EVALUATION OF INTERNALLY CURED CONCRETE FOR PAVING APPLICATIONS

PREPARED BY
Chetana Rao, Ph.D., Consultant
Michael I. Darter, Ph.D., P.E.

Applied Research Associates, Inc.
100 Trade Centre Drive, Suite 200
Champaign, IL 61820
(217) 369-4500

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ABSTRACT

Internally Cured Concrete (ICC) is a concrete mixture in which a portion of the coarse, 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 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 normal weight concrete by replacing a small portion of the normal weight aggregates with an equivalent volume of prewetted LWA that continue to release moisture well after placement. The resulting ICC exhibits physical and mechanical properties favorable for the performance of concrete structures.

ICC has been used on bridge decks in recent years in several States with good success, reducing significantly the amount of plastic shrinkage cracking and other random cracking. ICC has been used only on a few concrete pavement projects in the United States to date and these projects have also shown good results. ICC demonstrated good constructability and has shown excellent performance. The objective of this report is to evaluate the use of ICC in routine concrete pavement design and construction.

The two key benefits determined for ICC in concrete pavement is 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 tighter crack openings and reduced punchout failures in continuously reinforced concrete pavements. 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.

A long term implementation plan titled “Road Map for Internally Cured Concrete Pavements” was developed. This road map aims to give industry and government recommendations on how to proceed to achieve the goal of wider use of ICC in concrete pavement design and construction.

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LIST OF ABBREVIATIONS AND ACRONYMS

AADT	Average annual daily traffic
AADTT	Annual average daily truck traffic
AASHTO	American Association of State Highway and Transportation Officials
AASHTO ME Design	AASHTOWare Pavement ME Design Tool
ACI	American Concrete Institute
ACPA	American Concrete Pavement Association
ARA	Applied Research Associates, Inc.
ASR	Alkali-silica reactivity
CRCP	Continuously reinforced concrete pavement
CRSI	Concrete Reinforcing Steel Institute
CTE	Coefficient of thermal expansion
CTR	Center for Transportation Research
ESCS	Expanded shale, clay or slate lightweight aggregate
ESCSI	Expanded Shale, Clay, and Slate Institute
EUAC	Equivalent uniform annual cost
FHWA	Federal Highway Administration
FLWA	Fine lightweight aggregate
HMA	Hot mix asphalt
HVFA	High-volume fly ash
IC	Internal curing
ICC	Internally cured concrete
IRI	International Roughness Index
JPCP	Jointed plain concrete pavement
LCCA	Life cycle cost analysis
LTE	Load transfer efficiency
LTPP	Long-Term Pavement Performance
LWA	Lightweight aggregate (expanded shale clay and slate lightweight aggregate)
LWC	Lightweight aggregate concrete ("lightweight concrete" for short)
M&R	Maintenance & rehabilitation
ME	Mechanistic-empirical
NTTA	North Texas Tollway Authority
PCC	Portland cement concrete
PMIS	Pavement Management Information System
SCM	Supplementary cementitious materials
SPS	Specific Pavement Studies
SSD	Saturated surface dry
TxDOT	Texas Department of Transportation
TXI	Texas Industries, Inc.
UP	Union Pacific
w/c	Water-cement (ratio)
w/cm	Water-cementitious (ratio)

WSD	Wetted surface dry

CHAPTER 1. INTRODUCTION

Internally cured concrete (ICC) is defined in this report as a concrete mixture in which a portion of the coarse, intermediate, and/or fine aggregates (for example, 30 percent of sand) is replaced with similar sized prewetted lightweight aggregate (LWA). Internal curing (IC) using prewetted LWA is a means to provide hydrating concrete adequate moisture from within the mixture to replace chemical shrinkage water. Additional prewetted LWA may also be added to restore, at least partially, the moisture that escapes through evaporation.

Internal curing, which naturally takes place in lightweight aggregate concrete (LWC), has been specifically designed into normal weight concrete by the inclusion of a relatively small portion of prewetted LWA that continue to release moisture well after placement and into the hydration process (Bentz and Weiss, 2011; Weiss et al., 2012).

It's important to note that:

- ICC is not what is traditionally called lightweight concrete, where all or most of the coarse and/or fine aggregates are lightweight. ICC exhibits only a slight reduction in unit weight, in the order of 5 percent depending on the volume of LWA included in the mixture design.
- IC is intended to supplement, not replace, conventional curing practices. It may offset substandard curing to some extent but does not substitute for properly applied white pigment curing or moist curing in a construction project.
- As described in ASTM C1761, *Standard Specification for Lightweight Aggregate for Internal Curing of Concrete,* there are several types of LWAs available. This report focuses exclusively on expanded shale clay and slate (ESCS) LWA because it's ready available, provides sufficient absorption and desorption, and has a long proven performance history in both laboratory and field studies.
- Internally cured concrete uses absorptive materials in the mixture that supplement the standard curing practices by supplying moisture to the interior of the concrete (ACI 308R-01). This process adds moisture without affecting the *w/cm*. The moisture is desorbed for internal moisture augmentation at the time needed to further hydrate the cement. This water addition can be achieved using several materials (Jensen and Lura 2006; Kovler and Jensen 2007), including prewetted lightweight aggregate, super-absorbent particles, wood fibers, and absorbent limestone aggregate. (ACI (308-213)R-13)

OBJECTIVE

The objective of this project is to evaluate the use of ICC in concrete pavement design and construction. Evaluations were conducted for design, construction, performance, and life cycle costs of ICC for concrete pavements.

BACKGROUND

ICC has been used on bridge decks in recent years 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, particularly in high-performance concrete bridge decks (Streeter, Wolfe, and Vaughn, 2012; Schlitter et al., 2010; Ozyildirim, 2011; ESCSI, 2012a; Delatte and Crowl, 2012). In fact, the use of ICC for bridge decks is rapidly expanding given the remarkable effect on reducing cracking and the accompanying potential benefits and improved surface life (Henkensiefken et al. 2009). However, ICC has only been used on a few concrete pavement projects in the United States to date. All known projects are 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, and more has been placed since then. Several of these projects were surveyed in February 2013 and are documented in this report.

POTENTIAL BENEFITS

With the primary benefit of IC being improved hydration and improved SCM reaction many other concrete properties are also improved. For example the addition of a relatively small proportion of fine lightweight aggregate (FLWA) to a regular mixture in a bridge deck reduces dramatically the amount of plastic shrinkage cracking. The relatively small proportion of FLWA also causes small but collectively significant changes to several key mixture properties, which have been documented in both laboratory and field studies and include the following:

- Reduction in unit weight.
- Reduction in elastic modulus.
- Increase in strength.
- Reduction in coefficient of expansion.
- Reduction in shrinkage.
- Reduction in permeability.

(See 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.) Each of these small changes is potentially beneficial to concrete pavement performance; however, the combined effect of all these changes can be substantial. In addition, there may be other beneficial effects that are possible but have not been fully documented to date, including:

- Reduction in slab upward curling caused by a reduction in the moisture gradient. In a study conducted by Ya and Hansen (2008), prewetted fine lightweight aggregate was found to be effective in reducing moisture warping in addition to eliminating autogenous shrinkage. Intuitively this seems accurate as IC provides moisture uniformly within the system and in a pavement, the tendency toward uniform moisture gradient may reduce slab upward curling. Note that the term curling is normally used to define the change in slab surface curvature due to temperature gradient and warping is used to define the change in slab surface curvature due to moisture gradient. In this document, the term "curling" is used to describe the effect from both causes (which is often done by others) in an attempt to simplify and avoid confusion. A reduction in curling from moisture gradient alone would be a very beneficial.

- Reduction in long-term drying shrinkage, which would reduce joint and crack widths. Field observations show fewer and smaller crack widths with ICC.
- Reduction in permeability, which may lead to reduction in joint deterioration in harsh freeze-thaw climates. This is a complicated problem that is currently being investigated by several researchers.
- Reduction in zero-stress temperature of the concrete mixture. Research is needed to determine if this occurs and its magnitude. If significant, it could lead to narrower crack and joint widths which improve joint/crack load transfer.

While the direct benefits of IC include a reduction in drying shrinkage and improved hydration, potential findings from this study indicate that the combined effects of unit weight reduction, elastic modulus reduction, strength increase, and coefficient of thermal expansion (CTE) reduction add up to a significant positive impact on slab fatigue and associated cracking initiating both from the top of the slab and the bottom of the slab. There also exists a potential for controlling the opening of shrinkage cracks (including sawed joints), which improves the shear transfer ability of the cracks and joints, leading to higher load transfer efficiency (LTE) and longer service life. Further, the reduction in permeability may decrease concrete disintegration at the joints, which is valuable in areas where this distress is prevalent, such as the Midwest and wet-freeze climatic zones.

The AASHTOWare Pavement ME Design tool (AASHTO ME Design) includes inputs for jointed plain concrete pavement (JPCP) and continuously reinforced concrete pavement (CRCP) for the key ICC properties that are known to have some effect. These inputs include flexural strength and/or compressive strength, splitting tensile strength (for CRCP), elastic modulus, unit weight, CTE, and shrinkage. Other inputs that ICC may influence include permanent curl/warp and zero-stress temperature. The change in these inputs between conventional concrete and ICC are small, and thus it appears that the procedure may be utilized to design ICC pavement. Various design comparisons made using AASHTO ME Design for JPCP and CRCP using both conventional concrete and ICC show that using ICC results in a slab thickness reduction of approximately ½ to 1 inch to meet the same performance criteria. Alternatively, ICC pavement with the same structure is be predicted by the AASHTO ME to have a significantly longer life than conventional PCC. So there is a potential savings in cost of design that may balance out the increase in materials cost of ICC. The reduction in concrete shrinkage cracking, permeability, and perhaps upward curling are among other potential benefits resulting in improved performance that would also make ICC pavements cost-effective over the life cycle of the pavement project. See ACI (308-213)R-13 and ACI 213R-13 for details on IC.

ORGANIZATION OF THE REPORT

This report first describes the ICC that is being evaluated for paving applications (chapter 2). The AASHTO ME Design procedure is described in chapter 3, along with an assessment of its applicability to ICC pavement. Chapter 4 provides the results from the field survey of ICC projects in the Dallas/Fort Worth area along with an evaluation of their pavement design and performance. Chapter 5 presents the performance of ICC pavement field projects. Chapter 6 then presents the computation of life cycle costs for conventional concrete and ICC pavements. A road map for further evaluation and implementation of ICC into regular concrete pavement construction is provided in chapter 7. Finally, chapter 8 presents the various findings and conclusions obtained of the field studies, the modeling studies, and the interviews with experts.

CHAPTER 2. INTERNALLY CURED CONCRETE

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, 2013). IC offers a means to provide hydrating concrete adequate moisture from within the system to restore, at least partially, typical "drying" of the paste. IC is achieved by proportioning a concrete mixture with materials that can hold and readily release water when needed for cement hydration. Such materials are typically LWA that replace fractions of coarse, intermediate and/or fine aggregates in a conventional concrete mixture. The LWA fraction is prewetted and maintained at a wetted surface dry condition during batching. (Note that the term wetted surface dry is used for LWA instead of the saturated surface dry term that is used for normal weight aggregate because many LWA particles may take months or even years to be fully saturated). After placement, as the paste starts to lose moisture during hydration, the absorbed water in the larger water-filled pores of the LWA is released into the paste to compensate the moisture lost due to the hydration process. This water supplied from the LWA to the nearby cement paste keeps it saturated and assists with continuing the hydration of the cementitious materials. In a fundamental sense, IC meets the time-dependent moisture needs of hydration to produce concrete with desired properties. For a detailed explanation of the fundamentals of cement hydration, please refer to Chapter 4 of the Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual (Taylor et al., 2007).

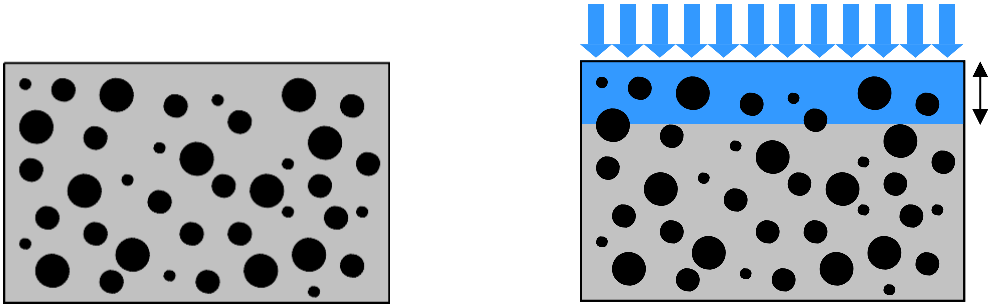
IC may be considered as providing moisture uniformly within the system, in contrast to traditional top-down curing methods, or as in pavements with only applied curing compound. As illustrated in Figure 1, prewetted LWAs provide moisture throughout the mass of the concrete. This alone can reduce shrinkage 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 uniform moisture gradient may reduce slab curling.

Interestingly, there exists historical evidence of the use of natural LWA concrete in the ancient Roman Empire, the most well-known being its use in the Pantheon (ESCSI, 1971; Bremner, and Ries, 2009). In the early 1900s, Stephen J. Hayde developed a firing process to produce artificial LWA from naturally occurring clay, shale, and slate raw materials. These aggregates were extensively used to build concrete ships during World Wars I and II. During the 1950s, the internal curing potential of LWAs was discovered, but the last two decades have seen a surge in the use of ICC based on a scientific understanding of the IC process and the user's ability to achieve desired properties in the concrete by appropriate mixture proportioning techniques (Klieger, 1957; Philleo, 1991). ICC has been used on several construction projects in the last decade, especially in the construction of bridge decks, floor slabs, and to a limited extent in pavements. Some State agencies (Indiana and

New York) have developed standard specifications for using ICC in routine engineering practice or are considering establishing standard procedures (ESCSI, 2012b; Greene and Graybeal, 2012).

In doing this study, four reference documents stand out as practical overall tools that cover the benefits, design, and use of ICC in detail:

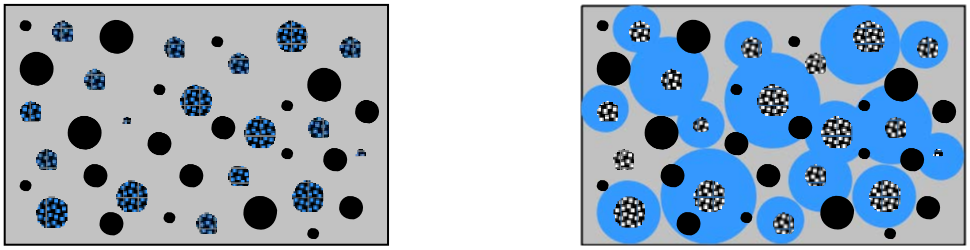
- ACI (308-213)R-13, *Report on Internally Cured Concrete Using Prewetted Absorptive Lightweight Aggregate.*
- ACI 213R-13, *Guide for Structural Lightweight-Aggregate Concrete.* This document has passed all ACI committee approvals and will be published later this year.
- Bentz, D.P., and Weiss, W.J., *Internal Curing: A 2010 State-of-the-Art Review, NISTIR 7765, U.S. Department of Commerce,* February 2011.
- ASTM C1761/C1761M-12, *Standard Specification for Lightweight Aggregate for Internal Curing of Concrete.*



a) Conventional concrete

b) Conventional concrete after curing

CONVENTIONAL CURING



c) Concrete with IC

d) Concrete with IC after curing

INTERNAL CURING

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

IC Benefits

It was almost intuitively understood that the use of prewetted LWAs could help reduce plastic shrinkage cracking. The additional internal free moisture available, particularly soon after the onset of drying, enables a more complete hydration process. The improved interfacial transition zone reduces stress concentrations between the paste and the aggregate surface (Peled, Castro, and Weiss, 2010). This, in combination with reduced internal plastic shrinkage stresses, subsequently reduces the amount of early age cracking in the concrete (Henkensiefken et al., 2010). This phenomenon is analogous to using aggregates with high absorption to control cracking (Delatte, Mack, and Cleary, 2007). Further, as agencies began to adopt high-performance concrete, which typically has a low water-cement (w/c) ratio and an increased propensity for autogenous shrinkage, ICC presented a great tool for the control of cracking in bridge decks (Bentz, Geiker, and Jensen, 2002; Bentz, Lura, and Roberts, 2005; Varga, Castro, and Weiss, 2012; Byard, 2012).

ICC mixes have been shown to reduce cracking in bridge decks. Both laboratory and field test data have shown significant reduction in crack widths (Kim and Won, 2008; Bentz and Weiss, 2011). Laboratory test results have shown decreasing plastic shrinkage crack widths with increasing LWA substitution (Henkensiefken, et al., 2010). Crack width reductions of up to 65, 89, and 100 percent were observed for LWA contents of 6, 10, and 18 percent (by weight of total aggregate content), respectively. For 6 percent replacement, which is the range of interest for paving mixes, measured CRCP crack widths were significantly less for ICC than conventional concrete. More detailed discussion on crack width reductions in ICC pavements is provided in chapter 3 (Kim and Won, 2008; Friggle and Reeves, 2008).

The reduced shrinkage, especially in restrained systems or partly restrained systems like pavements, delays the time at which the zero stress is achieved (post final set). The zero stress temperature is defined as the temperature (after placement and during the curing process) at which the PCC layer exhibits zero thermal stress. If the PCC temperature is less than the zero stress temperature, then tensile stress develops in the slab. Byard and Schindler (2010) explained this phenomenon in detail. They also provided ample laboratory test data recording temperatures at set and at zero stress. In the context of a pavement, this implies that the zero-stress temperature is slightly reduced by about 5 percent, based on laboratory test data. This may not be significant for altering pavement performance unless paving is performed under extremely high ambient temperature conditions, which often do occur.

Over time, the concrete construction industry has come to recognize that IC has other far-reaching benefits (Hoff, 2002; Bentz and Weiss, 2011; Weiss et al., 2012). For example, by reducing the autogenous and drying shrinkage, ICC has a potential to withstand larger temperature variations before cracking (Schlitter 2012). A second benefit, consequential to controlled cracking and reduce permeability, is the ability to curb corrosion in reinforcing steel and chloride ion penetration caused from the use of road salts and other chemicals in harsh winter climates. Also, the improved hydration produces a denser microstructure and, hence, lower permeability, which was noted in mixes with LWA (Thomas, 2006; Ozyildirim, 2011; Weiss et al., 2012). It is worth emphasizing here that the control of moisture movement in a cement paste is considered the single most effective means to mitigate a host of durability issues, including freeze-thaw problems, D-cracking, chloride transport, and perhaps even alkali silica reactivity (ASR) (Bentz and Weiss, 2011; diBella et al., 2012). In general, studies have shown that ICC has superior, or at least similar, performance to normal concrete.

IC may be especially useful in concrete mixture designs wherein prolonged hydration is expected; therefore, continued supply of moisture from IC can sustain the hydration reactions (Russell, 1973, 1978; Castro et al., 2010; Delatte and Crowl, 2012; de la Varga, Castro, and Weiss, 2012). For example, in high-volume fly ash (HVFA) mixtures, which contain more than 40 to 50 percent fly ash replacement for cement, the fly ash particles require extended curing to fully achieve hydration. The role of IC becomes more dominant because of internally providing the needed moisture, but also because it can be a challenge to externally provide moist curing for periods beyond 3 to 14 days after placement. Likewise, Type K cement (expansive cement used as shrinkage compensating cement) mix designs were found to perform better with the use of LWA than with normal weight aggregates (Russell, 1973, 1978) because moisture from LWA allows the expansive reactions in the Type K cement to continue longer and achieve more expansion.

In recent years, other promising benefits of IC on mechanical properties of concrete have come to light (Hoff, 2002; Byard and Schindler, 2010; Maruyama and Teramoto, 2012). A recent laboratory study evaluated the performance of concrete mixture designs with prewetted shale, clay, and slate LWAs in various proportions in concrete mixture designs cured at different temperatures. The study showed that the higher the amount of prewetted aggregates, the lower the density, modulus of elasticity, CTE, autogenous shrinkage, and zero-stress temperature (Byard and Schindler, 2010). The tests also indicated an increase in compressive strength and splitting tensile stress. The use of LWA also delayed the onset of cracking. There were, at times, notable differences between LWA types—shale vs. clay vs. slate—and differences between the two curing temperatures—fall vs. summer temperature conditions. But the results were also influenced by differences in the selection of LWA quantity and size distribution in the mixture design, suggesting the options of using different LWA size distributions in a mixture design. The different mixture designs used in this study are discussed in the next section on IC mix design.

Internal Curing for Pavements

The successful use of IC in bridge decks and floor slabs was encouraging for the industry to explore IC for paving applications during the past decade. In fact, a 1965 study investigated the mechanical properties in structural concrete and effects of restrained and unrestrained volume changes for concrete pavement design (Ledbetter et al., 1965). The study estimated lower curling stresses and deformations with lightweight concrete and recommended its use in paving, while also emphasizing the need for proper curing.

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. Also, these projects cover a range of facility types and traffic levels. A detailed discussion of the paving projects is provided in chapter 4.

An innovative application was in the use of ICC in a high early strength mix design paving project, where the pavement was required to be opened to traffic in 12 hours. ICC was incorporated into the high early strength mix that used Type III cement and a non-chlorine accelerator. Given that high early strength pavement slabs typically experience extreme shrinkage cracks in the early stages, and durability problems associated with high permeability issues, ICC will reduce the cracking potential of the slabs. Also, the reduced modulus of elasticity will control the development of excessive stresses.

The United States has a fairly large concrete pavement market. The American Concrete Pavement Association (ACPA) estimates that the quantity of paving is about 60 to 70 million square yards annually (Voigt, 2013). The successful use of ICC for field projects has opened a promising opportunity for the use of LWA in routine practice.

