw cycles under saturated conditions. Other potential beneficial effects include reduction in upward slab curling and less detrimental effects of long term drying shrinkage.

Summary of ICC Pavement Performance

Field visits were conducted to five ICC pavement projects in the Dallas-Fort Worth area. All projects had been in service for 7 to 8 years since construction, except for the high early strength ramp which was just 1 year old. The projects carried a wide range of traffic, from just 10 trucks a day on the residential pavements, to 240 trailer trucks per day at the intermodal facility, to over 5,000 trucks per day on the freeway. The CRCP freeway project and the residential projects also used conventional concrete that offered control sections for comparison.

Visual surveys were performed in February 2013 to assess the performance of these pavements. In general, all pavements were found to be in very good condition. The five ICC projects did not exhibit any structural distress and did not show any significant signs of shrinkage cracks, spalling, or other non-traffic durability distresses.

The AASHTO ME design procedure was used to predict the performance of ICC and conventional pavements on the CRCP freeway, the JPCP intermodal facility, and the JPCP residential streets. All design inputs were the same except concrete strength, CTE, unit weight, and modulus of elasticity. The results of the analysis consistently indicated that the ICC pavements performed better with longer expected structural life than the conventional concrete sections.

This demonstrates the ability to reduce marginally the structural slab thickness (by 0.5 to 1.0 inch) and, thus, slightly reduce construction cost yet achieve equivalent or better

performance. Alternatively, if it is not desired to reduce slab thickness by this amount, an ICC pavement of equal thickness to a conventional concrete pavement can increase the pavement life and reduce the need for M&R.

Performance benefits using the AASHTO ME design procedure for ICC are purely structural (e.g., fatigue cracking). ICC offers additional durability and construction benefits for pavements, like reduced plastic and drying shrinkage, lower permeability, and therefore the ability to control freeze-thaw cracking and joint deterioration. These benefits can contribute to reduced maintenance over the service life of the pavement

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