LWA plants are also quite widely distributed nationwide, so LWA can be sourced from within reasonable hauling distances. Clearly, the size and scope of each paving project will determine the cost efficiency of incurring the additional cost, which may be offset by the design and performance benefits contributed by ICC. Currently, expanded shale, clay, and slate LWA plants are situated in the following locations:

- Livingston, AL
- Proctor, AR
- Frazier Park, CA
- Boulder, CO
- Brooklyn, IN
- Marquette, KS
- Louisville, KY
- Erwinville, LA
- New Market, MO
- Aquadale, NC
- Gold Hill, NC
- Cohoes, NY
- Saugerties, NY
- Independence, OH
- Streetman, TX
- Coalville, UT

ICC MATERIALS AND MIXTURE DESIGN

As explained previously, ICC mixtures are designed with LWA batched in a prewetted surface dry condition, and the LWAs are expected to make moisture available periodically when needed after the concrete begins to desiccate. Expanded shale, clay and slate LWAs are manufactured in a rotary kiln using naturally mined slate, shale, or clays. The raw materials are sized in a standard process and fed through a rotary kiln, where they are subjected to temperature levels of approximately 2,000 °F (see Figure 2). This heating process releases gases from the materials, causing the formation of pores and an expansion of the material. This expansion in volume is what gives the aggregate a lower density, and the creation of pores gives it an ability to absorb water. The material is cooled and crushed to particle sizes equivalent to those of normal weight concrete aggregates. LWAs can be blended to desired size distributions, or blended with normal weight aggregates to obtain size distributions appropriate for concrete mixture designs.

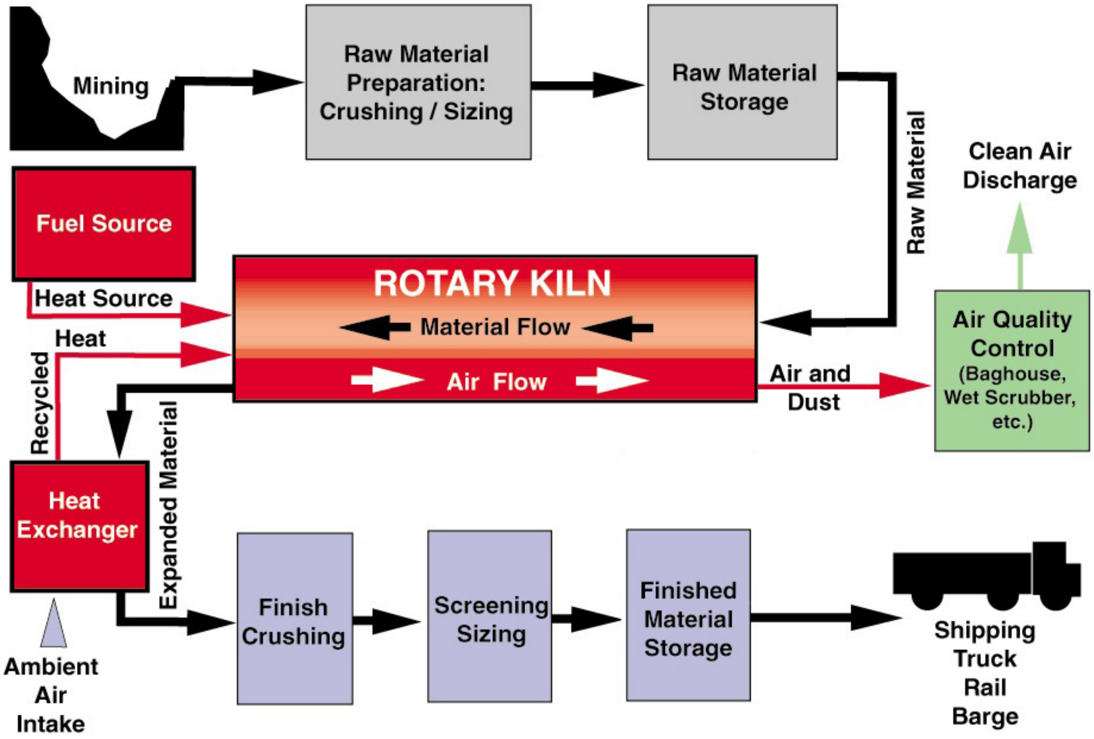


Figure 2. LWA production process in a rotary kiln (image courtesy ESCSI, accessed from http://www.escsi.org/ContentPage.aspx?id=524)

ICC is very similar to normal weight concrete and is designed by modifying the relative quantities of coarse, intermediate and/or fine aggregates in the mixture design. ICC mixtures have been produced by replacing various quantities and size distributions of normal weight aggregates with LWA. The most common practice is to replace a portion of the normal weight fine aggregate with FLWA. This is primary due to FLWA having a better distribution, are easier to produce, and are typically less expensive.

In mixture designs with fine aggregate replacements, roughly 30 to 33 percent by volume of the normal weight fine aggregate is replaced with FLWA. This is a straightforward replacement, and this type of replacement provides a more uniform distribution of moisture within the ICC (Barrick, 2013). It is important to note here that LWA replacements are volumetric replacements and not replacements by weight while batching for unit volume. Adjustments to the weight are necessary to account for the difference in density between LWA and normal weight aggregates. For example, while batching for a cubic yard of ICC, for a volumetric replacement of 5 ft^3 of intermediate LWA, it may be necessary to replace 300 lb of coarse aggregate and 200 lb of sand with 300 lb of intermediate LWA. In other words, the 300 lb of coarse aggregate and 200 lb of fine aggregate combined will occupy about the same volume as the 300 lb of LWA.

Table 1 shows example mixture designs for shale LWA from a recent laboratory study in which all LWA types (shale, clay, and slate) were tested (Byard and Schindler, 2010). For each LWA type, four different proportions of LWA replacements were made. The four mixture designs (per cubic yard) presented are:

- Conventional concrete with normal weight aggregates, which serves as the control. No LWA is included in this mixture.
- IC concrete (ICC) mixture in which a portion of the normal weight fine aggregates was replaced with FLWA. Note that the replacement is not by weight. 332 lb of normal weight sand was replaced with 230 lb of FLWA.
- Lightweight concrete mixture in which 1761 lb of normal weight coarse aggregate was replaced with 933 lb. of coarse LWA. This replacement has also been supplemented by an increase in the amount of normal weight sand by 144 lb
- All lightweight concrete mixture in which all the normal weight coarse and fine aggregates have been replaced with lightweight coarse and fine aggregates, 948 and 908 lb, respectively.

At the time of the study, all these mixture designs are being used for bridge deck construction. This research clearly shows the comparison of ICC mixtures with traditional bridge deck mixtures. It also shows the benefits of internal curing in typical lightweight concrete mixtures. However, for paving applications, ICC mixtures with partial replacements of the fines and/or the intermediate size aggregates (coarse and fine fractions) typically are considered most suitable.

In mixture designs where intermediate size (3/8 inch to #8 or #16) LWA is used, a portion of both the normal weight fines and coarse aggregates are typical replaced. Many concrete mixtures use gap-graded aggregates and the addition of intermediate LWA helps fill the grading gap as well as provide internal curing. Table 2 provides an example of one such mixture design that was used on the Union Pacific Intermodal facility, a major JPCP project in Dallas-Fort Worth (discussed in chapter 4). This table provides the mixture proportions for both conventional and ICC mixes. Note that 300 lb of intermediate size LWA replace a combined 500 lb of normal weight coarse and fine aggregates. This amounted to 5 ft^3 of LWA replacement, which was determined in the laboratory as the optimum replacement necessary to get the strength benefits shown in Table 3. The gradation of the aggregates is shown in Table 4.

Table 1. Example mix designs showing the replacement of normal weight aggregates with shale lightweight aggregates.

Mix component	**Control**	**IC**	**Coarse LWA Mix**	**All LWA mix**
Water (lb/yd^3)	260	260	276	276
Cement (lb/yd^3)	620	620	658	658
SSD normal weight coarse aggregate (lb/yd^3)	1761	1761	*0*	*0*
WSD shale lightweight coarse aggregate (lb/yd^3)	0	0	**933**	**948**
SSD normal weight fine aggregate (lb/yd^3)	1210	878	1354	0
WSD shale lightweight fine aggregate (lb/yd^3)	0	**230**	0	908
Water-reducing admixture (oz/yd^3)	31	31	0	0
High-range water-reducing admixture (oz/yd^3)	0	0	39.5	16.5
Rheology-controlling admixture (oz/yd^3)	0	0	0	79.0
Air-entraining admixture (oz/yd^3)	0.8	0.8	6.6	2.9
Target total air content (%)	5.5	5.5	5.5	5.5
w/c	0.42	0.42	0.42	0.42

SSD = saturated surface dry; WSD = wetted surface dry

Table 2. Mixture proportions and properties of reference and [ICC] LWA modified concretes (Villareal and Crocker, 2007).

Material	Specification	Reference Mixture	LWA-modified Mixture [ICC]
Cement	ASTM C 150 Type I/II	451 lb/yd^3 (268 kg/m^3)	451 lb/yd^3 (268 kg/m^3)
Fly ash	ASTM C 618, Class C	113 lb/yd^3 (67 kg/m^3)	113 lb/yd^3 (67 kg/m^3)
Coarse aggregate	ASTM C 33, No. 57, crushed limestone	1840 lb/yd^3 (1092 kg/m^3)	1540 lb/yd^3 (914 kg/m^3)
Intermediate lightweight aggregate	ASTM C 330, 3/8 in. to No. 8 (9.5 to 2.36 mm)	0 lb/yd^3 (0 kg/m^3)	**300 lb/yd^3 (178 kg/m^3)**
Fine aggregate	ASTM C 33, natural sand	1301 lb/yd^3 (772 kg/m^3)	1099 lb/yd^3 (652 kg/m^3)
Water	ASTM C 94	242 lb/yd^3 (144 kg/m^3)	242 lb/yd^3 (144 kg/m^3)
Water-reducing admixture	ASTM C 494, Type A	4 fl oz/100 lb (260 mL/100 kg)	4 fl oz/100 lb (260 mL/100 kg)
Air-entraining admixture	ASTM C 260	As required	As required
Air content	3.0 to 6.0%		
Slump	2 ± 1 in. (50 ± 25 mm)		
f′c	4500 psi (31 MPa)		

Table 3. Comparison of cementitious materials and strengths in ICC relative to conventional concrete (Villareal and Crocker, 2007).

Mixture*	**Cementitious Material Content, lb (kg)**	**Average Slump, in. (mm)**	**Target Compressive Strength at 28 Days, psi (MPa)**	**# of Field Tests**	**Average Compressive Strength at 28 Days, psi (MPa)**	**Percent of Reference**	**Difference, psi (MPa)**
8204SF	517 (235)	2 (50)	3000 (21)	98	5130 (35.4)	—	—
8204SFX	517 (235)	2 (50)	3000 (21)	106	6070 (41.9)	118%	940 (6.5)
8206	564 (256)	5 (125)	4500 (31)	91	5230 (36.1)	—	—
8206X	564 (256)	5 (125)	4500 (31)	68	6510 (44.9)	124%	1280 (8.8)
8206SF	564 (256)	2 (50)	4500 (31)	65	5750 (39.6)	—	—
8206SFX	564 (256)	2 (50)	4500 (31)	110	6750 (46.5)	117%	1000 (6.9)

*Mixtures with the suffix "X" in the label included LWA [ICC].

Table 4. Aggregate gradation comparisons between ICC and normal weight concrete when intermediate size aggregates are replaced with LWA (Villareal and Crocker, 2007).

Gradation	**Crushed Stone**	**LWA**	**Natural Sand**
Sieve size			
Blend percentage by volume	49%	16%	35%
Percent passing:			
1-1/2 in. (37.5 mm)	100	100	100
1 in. (25.0 mm)	98.4	100	100
3/4 in. (19.0 mm)	74.8	100	100
1/2 in. (12.5 mm)	42.2	100	100
3/8 in. (9.5 mm)	19.4	**98.3**	100
No. 4 (4.75 mm)	5.4	**39.9**	96.6
No. 8 (2.36 mm)	1.2	**7.9**	88.3
No. 16 (1.18 mm)	0	**3.2**	77.1
No. 30 (600 µm)	0	0	57.7
No. 50 (300 µm)	0	0	16
No. 100 (150 µm)	0	0	1.3
No. 200 (75 µm)	0	0	0.2
Fineness modulus	6.99	5.51	2.63

Concrete suppliers and ICC material technologists opine that there may be other benefits to using an intermediate size gradation of LWA The larger coarse aggregates hold moisture longer and may be able to offer a longer period of internal curing in the mixture. This type of gradation may be more useful in dry and hot paving climates. Overall, it appears that, as a starting point, ICC mix designs used for bridge decks can be used for paving concretes as well (Villareal, 2013).

IC for Mixtures with Supplementary Cementitious Materials

IC helps with the curing process in mix designs with supplementary cementitious materials (SCM) such as fly ash or slag. The benefits can be substantial for multiple reasons. Fly ash replacement improves the workability of a concrete mixture and reduces the water demand, which in turn allows the use of lower w/cm. However, these mixes also need extended curing because of delayed reaction of the supplementary cementitious particles and delayed set times. IC using LWA can meet the additional water demand past the normal curing period. The enhanced curing, in many ways, makes it possible to fully realize other durability-related benefits offered by the incorporation of the SCM.

Designing an Internal Cured Concrete Mixture

The following quote from ESCSI publication 4362.1 (2012a) 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 expanded shale, clay, or slate (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&ekmensel=1b7c39fc_61_74_698_6 or by contacting the ESCS lightweight aggregate supplier.

Quality Assurance Considerations for ICC

The benefits of internally curing concrete are solely derived from prewetting the LWA for an effective transfer of moisture from the aggregate to the cement paste as needed. The moisture content in LWA ranges from about 7 to over 25 percent. For this reason it is imperative designers and users of ICC consult the LWA supplier for prewetting procedures and mixture design recommendations (Villarreal, 2007; 2013, ESCSI 2013). The effectiveness of internal curing is controlled by four factors (ACI 308, 2013; Bentz et al.2005):

1. The amount of water in the LWA.
2. The LWA particle spacing factor.
3. The LWA pore structure.
4. Strength and shape of the lightweight aggregate.

Items 3 above is inherent to the selected material source, the overall aggregate gradation of the mixture, the size distribution of the LWA (fines vs. intermediate size), and the percentage replacement of LWA control item 2. These two factors are often optimized in the mixture design stage. Also, central to the mixture optimization and the measured mechanical properties is the amount of water in the prewetted LWA in which the pores are filled with water prior to mixing. It is also critical to ensure that the aggregates are capable of releasing the expected amounts of moisture.

Failure to properly prewet the aggregate can lead to concerns ranging from yield issues to slump loss, segregation, and finishability. Lack of adequate moisture in the aggregates can result in a dryer mixture as the LWA will tend to absorb moisture from the paste. This may lead to problems in slump loss, and general constructability. Also, during vibration and finishing, the LWA may rise to the top of the slab because of their lower density.

Concrete Batching, Mixing, Transporting, Placing, and Finishing

The batching, mixing, transportation, placing, and finishing of ICC is not significantly different from any other common concrete practice. In batching, the lightweight aggregate and mixing water should be placed in the mixer first for further assurance that the lightweight aggregate is properly prewetted. When the lightweight aggregate meets the criteria cited in this report, the concrete mixture exhibits batching mixing, transporting, placing and finishing characteristics that are similar to an equivalent conventional mixture without internal curing (ACI(308-213)R-13).

As stated previously, the industry recommends that the LWA supplier's recommendation for prewetting the LWA be followed to ensure the aggregate is ready for ICC application. Prewetting coarse LWA is commonplace in making structural lightweight concrete, so the means and methods are easily available to be applied to paving applications. . What is not as common, but equally easy to do, is prewetting the FLWA. The most common method of prewetting FLWA is by sprinkling. The following guideline is offered to give a general understanding of how the process works.

Construct ESCS lightweight aggregate stockpile(s) at the production facility so as to maintain uniform moisture throughout the pile and to prevent contamination of the LWA with foreign material. Using an approved sprinkler system, continuously and uniformly sprinkle the stockpile(s) with water, turning or mixing the pile(s) as needed to reduce moisture variation. Sprinkling should continue for a minimum amount of time (consult the LWA supplier; a minimum of 48 to 72 hours is common) or until the absorbed moisture content of the stockpile reaches the specified minimum absorption as determined by test method NY 703-19E.

If a steady rain of comparable intensity occurs, turn off the sprinkler system until the rain ceases. At the end of the wetting period, or after a rain event, allow stockpile(s) to drain for a significant amount of time (usually 12 to 15 hours) immediately prior to use.

Covering stockpile(s) with a non-permeable cover after saturation will help reduce loss through evaporation and increase the moisture consistency of the stockpile(s).

Turn or remix stockpile(s) prior to use.

Other methods of material prewetting proven to supply and maintain adequate and consistent moisture in the field may be available. Consult with the ESCS lightweight aggregate supplier.

ICC in the Field

The quantity of ESCS material must be adjusted, when needed, to maintain the required amount of internal moisture for internal curing. The methods used in the handling and storage of the ESCS material will have a considerable impact on how much and how often these adjustments must be made. Prewetting the LWA, maintaining the desired moisture level, and controlling the excess free moisture present on the ESCS material will reduce the amount of batch to batch variability and needed mixture adjustments, as well as greatly increase the ease of use at the batch plant.

Fresh Concrete Properties

Issues involving the concrete unit density, air content, and testing methods required for structural lightweight concrete typically are not encountered with an ICC mixture because only a small quantity of ESCS material is used in the concrete mixture. A small increase in air generation during batching may be experienced due to the surface texture of the ESCS material. This is typically small and can be easily addressed during the concrete mixture's trial batch stage of design testing. Testing for air content of the plastic concrete may reliably be performed using ASTM C-231 (pressure method), but correlation testing with ASTM C-173 (volumetric method) during concrete mixture trials is advisable.

IMPACT OF ICC ON CONCRETE MATERIAL PROPERTIES

Based on laboratory test data reported in the literature and field results, the following are typical changes to concrete material properties from internal curing with roughly 300 lb or 5 ft^3 of LWA volumetric replacement for conventional concrete.

- Compressive strength increase of 5 to 10 percent, or up to 20 percent if test data are available.
- Flexural strength increase of 5 percent.
- Splitting tensile strength increase by 5 percent.
- Elastic modulus reduction by 5 percent.
- CTE reduction by 5 percent, or up to 10 percent if test data are available.
- Unit weight reduced by 7 pcf (for about 5 ft^3 of LWA inclusion).
- Zero-stress temperature reduction by 5 percent.
- Reduction in shrinkage crack width in CRCP by as much as 60 percent. A reduction of 20 percent is conservative and acceptable in the absence of field test results.
- Reduction in permeability of 10 percent or more is typical.

Note that these changes pertain only to mixture designs with a portion of fine aggregates or a portion of the intermediate size aggregates replaced with LWAs. They are not applicable to lightweight concrete mixtures in which the entire coarse aggregate or fine aggregate fractions or both are replaced by LWAs. Also, the impact on material properties may be different for high performance concrete mixtures designed with IC.

IC and Concrete Pavement Sustainability

ICC may have significant sustainability and durability advantages. The potential of ICC for increased durability and longer life would be a major component of sustainability. One of the current major interests of many State highway agencies is to build concrete pavements that will have longer lives. In fact, many States call this their "long life pavement program." Design lives have been increased from 20 years to 30, 40, 50, and even 60 years in some States. California has researched the use of 100-year design life, which was of interest to environmental, and natural resource groups, as well as government. This trend is expected to continue as traffic congestion increases and sustainability gains more importance.

Cusson et al. (2010) compared the service lives of theoretical high-performance concrete bridge decks with and without internal curing. Based on his 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-13). Although this was done for bridge decks, it indicates the possible potential for concrete pavements.

Recent work with the use of SCM has suggested that substantially less cement clinker can be used in a mixture, resulting in a lower carbon footprint (De la Varga et al. 2011). This may also be true for mixtures with increased limestone powder replacement for cement (Bentz et al. 2009; ACI 213R-13).

Durability of ICC Pavements

Perhaps the greatest potential benefit of ICC lies in its ability to provide good curing throughout the entire concrete slab thickness, as opposed to only spray-on white curing compound or just curing the surface layer with external curing. Clearly, this supports a thorough hydration of all cementitious particles and most importantly a tighter, low-permeability cement matrix. The obstruction of water permeating into the concrete is a certain way to reduce a variety of potential durability issues, including ASR, sulfate problems, corrosion, freeze-thaw damage, and D-cracking.

Joint deterioration is considered one of the most serious of materials-related distresses that is not addressed through the AASHTO ME Design structural models. Concrete more susceptible to moisture ingress (i.e., concrete with high permeability) tends to disintegrate at transverse joint locations for various reasons. In many States in the Midwest there exists substantial joint deterioration below the surface which eventually spalls out requiring repair. For example, in research studies conducted in Michigan in the 1990s (Smith, et al. 1990), cores taken at transverse joints from concrete pavements built on dense asphalt bases with no permeability showed extensive material disintegration (the percent joints spalled was 60 for these sections) compared to sound concrete cores from pavements with exactly same concrete mixture that were built on permeable asphalt bases where free water could drain downward at the same site (the percent joints spalled was 9). Similar disintegration has been found at many joints across the Midwest. Joint repairs are a key maintenance activity in the maintenance and rehabilitation (M&R) schedules of several State highway agencies. This situation is much more critical in wet-freeze climates than in warmer and drier climates.

While there are no current tools to predict durability performance in a pavement or assess its impact on the development of structural distresses (cracking, faulting, corner breaks, spalling, etc.) or functional distresses (ride quality), a durable concrete material assures a long life with less M&R intervention over the life of the pavement as long as the design has adequate structural capacity.

CHAPTER 3. PAVEMENT DESIGN AND PERFORMANCE PREDICTION FOR ICC

INTRODUCTION

The AASHTO ME Design procedure was completed in 2006 after several years of intensive development. The procedure was approved by all of the States in 2007 as an AASHTO standard and is being implemented and used by many States at the present time. The procedure can be used to design and or analyze JPCP and CRCP, as well as asphalt pavements. The inputs for concrete materials and the mechanistic-based models make it possible to use the procedure to analyze ICC pavement, both JPCP and CRCP. This chapter describes the key inputs and the justification for using the procedure for ICC pavement.

AASHTOWARE PAVEMENT ME DESIGN PROCEDURE

The AASHTOWare Pavement ME Design procedure—or AASHTO ME Design—is based on mechanistic-empirical design concepts. The design procedure calculates pavement responses such as stresses, strains, and deflections under axle loads and climatic conditions and then accumulates the damage over the design analysis period. The procedure then empirically relates calculated damage over time to pavement distresses and smoothness based on performance of actual projects throughout the United States.

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.

The algorithms and models used for pavement design and analysis are presented in the Mechanistic-Empirical Pavement Design Guide, Interim Edition Manual of Practice (AASHTO, 2008). The models were calibrated and validated using extensive pavement performance data from the United States and southern Canada. All of the JPCP and CRCP used for calibration included conventional concrete. However, the key properties of the concrete slab varied widely across these hundreds of pavement sections.

The key question is: Can AASHTO ME Design be used to analyze and design JPCP and CRCP projects that include ICC? The applicability of the procedure to ICC pavement is evaluated based on consideration of the inputs and of the models and algorithms involved.

DESIGN INPUTS AND MODELS AFFECTED BY ICC

ICC properties are altered in a manner that is beneficial for pavement performance, as summarized in chapter 2. Increased strength, reduced modulus, reduced shrinkage, reduced unit weight, and reduced CTE reduce stresses and improve performance. However, the IC process has other major influences on the behavior of the pavement and in the development of distresses. For example:

- ICC can alter the built-in slab deformation and built-in stresses in JPCP and CRCP due to reduced concrete shrinkage.
- ICC can alter the crack spacing patterns and crack opening magnitudes in CRCP due to reduced concrete shrinkage.
- ICC can reduce tensile stresses in concrete slabs and decrease the rate of fatigue damage accumulation, especially at the top of the slab.

Effect of ICC on Built-in Stresses

Temperature or moisture differentials between the top and bottom of a concrete slab cause the slab corners to curl down or curl up depending on the gradient type. Positive temperature or moisture gradients (i.e., higher temperature or moisture at the top of the slab relative to the bottom of the slab) cause the top surface to expand relative to the bottom surface. Likewise, negative gradients cause the bottom surface to expand relative to the top. When restraints from the dead weight of the slab and the frictional resistance of the base come into effect, high tensile stresses exist at the bottom and top of the slab for positive and negative gradients, respectively (see Figure 3). These differentials occur in a cyclic fashion on a daily and seasonal basis throughout the service life of a pavement. Stresses resulting from these cyclic changes add to the load-related stresses.

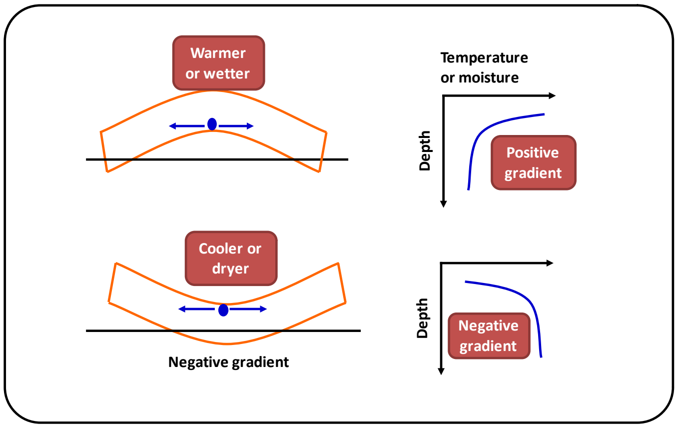


Figure 3. Concept of slab curling and warping.

Additionally, field slabs develop permanent effective built-in stresses that account for gradients locked into the pavement as a result of built-in temperature gradients, concrete shrinkage gradients, and creep. In other words, temperature gradients induced in the slab due to ambient temperature conditions at the time of set, combined with shrinkage at the time of placement and creep over time, are permanently locked into the slab (see Figure 4). Reducing the shrinkage component of upward curling will significantly minimize built-in gradients and result in more uniform slab support. Note that the reduction in the shrinkage gradient is a result of more uniform curing (refer back to Figure 1) throughout the depth of the slab and the reduction in shrinkage from the surface.

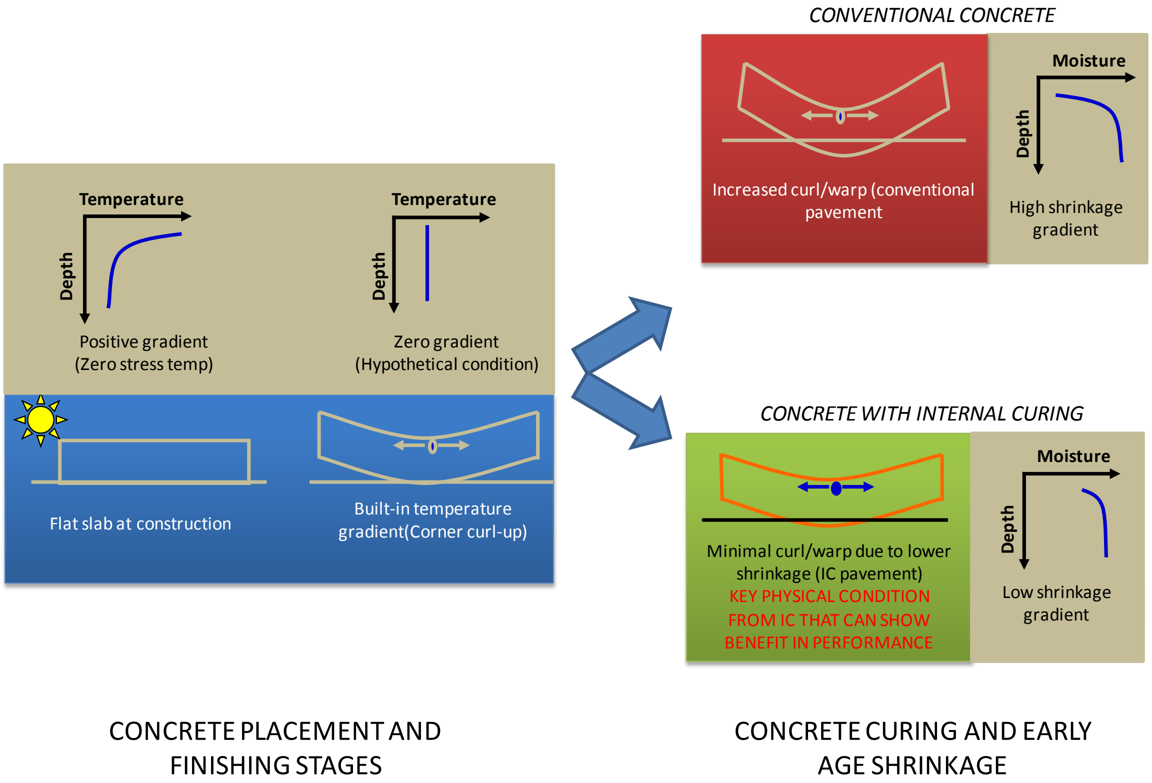


Figure 4. Construction-related permanent built-in temperature and shrinkage gradients.

Effect of IC on Crack Spacing in CRCP

CRCP are constructed without transverse joints, and the slab is reinforced with longitudinal steel bars to keep transverse cracks tight. As the concrete sets and begins to shrink, the steel restrains the concrete and causes transverse cracks at a spacing of about 2 to 8 feet. The crack pattern is highly dependent on concrete shrinkage in addition to a variety of other factors, including slab thickness, concrete CTE, and concrete strength. The crack spacing also essentially determines the length of the slab that is expanding and contracting at each transverse crack, which affects the crack opening at the specific location.

The reduced shrinkage from ICC will result in longer crack spacings in the initial years, but as drying shrinkage approaches that of normal concrete, additional shrinkage cracks will develop in ICC CRCP at spacings close to those of conventional concrete (see chapter 4). However, the increased tensile strength and controlled shrinkage will tend to maintain the cracks tight.

Effect of ICC on Fatigue Damage

The reduction in elastic modulus is a huge benefit for the reduction of stresses and fatigue damage in both JPCP and CRCP designs. In combination with increased strength and reduced CTE, a significant reduction in fatigue damage is guaranteed. However, the development of stresses and the damage accumulation are dependent on the slab thickness, other design features (shoulder type and lane width), and level of traffic.

Figure 4 shows that concrete undergoes early age shrinkage, which has long been recognized as the most critical component of ultimate shrinkage that needs to be controlled for long-term performance. Further, concrete also undergoes drying shrinkage after the concrete has set, and this component of shrinkage typically occurs due to drying and rewetting of the concrete from the ambient relative humidity conditions. Laboratory data have shown that a portion of shrinkage strain is reversible upon rewetting. The lower the initial shrinkage, the greater the ability to recover shrinkage strain upon rewetting. Concrete with IC therefore presents a great potential to increase reversible shrinkage—that is, rewetting can benefit concrete with IC more than without IC.

In a concrete pavement, the bottom of the slab remains wet, and drying occurs in the top of the slab. As illustrated in Figure 3, moisture changes induce shrinkage stresses that are additive to the temperature and load-related stresses in concrete. The AASHTO ME Design procedure uses a user-defined ultimate shrinkage development model based on the form of ACI's shrinkage equation (old ACI equation). By defining the time taken to develop half the ultimate shrinkage and the magnitude of ultimate shrinkage, the user indirectly provides an estimate of concrete shrinkage over the life of the concrete pavement.

A review of the AASHTO ME Design models and algorithms does not indicate there are any potential problems to designing or analyzing either JPCP or CRCP that incorporate ICC.

Are key ICC inputs within the range of normal concrete inputs?

The key inputs affected by ICC that are also inputs of the AASHTO ME Design procedure include concrete strength, modulus of elasticity, CTE, and unit weight. These are listed in Table 5 along with the means and ranges of these inputs that were used in the national calibration work. The typical value of each input for ICC mixtures is also shown.

The results show that the potential concrete inputs for ICC mixtures are well within the range of the conventional concrete from across the country. For example, the modulus of elasticity of an ICC mixture has been reported in the literature to be about 5 to 10 percent lower than conventional concrete (Byard, 2010). If conventional PCC modulus, E_c, was, say, 5 million, the ICC E_c would be expected to be about 4.5 million psi. This is well within the range of the calibration data, which show E_c measured down to 2.5 million psi. The same results appear to hold for all the other inputs listed.

Table 5. Summary of concrete inputs for conventional concrete pavements used in the national calibration work, along with expected impacts for ICC.

AASHTO ME Input	Range of Input from National Calibration Database	Typical ICC Impact	Comments
Flexural strength, psi	440 to 960 (716 mean)	Approximately 5-20% higher	ICC flexural strength within range of calibration data
Modulus of elasticity, psi	2.5 to 5.6 (4.1 mean)	Approximately 5% lower	ICC modulus of elasticity within range of calibration data
Unit weight, pcf	134 to 155 (147 mean)	Approximately 6 pcf lower	ICC unit weight within range of calibration data
CTE, $*10^{-6}/^{o}F$	3.4 to 7.6 (4.7 mean)	Approximately 5% lower	ICC CTE within range of calibration data

Thus, for these key inputs, AASHTO ME Design appears capable to consider their impact as they change slightly from conventional mixtures.

There are other properties of ICC mixtures that may affect pavement performance, and some of these are included in the AASHTO ME Design procedure. Table 6 lists these factors and their potential impacts. AASHTO ME Design does include permanent curl/warp temperature gradient, ultimate shrinkage, and zero-stress temperature as direct inputs. Two other inputs, permeability of the concrete and curing of the slab, are not included in AASHTO ME Design. It is well known and measured that ICC has less permeability and also has much less shrinkage cracking.

Appropriate ICC/AASHTO ME inputs for these factors are well within the range of the national calibration data for each input.

Table 6. Summary of additional concrete inputs that may affect performance of JPCP and CRCP.

Concrete Material or Slab Factor	Impact on Performance	Input to AASHTO ME Design?	Comments
Permeability	May affect joint deterioration	No	Durability factor not included in AASHTO ME Design
Permanent curl/warp temperature gradient, °F	Very significant; affects top-down and bottom-up cracking and joint faulting	Yes	Impact of ICC on this input is unknown, but may be significant*
Zero-stress temperature	This temperature affects width of joints and cracks	Yes (calculated or manual)	Impact of ICC on this input is unknown
Ultimate shrinkage	Impact on curling and joint and crack openings	Yes (calculated or manual)	Impact of ICC on this input is unknown
Curing of concrete	Potential of shrinkage cracks	No	Durability factor not included in AASHTO ME Design

*In a study by Ya and Hansen (2008), prewetted lightweight fine aggregate was found to be effective in reducing moisture warping. For the mixtures examined, at least 70 percent of moisture warping was reduced within a drying time of 16 days. The results indicate that IC may be effective in reducing slab warping.

CHAPTER 4. EXISTING INTERNALLY CURED CONCRETE (ICC) PAVEMENTS

INTRODUCTION

Several concrete pavements in the Dallas-Fort Worth region have been constructed with ICC. In general, a relatively small substitution of intermediate size LWA sourced from Texas Industries, Inc. (TXI) was incorporated into the concrete mixture. This substitution is similar to that incorporated into more than two dozen bridge decks over the past few years in the United States, and these bridges have shown far less random or plastic shrinkage cracking of any type. It was believed that the ICC would also have the same effect on concrete pavement slabs (exhibit fewer shrinkage and plastic cracking) and be easier to construct.

Field visits were arranged, and on February 11 and 12, 2013, visual surveys were conducted to determine the performance of ICC pavement projects. The individuals participating in the field surveys were Dr. Michael I. Darter from Applied Research Associates, Inc. (ARA), Dr. Chetana Rao (consultant), John Ries from the Expanded Shale, Clay, and Slate Institute (ESCSI), Don Reeves (TXI), Jack Sinclair (TXI) and Victor Villarreal (TXI). Five ICC projects were selected for field surveys, of which only two sites also included a companion section constructed with conventional concrete. These sites are identified as follows:

1. State Highway 121 (SH 121) southbound lanes between I-75 and Dallas North Tollway, north of Dallas. This CRCP project, built in November 2006, contains an approximately 1,400-ft-long ICC segment on the outer lane and shoulder. The rest of the project used conventional concrete. Therefore, this site provided a direct comparison of ICC and conventional concrete sections with identical designs. A meeting was also held with Ms. Tracey Friggle Logan of the Texas Department of Transportation (TxDOT) regarding the SH 121 site.
2. I-635 off ramp near I-80, Dallas. This project used ICC in a high-strength concrete mixture designed for early opening and was placed in 2012.
3. Union Pacific intermodal facility located 12 miles from downtown Dallas, within the city limits of Hutchins and Wilmer. This project was built in 2005.
4. Windsor Park South, a residential subdivision in south Fort Worth, which was constructed in 2006-2007.
5. Alexandria Meadows North, a residential subdivision in north Fort Worth, which was constructed in 2006-2007. This subdivision contained streets that included ICC and streets that contained only conventional concrete.

This chapter provides a brief summary of the design, materials, construction, and performance of each of these concrete pavement sections as available. It also provides an analysis of the performance using the AASHTO ME Design procedure.

Performance Evaluation

The AASHTO ME Design software was used to model the expected performance of sites 1, 3, and 5. At sites 1 and 3, comparisons between the performance of ICC and conventional concrete were made with appropriate inputs for the two material types. A summary of field findings and computer analysis results is provided in this report, along with some overall findings.

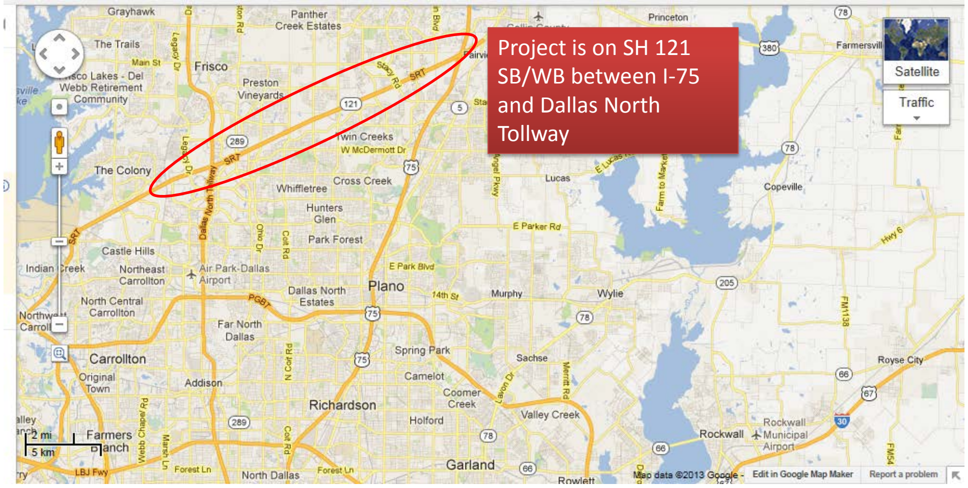
The analysis was performed in a conservative manner while comparing the expected performance of ICC with conventional concrete pavements. For cases where laboratory-measured inputs were available, they were used directly in the analysis. Conservative estimates were used for inputs that were not readily available. Justification and references are provided as much as possible for the various inputs.

Calibration Factors

The national calibration factors were used in these analyses, which allow the use of laboratory-measured PCC properties (ARA, 2011). (Note that formerly used calibration coefficients derived in 2007 need an adjustment to the PCC CTE input.) Additionally, for the ICC CRCP section, the crack width coefficient was reduced from 1.0 to 0.8 to simulate the tighter crack width observed in the field. Therefore, in estimating the crack widths for the ICC sections, the crack widths are 80 percent of the value calculated by the national calibration models. More data are needed to verify this on the field; however, field observation indicates the crack width could be significantly lower.

STATE HIGHWAY 121 NORTH OF DALLAS

This section of SH 121 west of I-75 and east of the Dallas North Tollway (see Figure 5) is controlled by the North Texas Tollway Authority (NTTA). This CRCP project was constructed in November 2006 with a conventional concrete mixture and limestone aggregates for a majority of the project. The outer lane and the shoulder of a segment approximately 1,400 ft long in the southbound lanes were built using an ICC mixture design using intermediate LWA. The ICC segment extends between Preston Road and Parkwood Boulevard, approximately between stations 765+00 and 779+00. The color of this short segment is slightly darker than the surrounding concrete of the inner traffic lanes. A satellite image of the ICC segment is shown in Figure 6, and other photos of this section of SH 121 taken during the visual surveys in 2013 are shown in Figure 7, Figure 8, and Figure 9.



Project is on SH 121 SB/WB between I-75 and Dallas North Tollway

Figure 5. Location of SH 121 segment with ICC pavement (image courtesy Google™).

Experimental section begins and continues SB/WB. Note where the pavement color of the pavement surface turns darker.

Figure 6. Satellite image of ICC section on SH 121 (image courtesy Google™).

Figure 7. ICC placed in outer traffic lane and shoulder on Texas SH 121 in 2006.

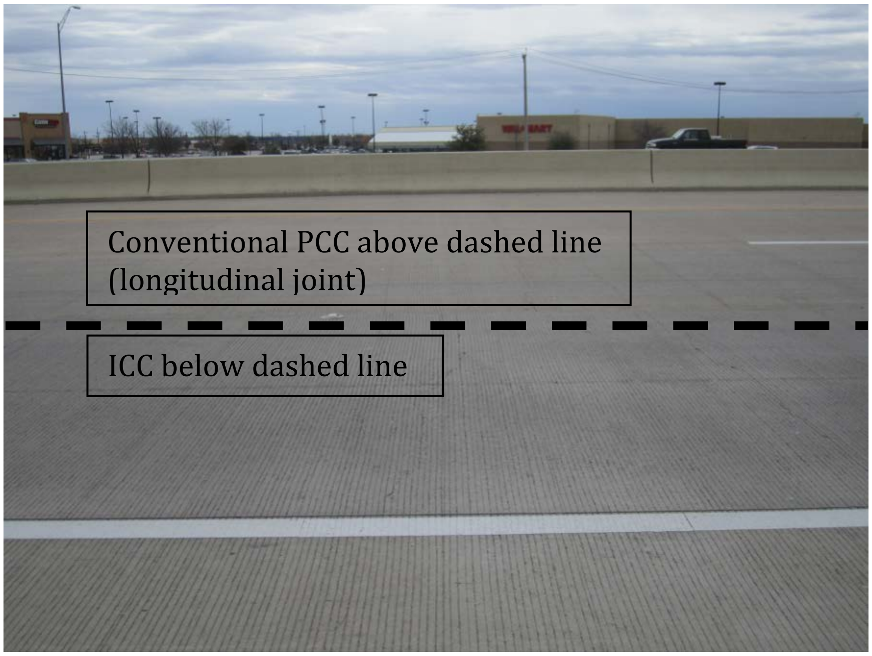


Figure 8. Transverse view of SH 121, with outer lane and shoulder constructed with ICC as illustrated.

Figure 9. SH 121 CRCP (shoulder and first inner lane are ICC, and the center and inside lane are conventional concrete).

Pavement Design, Materials, and Construction

The CRCP pavement design used the following materials and layer thicknesses (Friggle, 2013):

- 13-in. CRCP with 0.7 percent longitudinal reinforcement placed at mid-depth. Figure 10 shows a picture of a core taken from this project, displaying the location of the steel as well as the inclusion of intermediate size LWA in the mix design.
- 4-in. asphalt concrete base layer.
- 10-in. lime stabilized subgrade.
- Natural subgrade. The soil unit map for this location was obtained from the Arizona State University Soil Unit Map Application developed by Zapata et al. (2012) and accessed at http://nchrp923b.lab.asu.edu/index.html. The soil in this location is an AASHTO classification A-7-6.

Figure 10. Close-ups of core taken from SH 121 CRCP from the ICC section. Note the small dark lightweight aggregate pieces throughout the concrete.

Because the use of ICC was experimental for this section, the project was tested and monitored after construction by the Center for Transportation Research (CTR), and specific details about tests during construction and crack surveys soon after construction were reported (Kim and Won, 2008). Additionally, Friggle and Reeves (2008) reported mix design, construction, and crack survey details.

The ICC segment of SH 121 CRCP used 1300 yd^3 of concrete. The mix design and the optimized aggregate gradation used in the project are summarized in Table 7 and Table 8, respectively (Friggle and Reeves, 2008).

Table 7. Mix design for SH 121 (Friggle and Reeves, 2008).

Cement Type I/II	413 lb/yd^3
Fly ash class C	91 lb/yd^3
1" - #4 limestone	1,084 lb/yd^3
11/2" – ¾" limestone	706 lb/yd^3
Concrete sand	857 lb/yd^3
Intermediate LWA	300 lb/yd^3
Water	241 lb/yd^3
Air-entraining agent	2.5 oz/yd^3
Water reducer	15 oz/yd^3

Table 8. Optimized aggregate gradation in SH 121 ICC (Friggle and Reeves, 2008).

% Passing						**Combined % Retained**
Sieve Size	**Coarse Aggregate 1**	**Coarse Aggregate 2**	**LWA**	**Fine Aggregate**	**Combined**	
2 in.	100				100	0
1/2 in.	99.3	100			99.8	0.2
1 in.	80	99.3			95.2	4.6
3/4 in.	51.8	85.8			84.3	10.9
1/2 in.	34	48.3	100		67.6	16.7
3/8 in.	12.1	19.8	99.8	100	52.9	14.6
No. 4	1.3	4.2	58.9	97.7	38	14.9
No. 8	0	1.4	15.5	87.9	27.1	10.9
No. 16		0	4.1	75.6	21.4	5.7
No. 30			0	58.9	16.2	5.2
No. 50				22.4	6.2	10
No. 100				2.6	0.7	5.4
No. 200				0.3	0.1	0.6
pan						0.1

The paving was performed in the month of November under relatively cooler temperatures (38 °F to 57 °F) with nominal daily temperature swings. The normal practice on this project was to produce concrete at the on-site batch plant, but because of inadequate bin capacity, concrete was brought to the job site from the central mix plant, about 5 miles from the job site, which offered the needed bin capacities to handle the additional LWA. At the start of the paving operations, the construction crew had to overcome a logistical challenge that posed itself as a result of altering the batch plant. The concrete was delivered to the job site in a ready mix truck instead of in the normally used dump truck with the capacity to discharge the concrete at 1-inch slump. It was found in the field that the ready mix truck had limitations with discharging the concrete at the required rate. Therefore, the slump was adjusted, and with the improved workability, the paving operation functioned efficiently. Other than this minor field adjustment, there were no reported issues with the paving operation or the constructability of the ICC mixture. The ICC concrete had normal finishing and texturing. The pavement has an excellent ride quality after 7 years with no distress occurrence.

Kim and Won (2008) report that the bleed water was not excessive and the level of bleeding aided good finishing. The concrete initial and final set times were 5 hours 28 minutes and 8 hours 29 minutes, respectively. The compressive strength of the cores was measured to be at least 4,800, 5,500, and 6,000 psi at 7 days, 14 days, and 28 days, respectively (see Table 9). There were no strength reports for the normal weight conventional concrete used in the project. Shrinkage results indicated a 10 to 15 percent reduction in shrinkage relative to the normal concrete used in the project (Figure 11) over a 28-day period.

Table 9. Measured compressive strength for SH121 ICC mix (Friggle and Reeves, 2008).

Age, days	Compressive strength, psi	
	CTR	TxDOT
1	1750	
4	3900	3860
7	4900	
8		5750
14	5300	
28	6000	

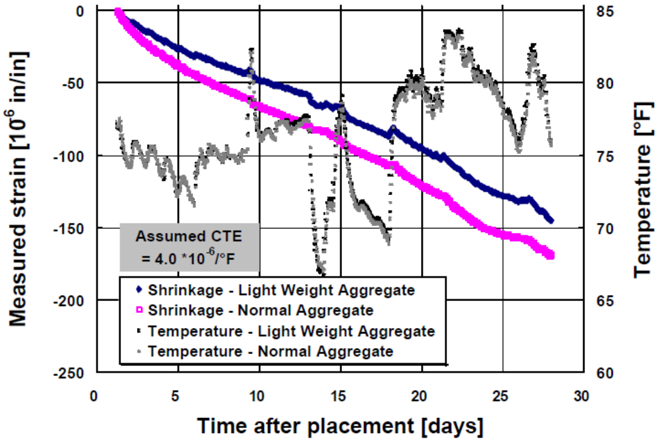


Figure 11. Shrinkage strain in ICC and conventional concrete over 28 days indicating 10 to 15 percent less shrinkage for ICC. Kim and Won (2008)

Field Performance and Surface Condition of Pavements

Crack surveys were performed on a 430-ft test section of the ICC CRCP in February 2007 at 76 days after construction (Kim and Won, 2008). The ICC section was reported to have developed shrinkage cracks at an average spacing of 31 feet—much larger than the typical 3 to 6 feet expected on normal concrete. This might be a result of lower shrinkage and lower set temperatures in the pavement. Based on a visual review of the distress survey maps, however, the crack patterns appeared to have a large variability (standard deviation of 24 feet).

In September 2007, 10 months after construction, detailed crack surveys were performed on the ICC section as well as the control conventional section in the adjacent lanes (Friggle and Reeves, 2008). A 500-ft section was selected for each survey. The findings again indicated much longer crack spacing for the ICC section (22.7 feet) than for the conventional section (9.4 feet). Further, and much more important, the cracks were tighter in the ICC pavement:

- ICC section: 91 percent of all cracks had an opening less than 0.004 inches. Only 4 percent had a crack opening of 0.006 inches.
- Conventional: 64 percent of all cracks had an opening less than 0.004 inches. 30 percent had a crack opening of 0.006 inches.

Figure 12 shows the crack distribution in the ICC and control sections, indicating that cracks remained very narrow in the ICC pavement despite the large crack spacings. This is a remarkable finding! Normally, longer crack spacing has a wider crack width, all other aspects being equal. Note that CRCP cracks tend to deteriorate rapidly under repeated heavy truck loadings when the crack openings exceed 0.020 inches.

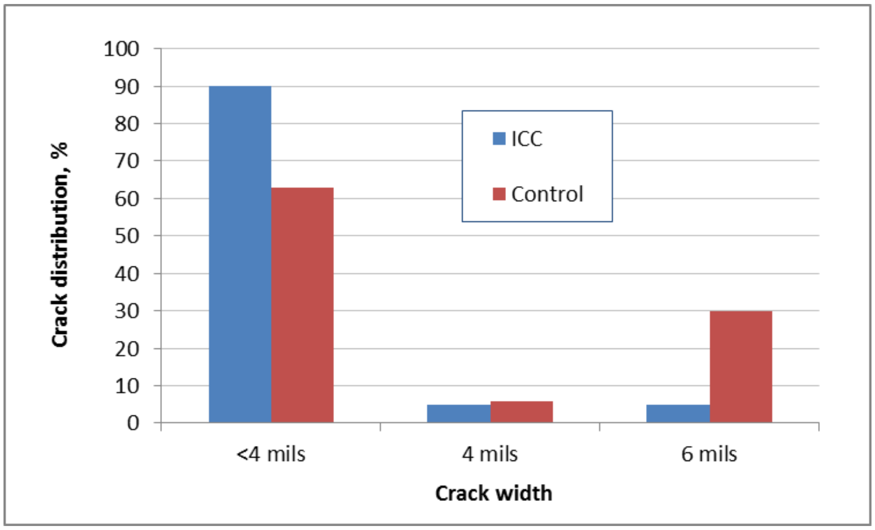


Figure 12. Crack opening distribution in ICC and conventional concrete at 10 months (1 mil = 0.001 inch) (Friggle and Reeves, 2008).

The NTTA collects digital images of the roadway annually. A review of the images collected between 2009 and 2012 along the entire ICC segment and the adjacent conventional concrete lanes indicates that the ICC section developed additional cracks over time and the longer-term 6-year stabilized crack spacings are quite similar in both sections. Note that the transverse cracks in the conventional and ICC lanes do not appear to be at the same locations across the longitudinal joint. As shown in Table 10 and Figure 13, the crack spacings were an average of 5.9 feet in the conventional concrete compared to 6.4 feet in the ICC pavement. Initially, there was a large difference in crack spacing, but after 6 years there is virtually no difference.

The key difference is in crack opening. The crack opening at 10 months was very different between conventional and IC concrete. This difference may still exist after 7 years, based on visual observations of the cracks. However, this needs to be confirmed through measurements of surface crack opening. Both the ICC section and the conventional concrete are performing very well after 7 years with no discernible differences. Both sections have a good ride quality as well.

Table 10. CRCP crack spacing measurements on SH 121 in Texas.

Measurement Year	**Conventional Concrete Inside Lane** (3rd lane from shoulder) Mean Crack Spacing, ft	**Conventional Concrete Lane Adjacent to ICC Lane** (2nd 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

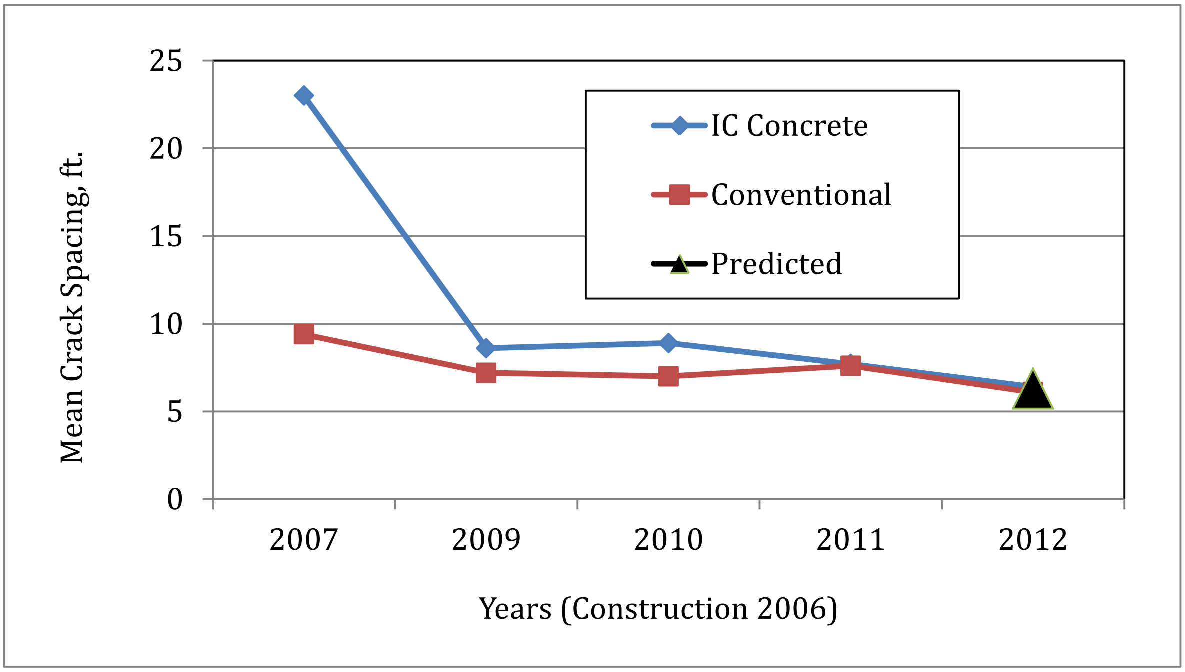


Figure 13. Crack spacing over time in SH 121 for ICC and conventional concrete (note that the "predicted" crack spacing is done using the AASHTO ME design procedure and represents long term or greater than 5 years).

Modeling with AASHTO ME Design Software

The SH 121 project was modeled using the AASHTO ME Design procedure. The purpose of the analysis was to evaluate the performance of the ICC pavement and compare against the conventional concrete pavement construction, which served as control. Therefore, both ICC and conventional concrete pavements were analyzed using this procedure. The various inputs used for the project under the broad categories of climate, traffic, design features, and layer properties as discussed below.

Climate

The AASHTO ME Design software contains a climate database with data from weather stations nationwide. The Dallas-Fort Worth weather station was selected for this project. The weather station contains the following hourly data from November 2006 to October 2004:

- Minimum Temperature.
- Maximum Temperature.
- Average Temperature.
- Maximum Range.
- Precipitation.
- Average Wind Speed
- Average Sunshine.
- Number Wet Days.
- Maximum Frost Depth.

The AASHTO ME Design procedure develops necessary weather data summaries that are used in the analysis of the design project being evaluated. As an example, for this specific location, the summary of annual climate statistics relevant to the pavement performance is shown in Table 11, and the variation in monthly temperature, precipitation, sunshine, number of wet days, and maximum frost are shown in the plots included in Figure 14.

Table 11. Summary of annual climate statistics for the selected weather station.

Mean annual air temperature (°F)	66.37
Mean annual precipitation (in.)	34.49
Freezing index (°F-days)	36.77
Average annual number of air freeze-thaw cycles	19.62

The software uses these data to develop the soil-moisture characteristic curved based on the Enhanced Integrated Climatic Model, thereby creating moisture and temperature profiles of the entire pavement structure from the soil subgrade to the top of the PCC surface. These moisture and temperature profiles also determine the extent of curling and warping stresses experienced by the pavement, hour by hour, in the analysis period.

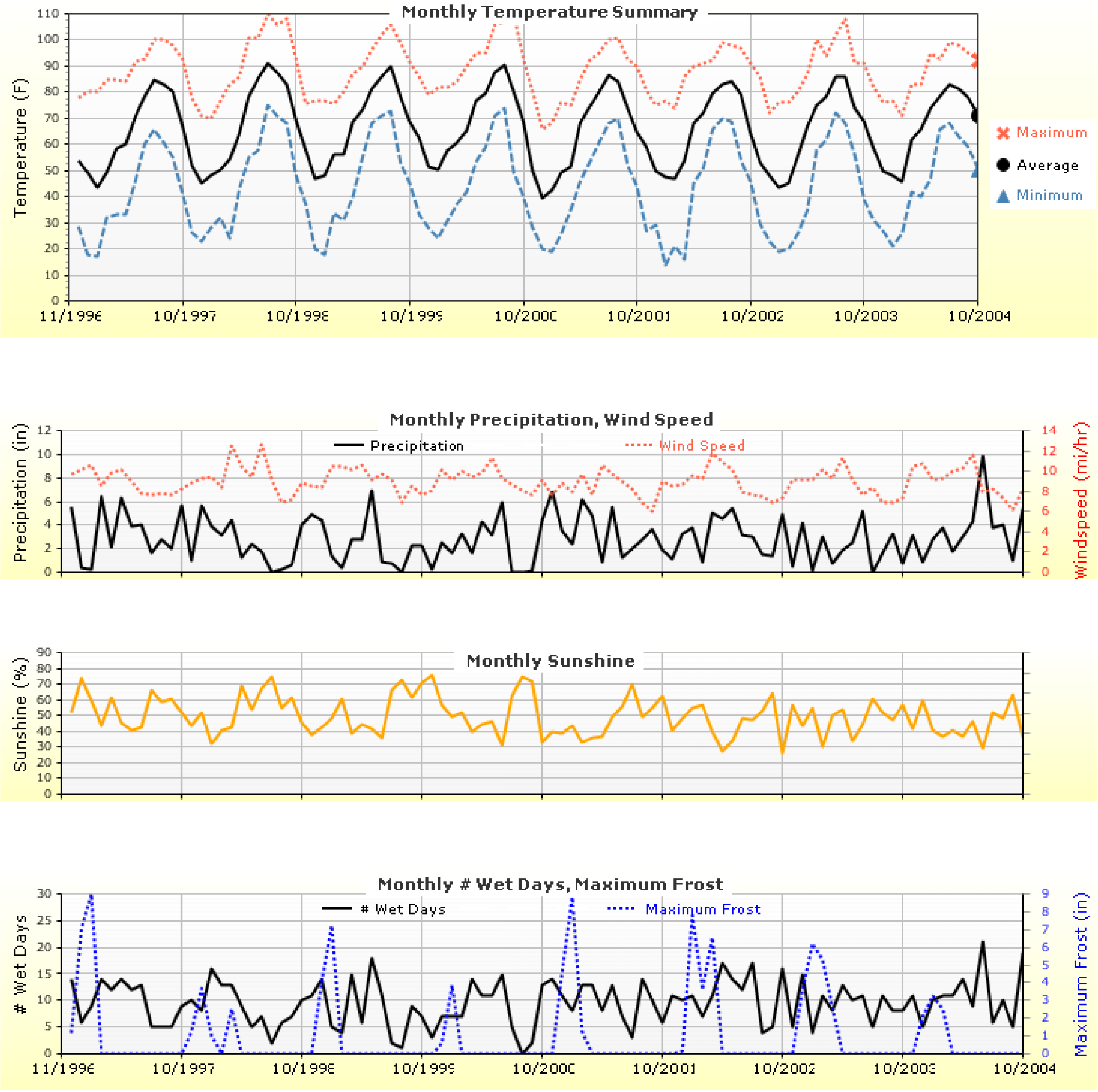


Figure 14. Monthly temperature, precipitation, wind speed, sunshine, wet days, and frost at the project location, as retrieved by the AASHTO ME Design software based on weather station information.

Traffic

SH 121 has experienced a significant increase in traffic since its construction to convert a non-freeway facility to a freeway. It is also likely the traffic distribution changed significantly over the initial years after construction. Table 12 provides the average annual daily traffic (AADT) obtained from the TxDOT website for the segment of the roadway with the ICC pavement. The project currently carries an average 103,000 vehicles per day in both directions. The TxDOT Pavement Management Information System (PMIS) database reported an average of 6.8 percent trucks on this segment in the southbound lanes.

Table 12. Traffic volume on SH 121 in the vicinity of the ICC section.

Year	Average Annual Daily Traffic	Effective Growth, %
2007	50000	N/A
2008	50000	0
2009	74000	48.00
2010	89000	20.27
2011	103000	15.73

These growth rates are representative of newly developed suburban areas or a roadway recently converted to a freeway facility. It is not practical to project these traffic volumes over the life of the project. Therefore, the following growth rates were assumed to estimate traffic over the project life of 30 years. A nominal 5 percent linear growth over first 5 years (2012-2016), 2.5 percent growth over the next 5 years (2017-2021), and 1 percent growth until year 30 (2036). The projected traffic was used to estimate an initial traffic and determine an effective annual linear growth rate, as shown in Figure 15.

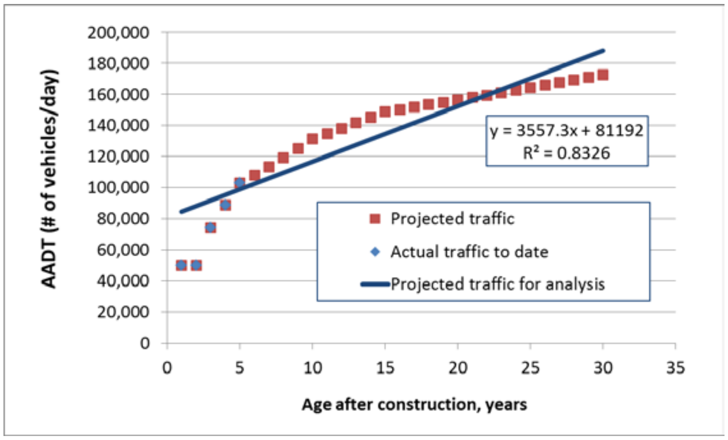


Figure 15. Traffic projection over 30-year design life based on initial traffic data on SH 121.

For the purpose of mechanistic analysis, an initial traffic of 81,192 vehicles per day and linear traffic growth of 4.4 percent were used. Based on a directional distribution of 50 percent, a lane distribution of 80 percent for the outer lane, and 6.8 percent truck traffic (Class 4 through 13), the annual average daily two-way truck traffic (AADTT) is 5,521 trucks. The results show that the outer lane is expected to carry cumulative truck traffic of 40 million heavy trucks. In general, these traffic conditions are representative of very heavily trafficked roadways.

The AASHTO procedure requires several additional traffic inputs to estimate the axle load distribution for each axle type, month by month over the analysis period. National default values were used for the analysis. For example, a truck traffic classification (distribution by vehicle class) representative of a principal arterial highway was used for the analysis (see Table 13). This traffic distribution consists primarily of single trailer trucks. Likewise, default values were used for several other traffic inputs related to the distribution of traffic over a 24-hour period by truck class, the number of axles per truck, axle configuration, traffic wander, axle spacings, and wheelbase.

Table 13. Vehicle class distribution for truck traffic used for SH 121.

Vehicle Class	Vehicle Distribution
4	1.3%
5	8.5%
6	2.8%
7	0.3%
8	7.6%
9	74%
10	1.2%
11	3.4%
12	0.6%
13	0.3%
Total	100%

Design Features and Layer Properties

The analysis used the as-built layer structure and design features. A majority of the design feature inputs used in the analysis were the same for both the conventional and ICC sections, as listed in Table 14. These include the frictional characteristics between the base and the slab and the longitudinal steel design. The key PCC inputs that are different between the ICC and conventional concrete are also listed in Table 14.

Table 14. Design features and PCC layer inputs for SH 121 ICC and conventional concrete sections.

AASHTO ME Design Inputs	Conventional Concrete (Control)	Internally Cured Concrete	Comments
Shoulder type	Tied PCC		Inputs are the same for ICC vs. conventional concrete
Steel content, percent	0.7%		
Bar diameter, inch	0.75		
Steel depth, inch	6		
Base/slab friction coefficient (dependent on base type)	7.50		
Mean crack spacing, inches	67 (71 measured)	76 (77 measured)	Calculated by AASHTO ME Design models (these are similar to field observations at 6 years)
Base layer	4-inch HMA, good quality base		Same
Lime stabilized subgrade	10-inch layer		
Subgrade	A-7-6 (properties from soil units)		
CRCP thickness, inch	13	13	
PCC compressive strength, psi	5,200	6,000	Both obtained from tests on similar mixtures
Modulus of elasticity, psi	4,372,000	4,009,500	From ACI equation using compressive strength & unit weight
CTE, με/°F	4.8	4.3	ICC obtained by reducing conventional PCC by 5%
Unit weight, pcf	143	137	ICC estimated at 6 pcf less (typical difference)
Ultimate shrinkage, με	603	592	Calculated by AASHTO ME Design from other inputs (unit weight, strength, and w/c ratio)
Permanent curl/warp effective temperature difference, °F	-10	-10	Assumed to be the same, but ICC may be lower, as discussed

The strength, modulus of elasticity, and CTE were either measured values or adjusted for the two mix designs based on laboratory test comparison results reported in the literature.

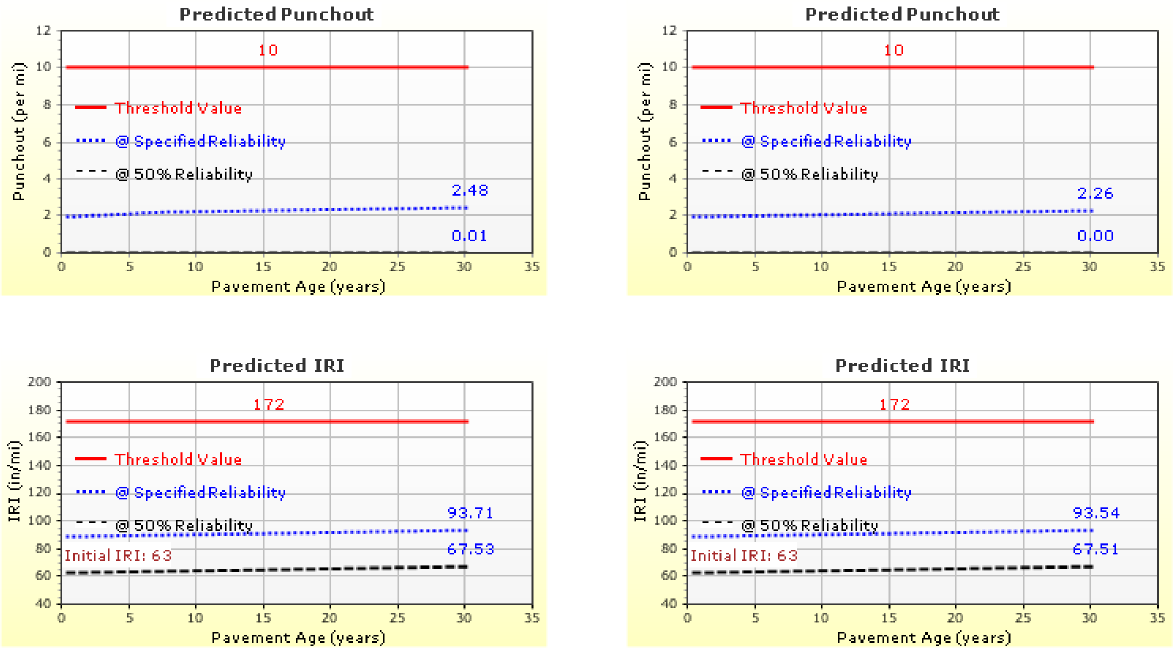
One parameter of interest, which may be altered with the use of ICC, is the long-term permanent effective curl-warp temperature gradient (deltaT). Although this input was set equal for this analysis, there are reasons to believe ICC may have lower value because the deltaT variable has three components:

1. Built-in temperature gradient during curing: This component should be the same between conventional and ICC mixtures placed at the same climatic conditions.
2. Permanent drying shrinkage gradient through the slab: This component may be lower with ICC mixtures because internal hydration occurs more uniformly throughout, thereby reducing the moisture gradient through the slab. Also, lower shrinkage on the slab surface should reduce the gradient as well. Sensitivity analysis shows that even a small reduction in the gradient may have a significant effect on improving performance.
3. Creep of the concrete due to slab weight: this component is partly dependent on the weight of the slab and ICC has an approximately 6 pcf lower unit weight.

Performance Prediction

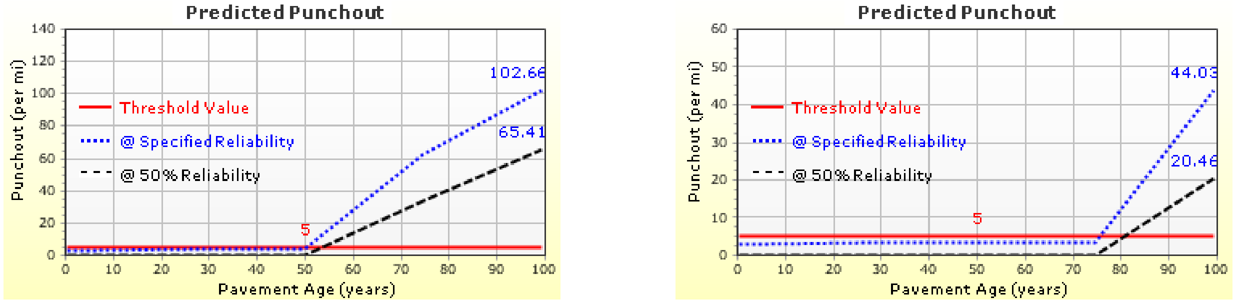
The 13-inch CRCP sections with ICC and conventional concrete were predicted to have excellent performance throughout the 30-year design life. The two performance criteria used in CRCP designs—punchouts and International Roughness Index (IRI)—were predicted to remain well below the threshold levels, as shown in Figure 16. The predictions are shown at 97 percent reliability levels, indicating very conservative designs for the expected levels of traffic. 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 IC concrete sections, respectively (see Figure 17).

The long predicted life of this project indicates a very conservative design. The projects were reanalyzed to optimize the design thicknesses using the AASHTO ME Design procedure. By way of optimizing the design, the minimum thickness of the CRCP (within +½-inch margin) that can satisfy the design criteria is determined for the selected steel content. The optimization, performed at 97 percent reliability, yielded design thicknesses of 11 inches and 10 inches for the conventional and ICC sections, respectively. The predicted performance of the optimized designs is shown in Figure 18. By optimizing the designs, the performance of the 11-inch conventional CRCP and the 10-inch ICC CRCP are almost identical. In fact, when the performances of the two designs are plotted on the same chart, the predictions practically coincide throughout the 30-year period.



CONTROL CRCP **ICC CRCP**

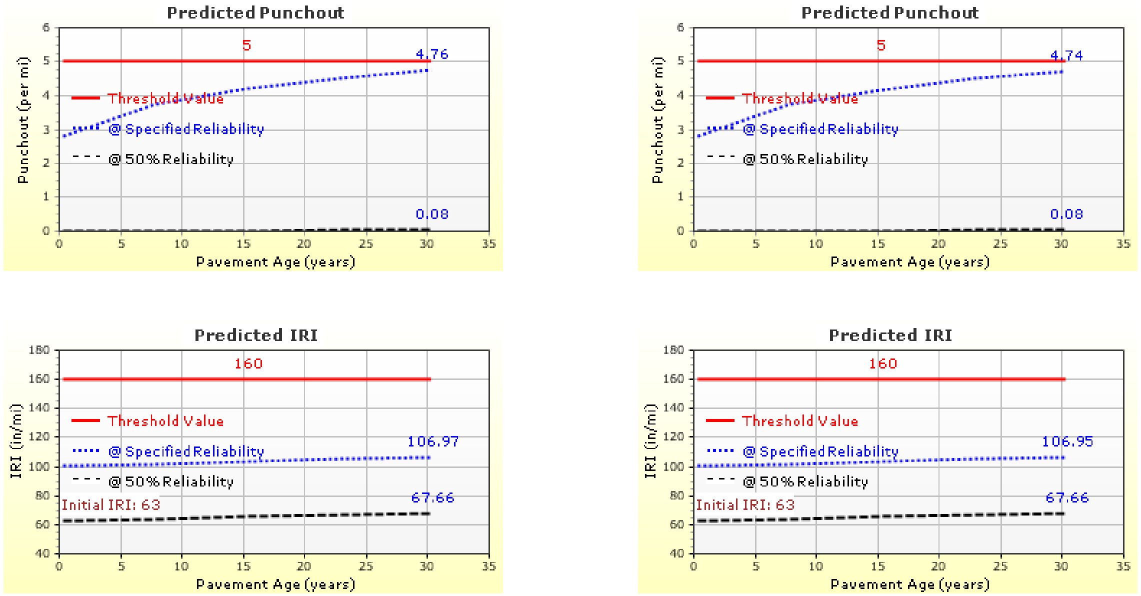
Figure 16. Predicted performance of as-built SH 121 conventional and ICC sections with 13-inch CRCP thickness.



a) Control section

b) ICC section

Figure 17. Long-term analysis of the SH 121 sections suggesting that the 13-inch CRCP will meet design requirements for 50 and 70 years with conventional concrete and ICC, respectively.



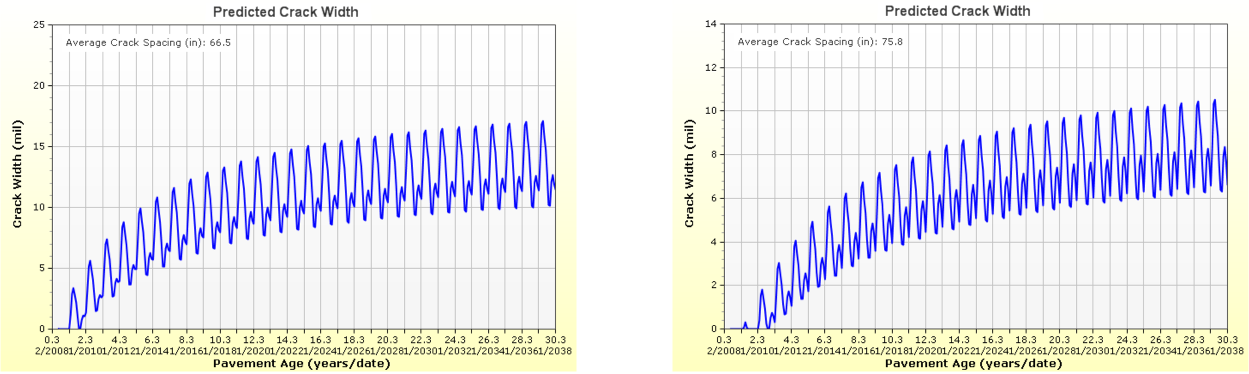
CONTROL – 11-in CRCP SLAB

IC – 10-in CRCP SLAB

Figure 18. Predicted performance of optimized designs for SH 121 conventional and ICC sections.

ICC CRCP has longer crack spacing (76 versus 66 inches) but narrower crack opening. Figure 19 shows the progression of crack openings in both sections. The crack openings remain much smaller in the ICC section because of the higher tensile strength, 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. This can be significant for post-design life performance, as minimizing crack opening is critical for controlling punchout development. Note that both sections have crack openings below the generally accepted threshold value of 0.020 inches over the 30-year design life.

The analyses of the SH 121 project suggest that ICC presents significant benefits and can reduce the design thickness by 1 inch but provide similar performance and reliability. The increased material costs incurred in a project with the use of LWA may be offset by the savings in design thickness. A life cycle cost analysis of the SH 121 project is presented in an ensuing chapter in the report.



a) Control section

b) ICC section

Figure 19. CRCP crack openings over the design life for SH 121 conventional and ICC sections.

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 a small proportion of LWA. This off ramp is located on I-635 (Lyndon Johnson Freeway) south of US Highway 80 in Mesquite.

Concrete Mix Design

The contractor was given the opportunity to design the mix 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. A photo of the concrete from this section, taken in February 2013, is shown in Figure 20.

Pavement Performance

A condition survey of the ICC lane and the adjacent lane was conducted, but it was impossible to get close enough to determine the crack spacing and width. Observations indicated both the ICC and control sections had typical transverse shrinkage cracks on the short segment surveyed. The IC pavement is in excellent condition, and no early age distresses exist.

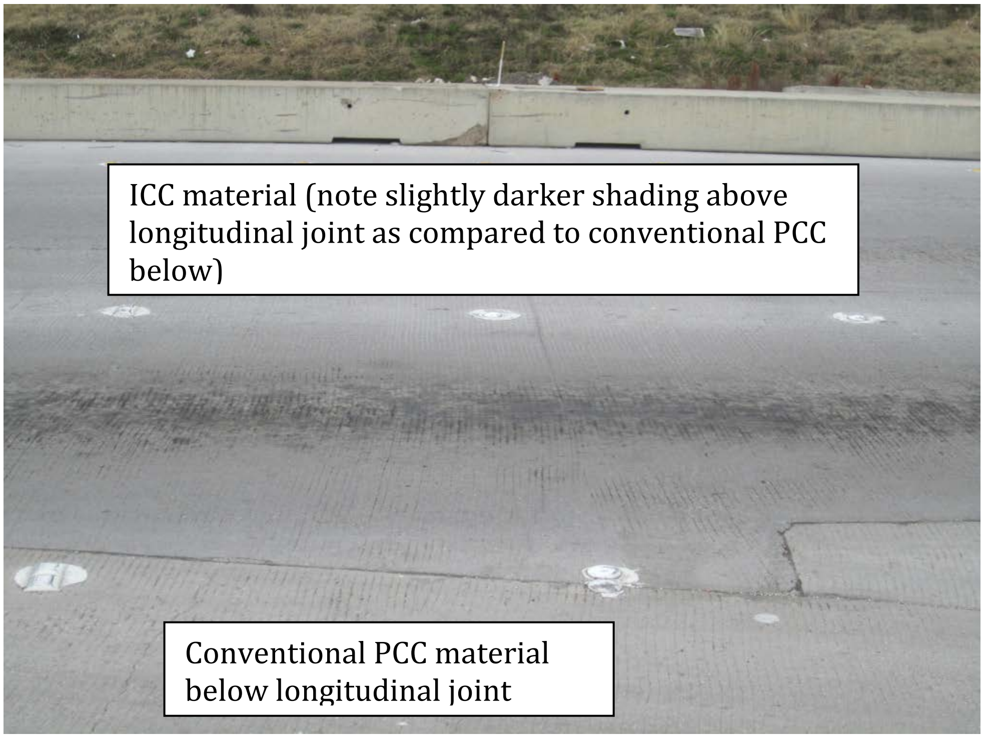


Figure 20. Photo of short section of I-635 off ramp that was constructed with ICC.

DALLAS INTERMODAL TERMINAL (UNION PACIFIC)

The 360-acre Union Pacific (UP) Intermodal Terminal is located 12 miles from downtown Dallas, within the city limits of Hutchins and Wilmer. The terminal is designed to support the growing volume of intermodal transportation activity in the region. The project location, shown in Figure 21, offers easy access to major highways. The railport is located adjacent to Interstate 45 at Fulghum Road, approximately 6 miles south of UP's Miller Intermodal Terminal and approximately 3 miles south of Interstate 20.

12 miles from Dallas, TX

Figure 21. UP intermodal facility location south of Dallas (Image courtesy Google™).

The terminal features 365,000 pounds lift capacity and 4,000 parking stalls. With 24-hour, 7-day-a-week operations, it has four loading tracks. The facility has a10-lane automated gate system entrance, and as shown in Figure 22, a short section of the roadway carried literally every truck entering and leaving the facility.

Figure 22. Aerial view of facility showing the maximum truck traffic zone (image courtesy Google™).

Pavement Design, Materials, and Construction

The following information was obtained for this ICC pavement:

- The construction was performed in 2005, and the paving was done almost year-round under a range of paving weather conditions typical of the Dallas-Fort Worth area. The facility was approximately 8 years old at the time of the visual survey.
- The project is a JPCP design and includes the following structural layers:
    - The slabs are 15 feet in length and 12 feet wide.
    - The thickness was 8.5 inches for the most part, but along the loading tracks (a very small area), the slab is 13 inches thick. The transverse joints were doweled.
    - An untreated aggregate base is approximately 12 inches thick.
    - The pavement is on a natural subgrade, which is an AASHTO A-7-6.
- The ICC mix design used a partial substitution of intermediate size LWA replacing an equal volume of normal weight aggregate. The mix design, strength properties, and gradation were presented in Table 2, Table 3, and Table 4. The following is from the technical paper presenting the ICC data and results:

  "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)

The ICC mixture strength increase is in the order of 18 percent above conventional PCC. This large increase may be due in part to the intermediate gradation filling in the gap of the gradation.

The UP Intermodal Terminal is the largest known IC paving project and used 250,000 yd^3 of concrete. Based on a thickness of 8.5 inches, this volume of construction is equivalent to 150 lane miles of ICC pavement.

Figure 22 shows the surface of the ICC pavement after 8 years and an exposed fractured face of the ICC from this project. The larger pieces of LWA are the black specs observable in both photos.

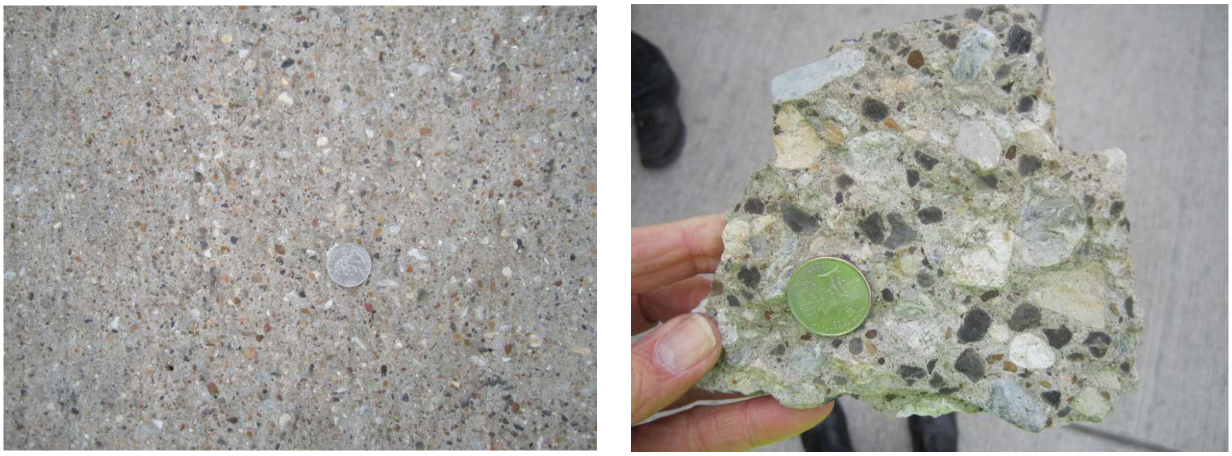


Figure 22. Photos of ICC with surface (left) and fractured face (right).

Pavement Surface Condition

The project shows excellent performance after 8 years in service. Both walking survey 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. There were a few small areas of spalling along joints. Figure 23 through Figure 25 show pictures of the facility and the excellent condition of the slabs. There were no conventional concrete pavements at the site for comparison.

Figure 23. ICC pavement at UP Intermodal Terminal.

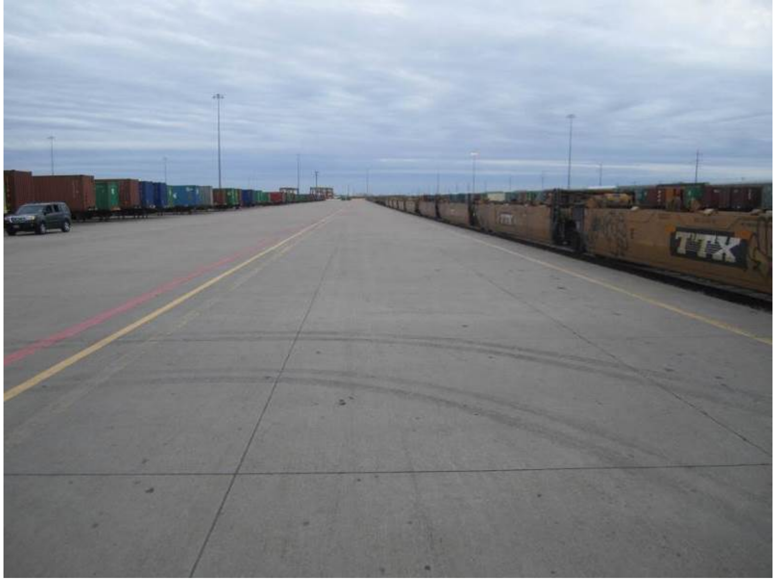


Figure 24. ICC pavement at the UP Intermodal Terminal showing rail cars on the right and truck containers parked on the left, with ICC pavement between them.

Figure 25. Heavy truck container entrance/exit traffic lane at the UP Intermodal Terminal.

The upward curl in the slabs (between diagonal corners) was measured at the time of the survey during cool February temperatures, as shown in Figure 26. The ambient air temperature at the time of curl measurements was about 55 °F. The temperature gradient through the slabs was not measured but was likely close to zero at the time of survey given the time of day and cool weather. Based on measurements made on at least 20 slabs around the facility, no measurable upward curl existed on the project.

Why is this important? As previously discussed, significant upward curling can lead to top-down transverse and longitudinal cracking over time with continued truck loading. Stress in the slab surface increases under truck wheel loads when the slab is curled upward because it is not supported below for a distance. It is not known if the lack of upward curling for these ICC JPCP slabs is due to the ICC, since there were no conventional concrete pavements at the site for comparison. However, no measurable upward curling is a good sign and points to the need for additional research to determine if ICC can reduce upward curling of slabs due to a reduction in moisture gradient through the slabs from improved curing throughout the slab depth. If so, this would be a significant benefit to both JPCP and CRCP performance.

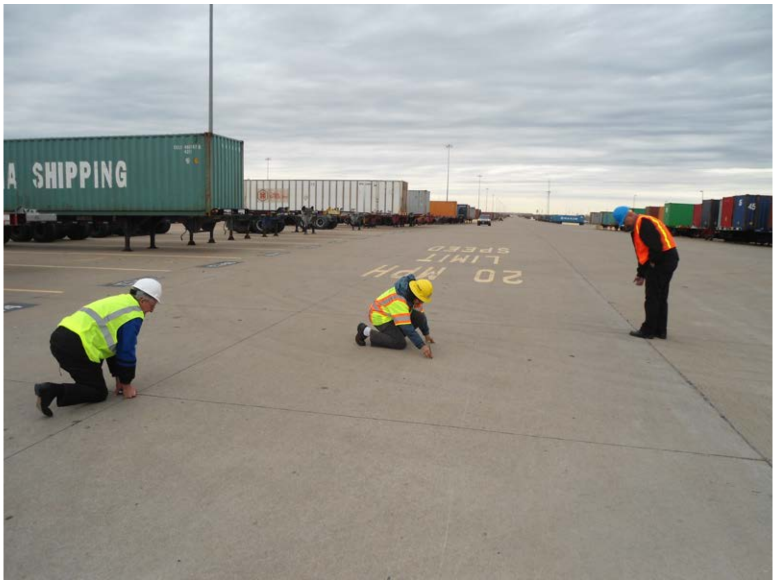


Figure 26. Measuring diagonal corner slab upward curl at the UP Intermodal Facility. No upward curling was measured on 20 slabs around the facility.

Modeling with AASHTO ME Design Software

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 results from the analysis of the ICC and the conventional concrete pavements were compared.

Climate

The Dallas-Fort Worth climate data in the program's weather station database was used. This analysis therefore used the same climate data as the analysis used for the SH 121 project.

Traffic

Truck traffic volume and loadings are highly variable across the access roads and 4,000 parking stalls. The container trucks in the facility were predominantly single trailer trucks, which are best represented by Class 9 trucks per the Federal Highway Administration (FHWA) truck classification. The volume for the inbound or outbound trucks was estimated at about 240 per day, all Class 9 trucks (i.e., 100 percent Class 9 trucks). Truck axle weight distribution would be container type loadings. It was assumed that these truck axle loads were similar to those of major highway Class 9 truck traffic. A compound growth rate of 2 percent was used in the analysis. These traffic considerations produced about 10 million cumulative trucks on the design inbound/outbound lane over a span of 60 years.

Pavement Layers and Design Features

The mix design and the pavement design used in the analyses of both the conventional concrete and ICC projects are presented in Table 2 and Table 15, respectively. Note that the major difference between the proportioning of the two mixtures is the inclusion of 300 lb/yd^3 of intermediate size LWA in the ICC mix to replace 300 lb/yd^3 of coarse aggregate and 200 lb/yd^3 of fine aggregate from the conventional concrete mix. This results in measurable differences in various concrete material properties. The unit weight and compressive strength were measured for the specific mix designs used in this comparison. However, other properties were either estimated from AASHTO ME Design models or were adjusted for the normal weight concrete based on trends in laboratory test results reported in the literature.

The analyses were performed for a design life of 60 years (inbound and outbound lanes). The as-built ICC pavement at the intermodal facility is expected to perform very well for the entire design period. As seen in Figure 27, the IRI, joint faulting, and transverse fatigue cracking are within the selected threshold levels of 160 in./mile, 0.12 inch, and 10 percent, respectively. The analysis considered mean predictions as well as predictions at 95 percent reliability levels.

Table 15. Summary of design inputs for ICC and assumed conventional concrete.

AASHTO Inputs	Conventional	ICC	Comment
PCC thickness, inch	8.5	8.5	Determined from measurement
Joint spacing, feet	12x15	12x15	
Joint design	Doweled joints, 1.25-in. diameter		
Unit weight, pcf	145	137	Measured values; ICC 6 pcf lower than control mix
Compressive strength, psi	5130	6070	Measured 28-day values
Elastic modulus, psi	4,127,000	4,123,000	From ACI equation using compressive strength & unit weight
w/c ratio	0.43	0.43	Determined from mix design
Permanent effective curl-warp temperature gradient (°F)	-10	-10	Default value assumed same for both designs
CTE, x 10^{-6} in./in./°F	4.8	4.3	Default for conventional concrete with limestone aggregates; reduced by 5% for ICC
Ultimate shrinkage, x 10^{-6} in./in.	611	592	Calculated by the AASHTO ME Design software based on the ACI equation
Base layer	12-inch crushed stone aggregate		Default modulus and gradation inputs for these materials
Subgrade	A-7-6 soil		

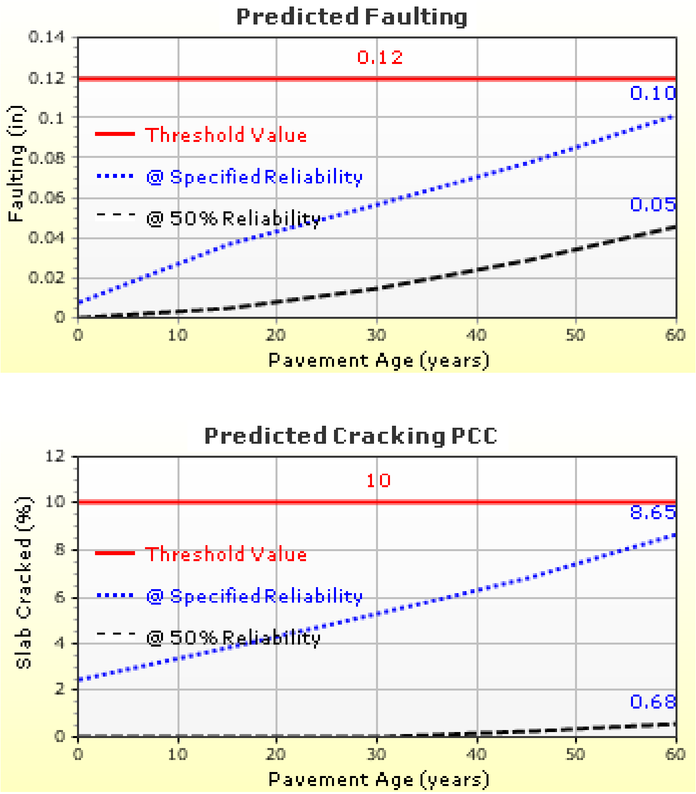


Figure 27. Predicted performance for the intermodal facility ICC pavement: IRI (top), joint faulting (middle), and cracking (bottom).

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/outbound JPCP would fail at 40 years due to excessive transverse fatigue cracking, as shown in Figure 28 (compare with Figure 27 bottom chart). The JPCP slab thickness for the conventional concrete, clearly, is inadequate to carry the 60 years of traffic. The IRI and faulting performance were acceptable, however.

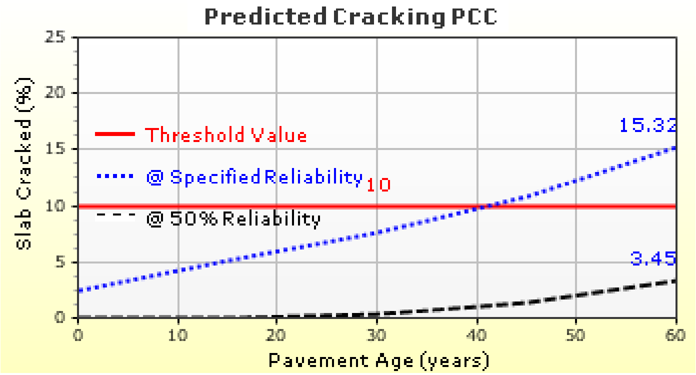


Figure 28. Predicted cracking in conventional concrete pavement for the intermodal facility.

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, a marginal ½-inch increase in thickness was needed to achieve the performance levels of 8.5 inches of ICC.

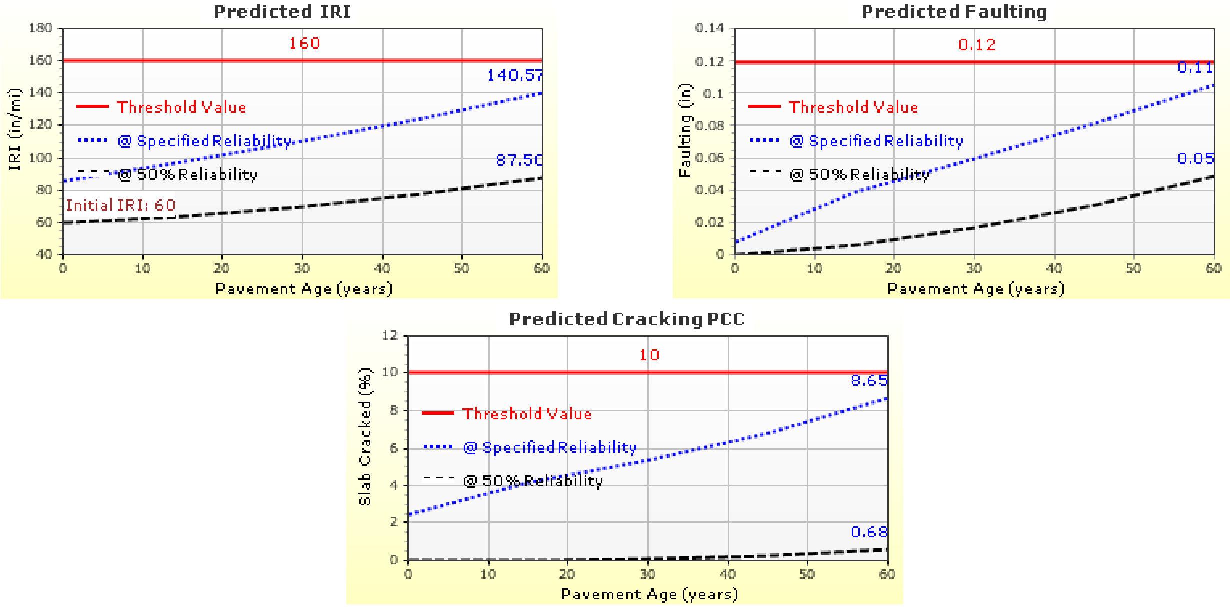


Figure 29. Performance of 9-inch conventional concrete JPCP for the intermodal facility.

WINDSOR PARK SUBDIVISION, FORT WORTH

Windsor Park is a residential subdivision in south Fort Worth. This subdivision is well laid out and is an attractive neighborhood with nice homes. The streets are constructed of jointed plain concrete with no dowel bars. All of the concrete pavements are internally cured and include a relatively small proportion of intermediate gradation LWA as described in the UP Multimodal Terminal JPCP mixes supplied by TXI. This project was built in 2006-07. The design is as follows:

- Jointed plain concrete with no dowel bars
- Joint spacing is 15 feet, and the slabs are standard 12-foot width
- Slab thickness of 7 inches
- Slab placed directly on the compacted subgrade
- Subgrade is a soft fine-grained soil

Traffic in this subdivision 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 for several years as homes were under construction.

Pavement Surface Condition

Walking surveys were conducted on several 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. Pictures of the subdivision and the pavement surface are shown in Figure 30 and Figure 31.

Figure 30. Residential ICC pavement constructed in 2005 at Windsor Park.

Figure 31. Close-up view of ICC pavement surface at Windsor Park subdivision. The black specs in the surface are the larger pieces of LWA.

The paving was done by slip form pavers for two lanes wide. The curbs were also paved in the same operation. This required grinding off portions of the curbs at driveways, providing a great view of the ground-off concrete face at every driveway. A photo of a ground concrete face is shown in Figure 32. The dark aggregates are the larger pieces of LWA.

Figure 32. Close-up of ground-off surface of ICC at Windsor Park subdivision.

Diagonal corner-to-corner curl measurements were made on several slabs. All slabs showed zero upward curl. The slabs were practically flat during cool weather in February.

Modeling with AASHTO ME Design Software

The Windsor Park ICC project was modeled with the AASHTO ME Design software. Results of the analysis are provided in the next section, under Alexandria Meadows. These projects were identical in design, materials, and traffic, so there is no need to duplicate the description of the analysis in this report.

ALEXANDRIA MEADOWS, FORT WORTH

Alexandria Meadows in north Fort Worth, built in 2005, was the second residential paving project surveyed by the team. ICC was used to pave many of the residential streets, as shown in Figure 33. There were also some streets paved with conventional concrete, as shown in Figure 34. The design and materials for these sections is identical to that of the pavement in the Windsor Park subdivision.

Pavement Surface Condition

The researchers surveyed several streets in this subdivision where ICC was used, as well as a few of the nearby conventional concrete streets. Figure 35 and Figure 36 show the exposed surfaces of the ICC pavement and of the conventional concrete construction. The former shows the inclusion of intermediate size LWAs. The ICC pavement was in excellent condition, and no pavement distresses were noted. The team observed only one random crack on the pavement surface, which seemed to have remained tight and had no spalling (see Figure 37). Both the ICC and conventional concrete were in excellent condition with no cracks or spalls.

Diagonal corner-to-corner curling was measured on several ICC slabs. Zero upward curling was recorded on every slab measured. Measurements were not taken on the conventional concrete pavements.

Figure 33. Alexandria Meadows subdivision streets constructed with ICC.

Figure 34. Conventional concrete streets built in Alexandria Meadows at about the same time (2005-2006).

Figure 35. Close-up of ground-off surface of ICC concrete at Alexandria Meadows.

Figure 36. Ground-off conventional concrete without LWA at Alexandria Meadows.

Figure 37. Small shrinkage cracks found on Alexandria Meadows on ICC pavement (Left) and conventional concrete pavement (Right).

Modeling with AASHTO ME Design Software

There are no known design and material differences between the two residential ICC projects surveyed. Thus, these performance predictions are valid for both projects. An analysis period of 60 years was used in the analysis.

Climate

The same Dallas-Fort Worth climate data were used for this analysis.

Traffic

The residential streets see minimal traffic on a regular basis. While the project did carry some construction traffic while the homes were being built, these residential streets do not see heavy traffic on a routine basis. A traffic level of 10 trucks/day in one lane/direction was assumed for the analysis, which results in about 400,000 trucks over a 60-year period in one direction.

Pavement Layers and Materials

The designs were evaluated with both ICC and conventional concrete. All material properties used for this analysis were identical those used for the UP intermodal facility analysis, as provided by TXI. The slab thickness was 7 inches, and no dowel bars were used at the transverse joints. Also, no base layer was used, as these pavements were constructed on a prepared subgrade.

Performance Predictions

The AASHTO ME Design analysis indicated that the ICC project will 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, as shown in Figure 38, Figure 39, and Figure 40. The performance was evaluated at a reliability level of 95 percent.

The conventional concrete meets all performance requirements for only a period of 25 years, as transverse cracking exceeds the design performance criterion, as shown in Figure 38. Joint faulting and IRI meet performance requirements for about 45 years, as shown in Figure 39 and Figure 40. These 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 is a significant increase of 66 percent. The only difference is that the ICC involves substitution of a small portion of the aggregates with LWA in the mixture design.

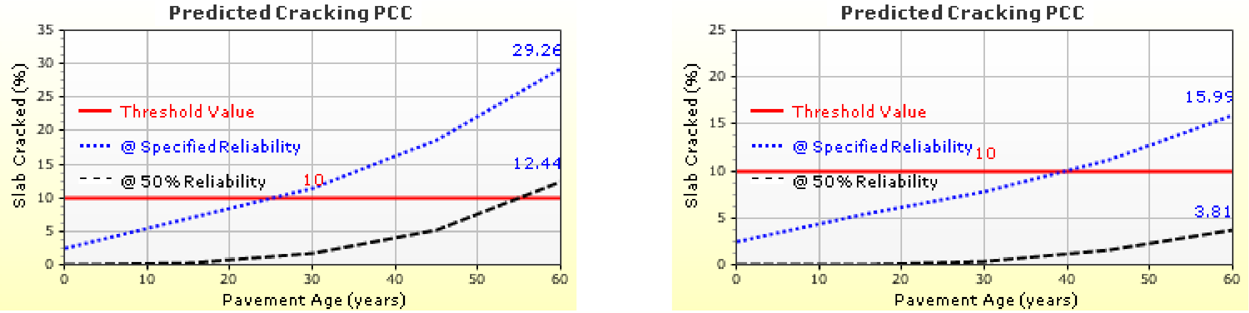


Figure 38. Comparison of cracking in conventional (left) and ICC residential (right) streets.

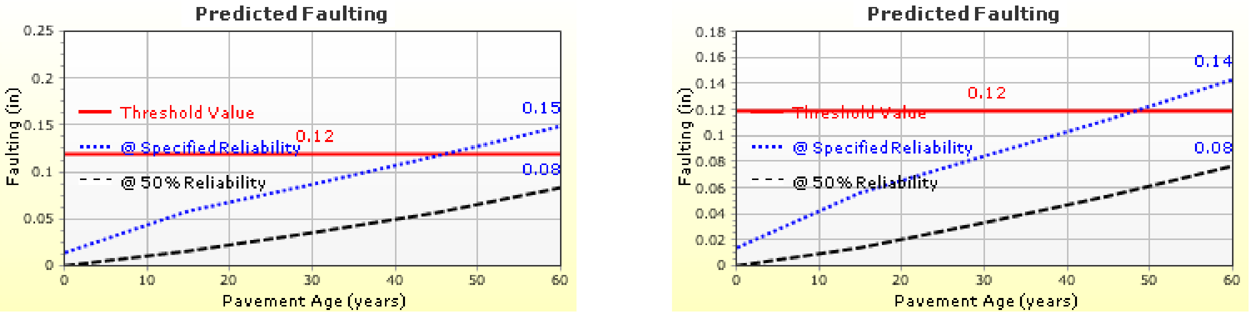


Figure 39. Comparison of joint faulting in conventional (left) and ICC residential (right) streets.

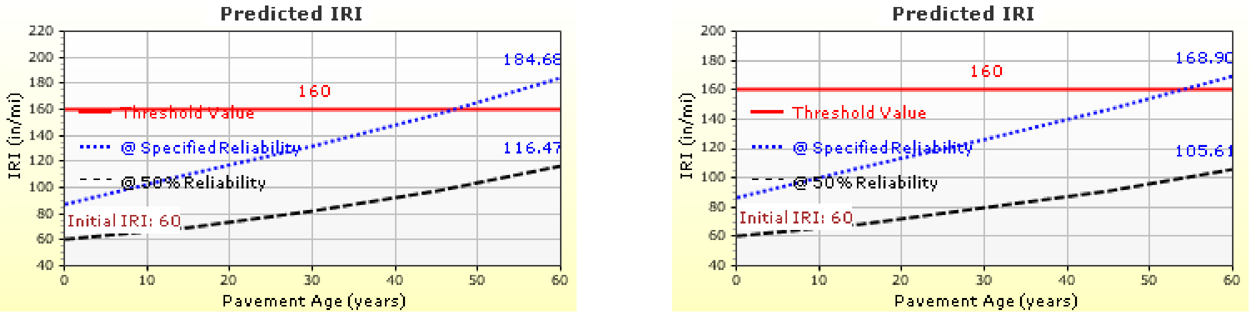


Figure 40. Comparison of IRI in conventional (left) and ICC residential (right) streets.

SUMMARY OF ICC PAVEMENT PERFORMANCE

Field visits were conducted to five ICC pavement projects in the Dallas-Fort Worth area, which included a CRCP freeway, a high early strength CRCP ramp, a large intermodal facility with JPCP slabs, and two residential areas with JPCP slabs. All projects have 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 carry 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. Of course, these pavements are only 8 years old, and a much longer time period is needed to fully demonstrate their improved durability potential.

The AASHTO ME Design procedure was used to predict the performance of the pavements into the future. The performance of the ICC pavements on the CRCP freeway, the JPCP intermodal facility, and the JPCP residential streets was predicted many years into the future. These projects were also analyzed using conventional concrete as a direct comparison. 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 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. These findings are all based on the results from the AASHTO ME Design analysis predictions.

It is important to realize that the performance benefits indicated for ICC using the AASHTO ME Design procedure are purely structural (e.g., fatigue cracking). ICC offers additional durability benefits for pavements, like reduced plastic and drying shrinkage, lower permeability, and therefore the ability to control freeze-thaw cracking and joint deterioration. All of these benefits can contribute to reduced maintenance over the service life of the pavement.

The analyses presented in this chapter using the AASHTAO ME design software do not directly reflect durability-related benefits in the pavement. The following statement is from Victor Villarreal, who was involved in ICC mixture design and placement since 2005 in the Dallas-Fort Worth area:

> “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 (LWA) was also evident, as the contractors reported that it reduced total placement time.” (Villarreal and Crocker, 2007)

CHAPTER 5. EVALUATION OF ICC FOR OTHER PROJECTS USING AASHTO ME DESIGN

SELECTION OF PROJECTS

The analysis discussed in the previous chapter was extended to other projects covering different climate zones in the country, as well as different traffic levels and designs. The following additional pavement projects were analyzed using both conventional and ICC concrete:

- I-45 JPCP: The UP Intermodal Terminal had relatively lower truck traffic volume compared to nearby I-45. The question arose what would be the impact of ICC if heavier truck traffic volume was used such as that just nearby on I-45? Therefore, a site on I-45 was selected near to the UP Terminal to make a comparison in designs and performance. Truck traffic similar to that on nearby I-45 (traffic volumes, truck distributions, and axle distributions). All other inputs were the same as at the UP Intermodal Terminal.
- LTPP SPS-2 sections: The FHWA Long-Term Pavement Performance (LTPP) Specific Pavement Study 2 (SPS-2) is the largest national concrete pavement field research being conducted. Fourteen states are part of the SPS-2 experiment. Each test site consists of 12 500-ft sections. While the climate and traffic are consistent for the 12 sections, other parameters have been varied. For example, there exist two mix designs with two different target strengths—low strength and high strength. There also exist three base types—aggregate, lean concrete base, and asphalt base—and two slab widths, 12 and 14 feet. One section from each of the following test sites was selected for evaluating the use of ICC:
    - Arizona section 04_0213, to represent dry-no freeze climate.
    - Colorado section 08_0213, to represent dry-freeze climate.
    - Iowa section 19_0213, to represent wet-freeze climate.
    - North Carolina section 37_0203, to represent wet-no freeze climate.

I-45 AASHTO ME DESIGN ANALYSIS

This project site is just east of the UP Intermodal Terminal, as shown in Figure 41. I-45 is a major connector between Dallas and Houston and carries heavy truck traffic. This simulated project was modeled after the intermodal facility for all inputs except traffic where I-45 truck traffic was utilized. A comparison was made between ICC and conventional concrete pavements.

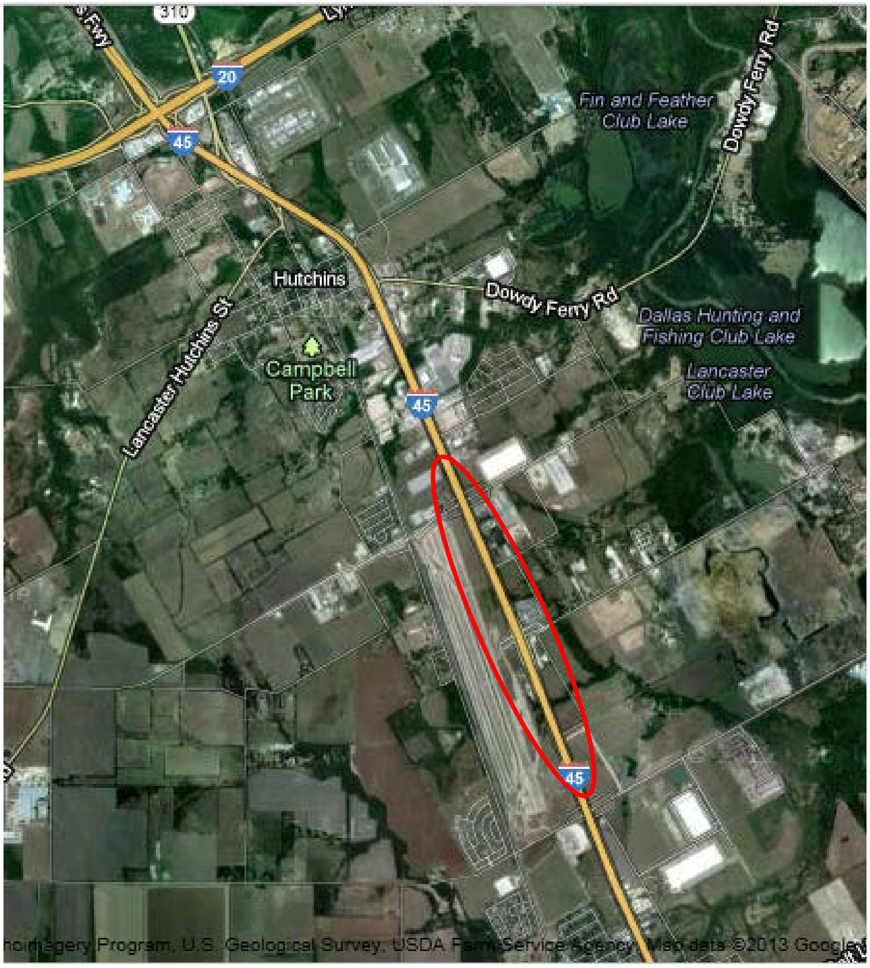


Figure 41. Location of the I-45 project selected just east of the intermodal facility.

Inputs

All inputs used for this project are similar to the inputs used in the analysis of the intermodal facility (see Table 15). The analyses were performed for a design life of 60 years. As seen in Figure 27, the IRI, joint faulting, and transverse fatigue cracking are within the selected threshold levels of 160 in/mile, 0.12 inch, and 10 percent, respectively. A reliability level of 95 percent was used for the analysis and traffic was those of the I-45 site nearby. Based on the information collected from TxDOT traffic counts, this highway has a two-way AADTT of 7,200 trucks. With a directional distribution of 50 percent, 3 lanes in each direction, and 75 percent traffic in the design lane, the project was designed for cumulative truck traffic of 40 million trucks over the design life.

The structural layers used in the analysis were:

- JPCP (thickness determined in design process)
- 12-inch crushed aggregate base layer
- Natural subgrade – fine-grained soil

Design

Optimizing the design thickness for the design traffic over the selected design life 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 16. The reported performance results were determined at a reliability level of 97 percent. Figure 42, Figure 43, and Figure 44 show the predicted performance for the optimized designs with 11.5-inch conventional JPCP and 10.5-inch ICC JPCP.

Table 16. 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 and will be discussed in detail in the next chapter.

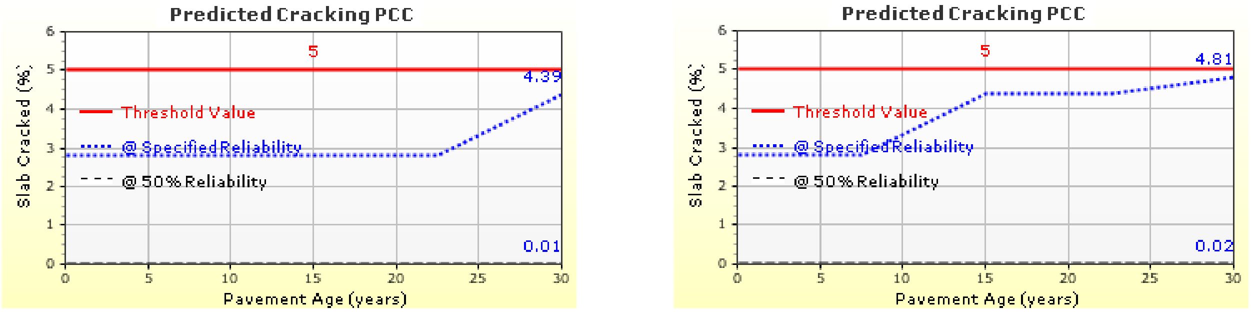


Figure 42. Transverse cracking in 11.5-inch conventional JPCP (left) and 10.5-inch ICC (right) JPCP for I-45 project.

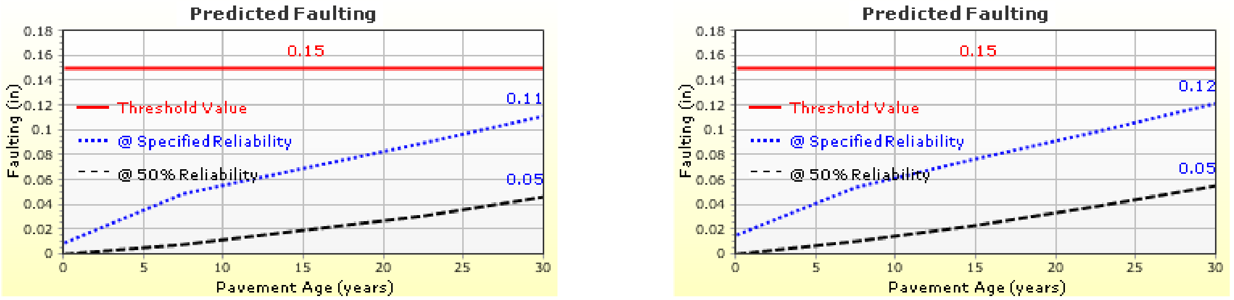


Figure 43. Joint faulting for 11.5-inch conventional JPCP (left) and 10.5-inch ICC (right) JPCP for I-45 project.

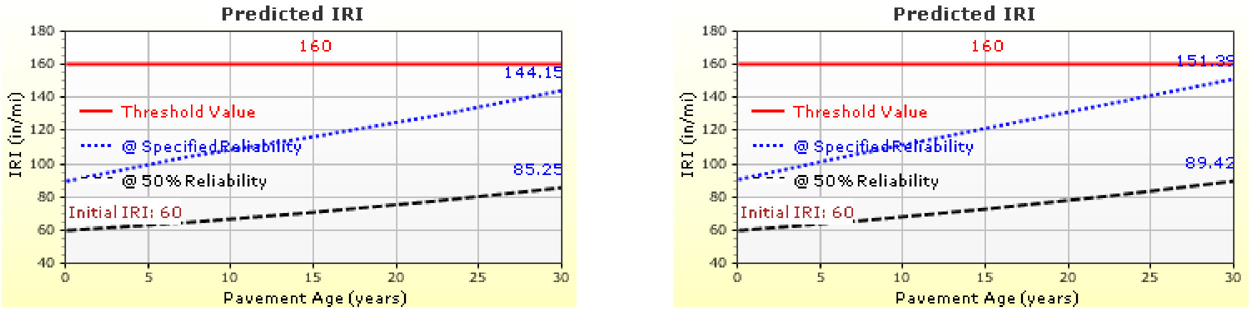


Figure 44. IRI in 11.5-inch conventional JPCP (left) and 10.5-inch ICC (right) JPCP for I-45 project.

LTPP SPS-2 SITES AASHTO ME DESIGN ANALYSIS

The inputs for the LTPP sections were obtained from the LTPP database, and the key inputs for the as-built conventional concrete sections are provided in Table 17. The inputs were revised for the analysis using ICC. The revised inputs for ICC are summarized in Table 18.

Table 17. Summary of key inputs in SPS-2 sections for the conventional concrete analysis (as-built pavement inputs obtained from LTPP database).

Design Input	Iowa	Arizona	Colorado	North Carolina
Design life, years	30	30	30	30
PCC thickness, inches	8.5	7.9	8.6	8.5
Slab width, feet	12	14	12	12
Unit weight, pcf	138	143	148	145.5
PCC CTE, x10^{-6} in./in./°F	4.4	4.8	4.8	4.06
Zero-stress temperature, °F	95	118	74.5	100.7
Flexural strength, psi	525	666	588	714
Modulus of elasticity, psi	3,100,000	4,500,000	3,600,000	4,380,000
Ultimate shrinkage, x10^{-6} in./in.	569.3	500.2	618.9	775
Aggregate type	Limestone	Granite	Granite	Granite
w/c ratio	0.61	0.58	0.59	0.7

Table 18. Summary of key inputs in SPS-2 sections for ICC JPCP analysis.

Design Input	Iowa	Arizona	Colorado	North Carolina
Design life, years	30	30	30	30
PCC thickness, inches	8.5	7.9	8.6	8.5
Slab width, feet	12	14	12	12
Unit weight, pcf	131	136	141	138.5
PCC CTE, x10^{-6} in/in/°F	4.18	4.56	4.56	3.857
Flexural strength, psi	562	713	629	764
Modulus of elasticity, psi	2,945,000	4,275,000	3,420,000	4,161,000
Ultimate shrinkage, x10^{-6} in/in	560	491.7	607.9	758.2
Aggregate type	Limestone	Granite	Granite	Granite
w/c ratio	0.61	0.58	0.59	0.7

The PCC input properties that were available for the conventional concrete were adjusted to establish the inputs for ICC. The following adjustments were made:

- Modulus of elasticity reduced by 5 percent
- Unit weight reduced by 7pcf
- CTE reduced by 5 percent
- Flexural strength increased by 5 percent

Some of these adjustments can impact other internally calculated material property values. For example, the change to the flexural strength will automatically increase the tensile strength based on models included in the AASHTO ME Design software. Likewise, the combined change to strength and unit weight will alter the estimate for ultimate shrinkage.

The selected sections have a wide range of traffic levels. The initial AADTT used for each project and the cumulative traffic over the 30-year design life are tabulated in Table 19.

Table 19. Traffic inputs used in the analysis.

Traffic Input	Iowa	Arizona	Colorado	North Carolina
Initial AADTT	500	2400	3000	734
Cumulative truck traffic	9.5 million	85 million	41 million	12.7 million

The designs were analyzed at a reliability level of 90 percent in these cases. Table 20 presents a summary of the predicted performance of the conventional concrete and ICC pavements for selected LTPP SPS-2 site conditions.

Table 20. 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		IRI at Year 30 @ 90% Reliability	
	Control	ICC	Control	ICC	Control	ICC
Arizona	8 years	22 years	97%	25%	182 in/mile	107 in/mile
Colorado	22	30	18	7	155	149
Iowa	9	30	68	4	235	115
North Carolina	7	21	80	24	195	146

Figure 45 shows the predicted transverse cracking in the SPS-2 sections at the end of 30 years at a reliability level of 90 percent. Cracking is reduced for all sections. However, the benefit in cracking performance is more significant in sections with higher elastic modulus (Arizona and North Carolina). Figure 46, which shows the number of years to reach the critical 10 percent cracking threshold, indicates the additional service life that can be obtained for these designs, which also affects the scheduling of maintenance activities. Based on these analyses, on average, more than 10 years of additional design life may be obtained. Figure 47 shows the pavement roughness at the end of 30 years. ICC pavements appear to retain a smoother ride quality over time than conventional concrete pavements.

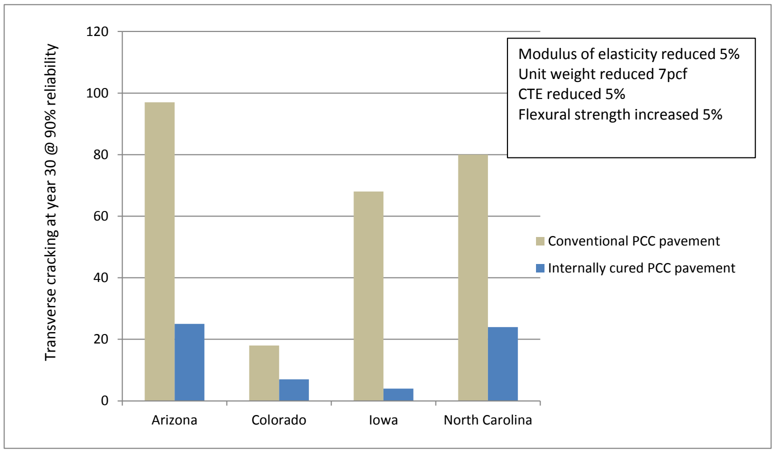


Figure 45. Predicted transverse cracking in SPS-2 sections for ICC and conventional concrete designs at 30 years.

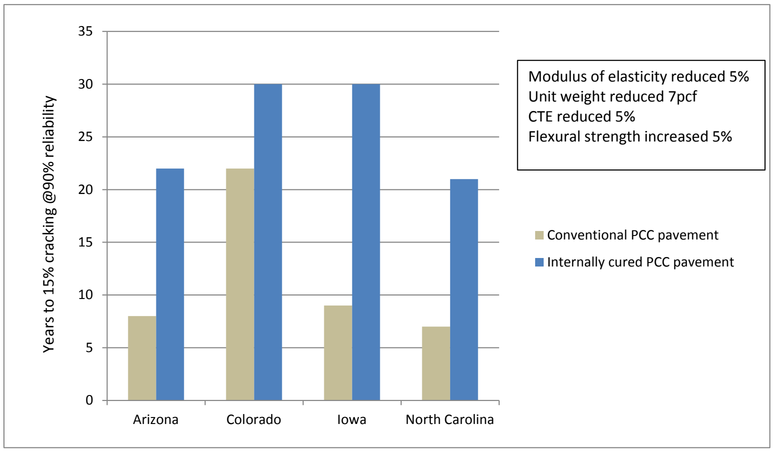


Figure 46. Years to reach 10 percent transverse cracking in SPS-2 sections for ICC and conventional concrete designs.

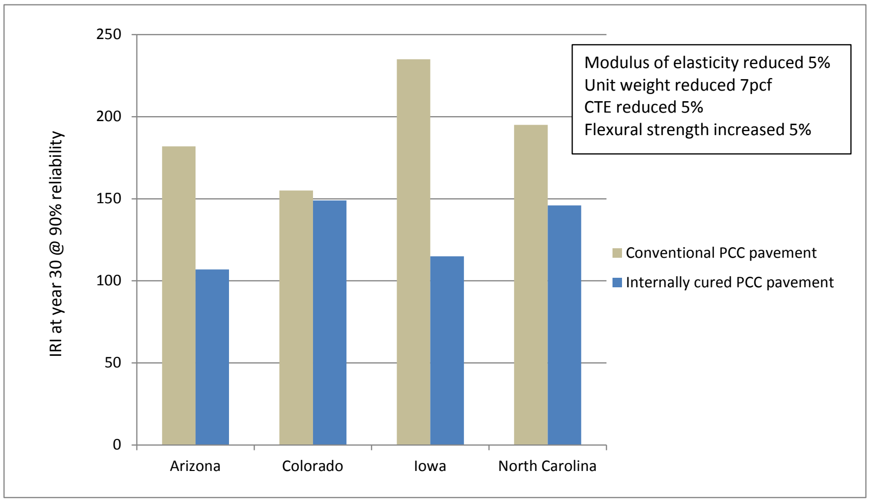


Figure 47. Predicted IRI in SPS-2 sections for ICC and conventional concrete designs

SUMMARY

This chapter presented a comparative analysis of several real-world projects that cover the major climate zones in the United States and a range of material inputs. Both ICC and conventional concrete designs were modeled using the AASHTO ME Design procedure. The optimized designs for I-45, and the as-built SPS-2 projects were analyzed to evaluate and compare the performance of ICC and conventional concrete designs.

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.

All of these benefits are related to the structural performance of the pavement. There are other perhaps even more significant benefits of ICC on the durability and construction side. These potential benefits include the following:

- Greatly reduced plastic and drying shrinkage cracking.
- Reduced permeability that may reduce the freeze-thaw damage to lower portions of slabs.
- Reduced permanent upward curling of slabs that would reduce the potential for top-of-slab transverse and longitudinal cracking.

CHAPTER 6. EVALUATION OF LIFE CYCLE COSTS OF INTERNALLY CURED PAVEMENTS

Highway agencies use life cycle cost analysis (LCCA) extensively to compare equivalent alternative pavement designs economically (e.g., asphalt design versus concrete design). LCCA can also be used to compare a conventional design with a new proposed design, such as an ICC design for JPCP and CRCP. Two examples are provided that illustrate what results may be obtained from such an economic comparison.

ASSUMPTIONS FOR LCCA

There are several assumptions that must be made for every LCCA involving pavements. These include length of design life, analysis period over which M&R treatments are applied, discount rate, unit costs of in-place materials, M&R activities of each alternative over time, and the initial design of each alternative considered. Assumptions made for these LCCA inputs are summarized in the following subsections.

Initial Design of Each Alternative

All alternatives were developed using the AASHTO ME Design procedure. The only difference between the conventional and ICC alternatives was in the concrete slab properties. All inputs such as reliability, performance criteria, joint design, base, and site conditions (e.g., subgrade, climate, and traffic) were identical. Each design was "optimized" to produce the minimum slab thickness required to meet the performance criteria at the design reliability for the design life, as would be done in typical design.

Length of Design Life

A design life 30 years was used for both the CRCP and JPCP designs.

Length of Analysis Period

An analysis period of 60 years was used for each CRCP or JPCP example. This required evaluating the performance of the selected sections beyond the 30-year design life used to optimize the thicknesses. The projects were analyzed over the 60-year analysis period.

Discount Rate

A discount rate of 3 percent compounded annually was used.

Unit Cost In-place Materials

The cost of CRCP and JPCP includes several components:

- Subgrade preparation
- Base course: This may vary depending on the base course material, unbound aggregate base or hot mix asphalt (HMA) base
- PCC slab: The unit cost of this item may vary depending on the following variables:
  - Concrete materials
  - Joints, which includes the cost of dowels for transverse joints and ties for longitudinal joints for JPCP
  - Longitudinal and transverse reinforcing steel for CRCP
- Wide flange terminal joints for CRCP

Additionally, the unit costs for the materials, depending on the cost estimation procedures, often include the labor and mobilization required for the construction. Therefore, the unit costs can vary by region and size of the project.

The unit costs for conventional concrete and ICC JPCP and CRCP were estimated based on the unit of the materials provided by TXI, which produces and supplies ready mix concrete of both types. TXI also supplied all of the ICC for all the field projects in Dallas-Fort Worth, discussed in earlier chapters.

Unit Cost Values Used in the Analysis

Concrete materials cost was reported as about $80/yd^3$ for conventional concrete and $10/yd^3$ additional for ICC in the Dallas-Fort Worth area. Note that this cost pertains to the unit cost of the PCC supplied. The unit cost for the pavement in place, based on the aforementioned cost components, was:

- Conventional concrete JPCP: $147/ yd^3
- ICC JPCP: $157/ yd^3 (~7 percent increase)
- Conventional concrete CRCP: $160/ yd^3
- ICC CRCP: $170/ yd^3 (~6.25 percent increase)

In the cost analyses, the cost for a unit volume was the basis to calculate the cost for a unit area (yd^2). Extra reinforcement cost adjustments were made for thickness change in the computation of unit costs for CRCP. For example, a CRCP thickness increase from 10 inches to 11 inches, with the same longitudinal reinforcement content of 0.7 percent, added an additional $2.09 to the unit cost per square yard.

Unit costs for other materials were assumed to be as follows:

- HMA base (Superpave 19 mm quality) - $40/ton

- Crushed aggregate base material - \$22/ yd^3
- Aggregate subbase - \$12.5/ yd^3
- Lime treated subgrade - \$14.17/ yd^3

NOTE: The authors recognize that unit costs may vary, perhaps significantly, across regions and projects. The costs of LWA will vary by region and by hauling distances from plants to projects. The unit cost values listed above were the basis for the LCCA presented in this chapter. A project-specific LCCA would be needed to assess the cost-effectiveness of ICC pavements in different locations.

Maintenance and Rehabilitation

The M&R treatments applied throughout the 60-year analysis period are typical of what many highway agencies would select. These included reinforced full-depth repair of CRCP for punchouts, slab replacement of JPCP for cracked slabs, and diamond grinding of both CRCP and JPCP to reestablish surface texture and smoothness. The quantities of repair for CRCP and JPCP over time were calculated from the predicted punchout and cracking outputs of the AASHTO ME Design software.

LCCA FOR SH 121 CRCP SITE

The SH 121 site was used to prepare a comparative LCCA example. As described previously, SH 121 is a freeway in the north Dallas area with a two-way AADTT of 5,521, which results in 40 million trucks in the design lane in 30 years and 111 million trucks over the entire 60-year analysis period at the selected growth rate. The climate is that of north Texas, and the subgrade is a fine-grained A-7-6 soil. The typical conventional concrete and ICC mixtures previously described were used in the LCCA.

CRCP Design

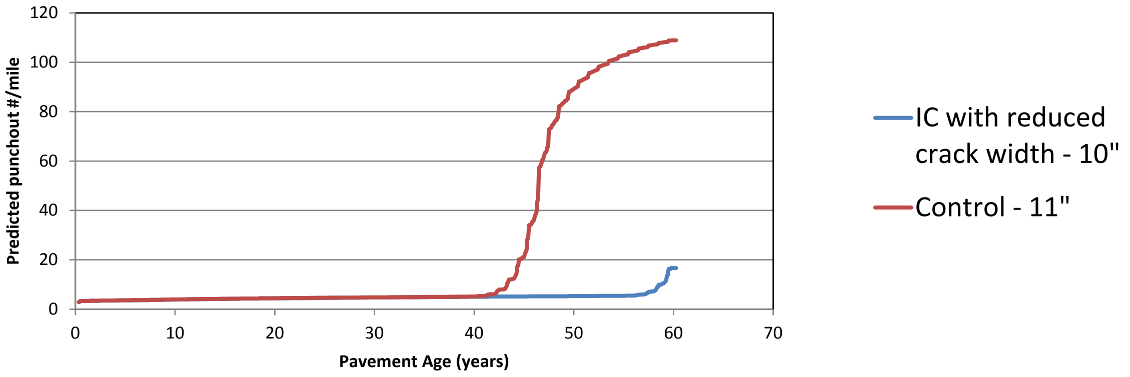
The optimized pavement design for a design life of 30 years was developed using the AASHTO ME Design procedure at this site. The inputs used in developing the optimized design were listed in Table 14, and the performance for a 30-year period was shown in Figure 16. A summary of the optimized design for conventional and ICC CRCP is presented in Table 21. These designs were confirmed to meet the requirements of the design criteria for 30 years.

Table 21. Summary of SH 121 CRCP design for conventional and ICC.

Design Feature	Conventional Concrete	Internally Cured Concrete	Comments
CRCP thickness, inches	11.0	10.0	Difference due to the change in CRCP inputs
Percent longitudinal reinforcement	0.7	0.7	Same
Base course	4-in HMA	4-in HMA	Same
Lime stabilized subgrade	10-in	10-in	Same
Subgrade	A-7-6	A-7-6	Same

Over a 60 year analysis period, the AASHTO performance predictions from the optimized designs for the conventional and ICC CRCP pavements are shown in Figure 48. Performance outputs from analyses are summarized in Table 22 and list the performance at 60 years and at the end of the 30-year design life.

Note that the ICC CRCP has longer crack spacing but much tighter cracks widths at both 30 years and 60 years. The results in Table 22 show that while the two pavements showed similar performance at 30 years, the benefit of tighter cracks has a huge impact in the long term to provide longer life and reduce maintenance costs.



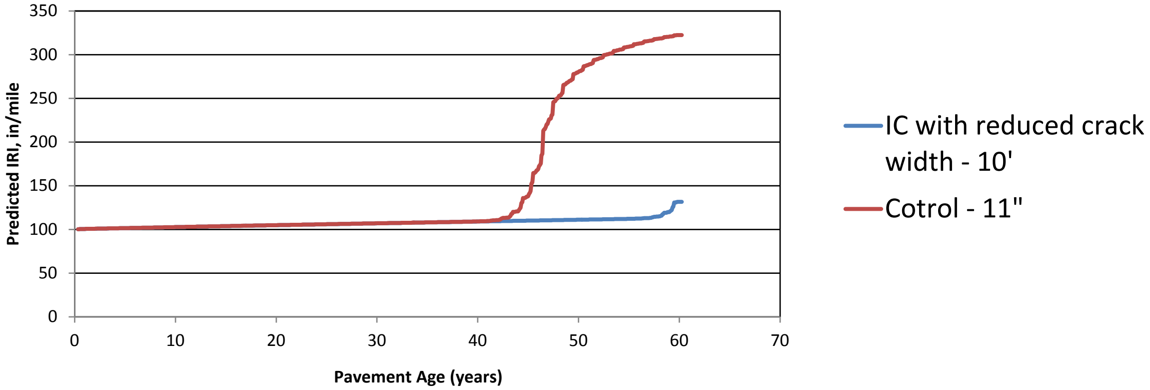


Figure 48. Predicted performance of SH 121 optimized designs for 60-year analysis period showing punchout development (top) and IRI (bottom).

Table 22. Summary of performance outputs at 60-year analysis period for conventional and ICC CRCP.

AASHTO Performance	Conventional Concrete	ICC	Comments
IRI, in./mile	>300	131	Same at 30 years, and lower in ICC at 60 years
Punchouts, #/mile	109	17	
Crack spacing, inches	67	76	ICC has longer mean spacing
Crack width, inches	0.019	0.012	ICC has tighter cracks
Crack LTE, %	50	61	LTE deteriorates less for ICC design

Maintenance and Rehabilitation

Table 23 shows the M&R treatments and M&R schedules for the two alternatives. Three treatments were specified for the two design alternatives, and these activities are scheduled based on the rate of distress development: full-depth reinforced repair of punchouts, diamond grinding of the surface to restore texture and smoothness, and a structural HMA overlay:

- Full-depth reinforced repairs were estimated based on the number of punchouts as predicted by AASHTO ME Design, which are different for the two alternatives.
- Diamond grinding was specified at 25 years to restore smoothness.
- Structural HMA overlay at 50 years for the conventional concrete and at 60 years for ICC alternative.

Table 23. SH 121 M&R schedule – 60-year analysis period.

11-inch Conventional Concrete CRCP		**10-inch ICC CRCP**	
Age	**# of Punchout Repairs**	**Age**	**# of Punchout Repairs**
15	4	15	4
25*	5	25*	5
42	19	40	6
50**	50	60**	17
* Diamond grinding included in maintenance activity			
** Includes repairs & structural rehabilitation with HMA overlay			

Life Cycle Cost Analysis

A typical LCCA was conducted using the assumptions previously listed. The costs were calculated per directional mile length of the roadway with two lanes and a shoulder. Table 24 provides a summary of the LCCA comparison results for the CRCP optimized designs. Table 25 and Table 26 provide details of the costs reported in Table 24 for conventional and ICC CRCP alternatives, respectively. The LCCA approach calculates the initial costs as well as the M&R costs at the given schedules. Next, all costs are normalized to the net present worth using the discount rate, which is a standard means to reduce the costs to a common point in time (the present time of construction). The total net present costs are then used to calculate the equivalent uniform annual cost (EUAC), which is the cost per year of owning and operating the pavement asset over the analysis period.

The initial cost is about 5 percent lower for ICC. The cost savings arise from the thickness reduction of 1 inch. The reduced M&R costs provide a much larger percentage of savings of with the ICC. The HMA overlay activity, which is scheduled at 50 years for conventional concrete and at 60 years for the ICC, results in a larger salvage value for ICC. Note that the life of the HMA overlay was assumed to be 20 years, and the salvage value indicated for the conventional concrete suggests a 10-year expected life from the overlay vs. a 20-year life from the ICC section. Overall, the ICC results in a 7.6 percent cost savings over the 60-year analysis period.

Table 24. LCCA comparisons for SH 121 conventional concrete and ICC alternatives for an analysis period of 60 years.

Cost Item	Control – 11-inch CRCP		ICC – 10-inch CRCP	
	Total Cost, $	**Net Present Worth, $**	**Total Cost, $**	**Net Present Worth, $**
Total initial cost	2,064,651	2,064,651	1,955,778	1,955,778 (5% saving)
Total M&R costs (1-60 years)	676,433	197,098	608,133 (10% savings)	155,548 (21% savings)
Salvage value (at year 60)		-57,754		-75,002
Net present value		$ 2,203,995		2,036,325 (7.6% savings)
EUAC		79,637		73,578

Alternative Approach for LCCA (using identical design thickness)

The results presented in Table 24 represent an analysis when an optimized design for the two alternatives is used, resulting in a thinner slab design for ICC and therefore savings in initial costs. An alternative approach to perform the LCCA is to assume identical design thicknesses for the two alternatives. This approach results in a higher initial cost for the ICC section because of the marginally higher unit cost of the ICC over conventional concrete. However, this approach may show life cycle cost benefits and also extended life for ICC.

Using this approach, where both conventional concrete and ICC result in 11-inch CRCP thickness, the performance of the pavements for a 60-year analysis period is presented in Figure 49. The increase in thickness of the ICC section provides a benefit with controlling punchouts and requiring fewer punchouts repairs, as shown in the M&R schedule in Table 27. The result of the LCCA comparing these two design alternatives is shown in Table 28. In this approach of ICC versus conventional comparisons, the initial cost of ICC is higher by 4.3 percent, the M&R costs of ICC are lower by 24 percent, and the net present value for the total ICC project is higher by 1.3 percent. Clearly, for this project, the approach of reducing initial cost, which provided 7.6 percent total cost savings with ICC, is more economical.

Table 25. LCCA for SH 121 CRCP optimized design with conventional concrete.

Conventional Concrete Pavement Performance Evaluation - CRCP Optimized for SH 121

Per Directional Mile

Section:	CRCP		Analysis period, years			60
Project Length, ft	5,280		Initial year of construction			2013
Number of Lanes	2		Discount rate, %			3.0%
Lane width, ft	12					
Median Shoulder width, ft	4		CRCP thickness	11	inch	
Outer Shoulder width, ft	10		HMA thickness	4	inch	
Pavement area (traffic lanes), sq.yd	14,080	sq.yd	LTB thickness	10	inch	
Pavement area (shoulders), sq.yd	8,213	sq.yd				
Total pavement area (traffic lanes + shoulders), sq.yd	22,293	sq.yd				
Total base/subgrade area (1' extra on either side), sq.yd	23,467	sq.yd				

CONSTRUCTION ITEMS	YEAR	QUANTITY	UNIT	UNIT PRICE	COST	2013 PRESENT WORTH
INITIAL CONSTRUCTION (year 0)						
Final subgrade preparation	0	23,467	sq. yd.	$2.50	$58,667	$58,667
10" Lime treated base course	0	6,519	cu. yd.	$14.17	$92,346	$92,346
4" HMA base course	0	5,210	tons	$40.00	$208,384	$208,384
11" CRCP (2 lanes plus median & right shoulders)	0	22,293	sq. yd.	$50.98	$1,136,489	$1,136,489
				Subtotal	**$1,495,886**	**$1,495,886**
MOT at 5%	0	6	month	$20,000	$120,000	$120,000
Design Costs at 10%	0				$149,589	$149,589
Miscellaneous at 10%	0				$149,589	$149,589
CSE Services at 10%	0				$149,589	$149,589
		TOTAL INITIAL CONSTRUCTION COSTS			**$2,064,651**	**$2,064,651**
FUTURE REHABILITATION NEEDS						
Maintenance & Repair						
Diamond Grind Existing Surface	15	0	sq.yd	$5.60	$0	$0
Full-depth pavement repairs	15	32.0	sq.yd	$200.00	$6,400	$4,108
MOT at 5%	15				$320	$205
Design Costs at 10%	15				$640	$411
Construction Inspection Services at 10%	15				$640	$411
Major Maintenance						
Diamond Grind Existing Surface	25	22,293	sq.yd	$5.60	$124,843	$59,626
Full-depth pavement repairs	25	4.0	sq.yd	$200.00	$800	$382
MOT at 5%	25				$6,282	$3,000
Design Costs at 10%	25				$12,564	$6,001
Construction Inspection Services at 10%	25				$12,564	$6,001
Minor Maintenance						
Diamond Grind Existing Surface	42	0	sq.yd	$5.60	$0	$0
Full-depth pavement repairs	42	20.0	sq.yd	$200.00	$4,000	$1,156
MOT at 5%	42				$200	$58
Design Costs at 10%	42				$400	$116
Construction Inspection Services at 10%	42				$400	$116
Major Rehabilitation						
Mill existing UTBHMWC	50	0	sq.yd	$3.50	$0	$0
Full-depth pavement repairs	50	528.0	sq.yd	$150.00	$79,200	$18,066
Place asphalt tack coat (9 sy/gal)	50	2,477	gallon	$1.70	$4,211	$961
2.0-in HMAC binder	50	2,475	tons	$65.00	$160,846	$36,690
2.0-in HMAC surface	50	2,475	tons	$65.00	$160,846	$36,690
MOT at 5%	50				$20,255	$4,620
Design Costs at 10%	50				$40,510	$9,241
Construction Inspection Services at 10%	50				$40,510	$9,241
				TOTAL INITIAL COST (year 0):	**$2,064,651**	**$2,064,651**
				TOTAL MAINTENANCE AND REHABILITATION COSTS (year 1 through 60):	**$676,433**	**$197,098**
				SALVAGE VALUE (at year 60):		($57,754)
				NET PRESENT WORTH:		**$2,203,995**
				EQUIVALENT UNIFORM ANNUAL COST:		**$79,637**

Table 26. LCCA for SH 121 CRCP optimized design with ICC.

IC Concrete Pavement Performance Evaluation - SH121 CRCP WITH CONTROLLED CRACK OPENING

Per Directional Mile

Section:	CRCP		Analysis period, years	60	
Project Length, ft	5,280		Initial year of construction	2013	
Number of Lanes	2		Discount rate, %	3.0%	
Lane width, ft	12				
Median Shoulder width, ft	4		CRCP thickness	10	inch
Outer Shoulder width, ft	10		HMA thickness	4	inch
Pavement area (traffic lanes), sq.yd	14,080	sq.yd	LTB thickness	10	inch
Pavement area (shoulders), sq.yd	8,213	sq.yd			
Total pavement area (traffic lanes + shoulders), sq.yd	22,293	sq.yd			
Total base/subgrade area (1' extra on either side), sq.yd	23,467	sq.yd			

CONSTRUCTION ITEMS	YEAR	QUANTITY	UNIT	UNIT PRICE	COST	2013 PRESENT WORTH
INITIAL CONSTRUCTION (year 0)						
Final subgrade preparation	0	23,467	sq. yd.	$2.50	$58,667	$58,667
10" Lime treated base course	0	6,519	cu. yd.	$14.17	$92,346	$92,346
4" HMA base course	0	5,210	tons	$40.00	$208,384	$208,384
10" CRCP (2 lanes plus median & right shoulders)	0	22,293	sq. yd.	$47.22	$1,052,741	$1,052,741
				Subtotal	**$1,412,137**	**$1,412,137**
MOT at 5%	0	6	month	$20,000	$120,000	$120,000
Design Costs at 10%	0				$141,214	$141,214
Miscellaneous at 10%	0				$141,214	$141,214
CSE Services at 10%	0				$141,214	$141,214
				TOTAL INITIAL CONSTRUCTION COSTS	**$1,955,778**	**$1,955,778**
FUTURE REHABILITATION NEEDS						
Maintenance & Repair						
Diamond Grind Existing Surface	15	0	sq.yd	$5.60	$0	$0
Full-depth pavement repairs	15	32.0	sq.yd	$200.00	$6,400	$4,108
MOT at 5%	15				$320	$205
Design Costs at 10%	15				$640	$411
Construction Inspection Services at 10%	15				$640	$411
Major Maintenance						
Diamond Grind Existing Surface	25	22,293	sq.yd	$5.60	$124,843	$59,626
Full-depth pavement repairs	25	4.8	sq.yd	$200.00	$960	$459
MOT at 5%	25				$6,290	$3,004
Design Costs at 10%	25				$12,580	$6,008
Construction Inspection Services at 10%	25				$12,580	$6,008
Major Maintenance						
Diamond Grind Existing Surface	40	0	sq.yd	$5.60	$0	$0
Full-depth pavement repairs	40	4.0	sq.yd	$200.00	$800	$245
MOT at 5%	40				$40	$12
Design Costs at 10%	40				$80	$25
Construction Inspection Services at 10%	40				$80	$25
Major Rehabilitation						
Mill existing UTBHMWC	60	0	sq.yd	$3.50	$0	$0
Full-depth pavement repairs	60	184.0	sq.yd	$150.00	$27,600	$4,685
Place asphalt tack coat (9 sy/gal)	60	2,477	gallon	$1.70	$4,211	$715
2.0-in HMAC binder	60	2,475	tons	$65.00	$160,846	$27,301
2.0-in HMAC surface	60	2,475	tons	$65.00	$160,846	$27,301
MOT at 5%	60				$17,675	$3,000
Design Costs at 10%	60				$35,350	$6,000
Construction Inspection Services at 10%	60				$35,350	$6,000
				TOTAL INITIAL COST (year 0):	**$1,955,778**	**$1,955,778**
				TOTAL MAINTENANCE AND REHABILITATION COSTS (year 1 through 60):	**$608,133**	**$155,548**
				SALVAGE VALUE (at year 60):		($75,002)
				NET PRESENT WORTH:		**$2,036,325**
				EQUIVALENT UNIFORM ANNUAL COST:		**$73,578**

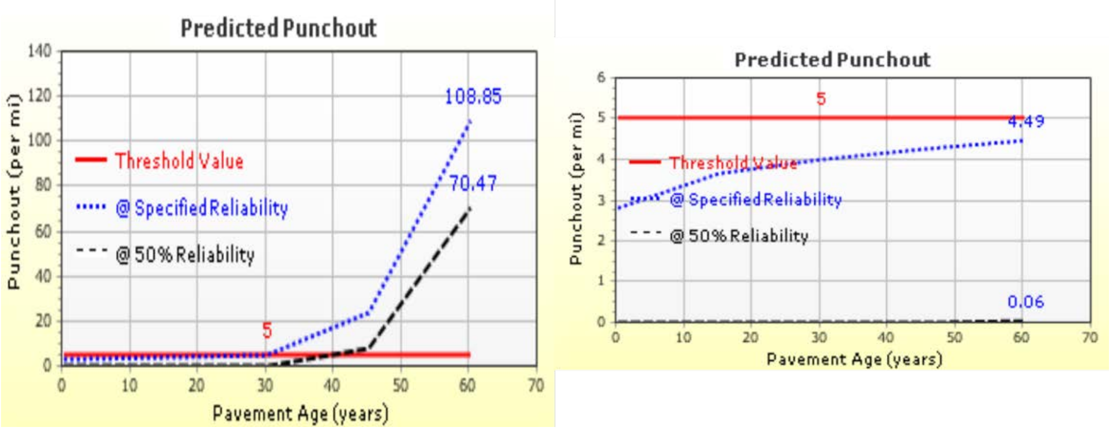


Figure 49. Comparison of 60-year performance for 11-inch conventional CRCP (left) and 11-inch ICC CRCP (right) on SH 121.

Table 27. SH 121 M&R schedule for alternative approach to LCCA.

11-inch Conventional Concrete CRCP		**11-inch ICC CRCP**	
Age	**# of Punchout Repairs**	**Age**	**# of Punchout Repairs**
15	4	15	4
25*	0.5	25*	0
42	2.5	40	0.2
50**	33	60**	0.2
* Diamond grinding included in maintenance activity			
** Includes repairs & structural rehabilitation with HMA overlay			

Table 28. Alternative approach to LCCA for SH 121.

Cost Item	**Control – 11-inch CRCP**		**ICC – 11-inch CRCP**	
	Total Cost, $	**Net Present Worth, $**	**Total Cost, $**	**Net Present Worth, $**
Total initial cost	2,064,651	2,064,651	2,153,205	2,153,205 (4.3% increase)
Total M&R costs (1-60 years)	676,433	197,098	572,433 (15% savings)	149,037 (24% savings)
Salvage value (at year 60)		-57,754		-69,248
Net present value		$ 2,203,995		2,232,995 (1.3% increase)
EUAC		79,637		80,685

LCCA FOR I-45 JPCP SITE

The I-45 section near the UP Intermodal Terminal was used for the JPCP LCCA. This project was analyzed for a 30-year design period, and the LCCA is being performed over a 60-year analysis period. As stated earlier, I-45 is a major freeway between Dallas and Houston with an initial two-way AADTT of 7,200, 40 million trucks in the design lane in 30 years, and 112 million trucks over the entire 60-year analysis period. The climate is that of north Texas, and the subgrade is a fine-grained A-7-6 soil. The actual conventional and ICC mixtures were used in the LCCA.

JPCP Design

The optimized pavement design was developed using the AASHTO ME Design procedure for both conventional and ICC sections at this site. A summary of the inputs used was presented in Table 15, and a summary of the optimized designs was presented in Table 16. The analyses were performed for a design life of 60 years. The as-built ICC pavement at the intermodal facility is expected to perform very well for the entire design period. The IRI, joint faulting, and transverse fatigue cracking are within the selected threshold levels of 160 in./mile, 0.12 inch, and 10 percent, respectively. The design resulted in a JPCP thickness of 11.5 inches for conventional concrete and 10.5 inches for ICC. For a design life of 30 years, the predicted performance charts for the two alternatives were presented in Figure 42, Figure 43, and Figure 44.

For an extended analysis period of 60 years, the AASHTO ME Design analysis predicted performance is summarized in Table 29. Both designs pass the 97 percent design reliability and performance criteria at 30 years, but both develop significant roughness and faulting over the 60-year period. The prediction of conventional and of ICC design performance shows that the conventional design performs slightly better than the ICC, but the difference is not large. This occurs because the ICC JPCP is 1 inch thinner. This saves on initial construction cost, which is a significant cost savings to achieve about the same performance.

Table 29. Summary of performance outputs for 60-year analysis period for conventional and ICC optimized JPCP.

AASHTO ME Performance	11.5-inch Conventional Concrete	10.5-inch ICC	Comments on Condition at 60 Years
IRI, in./mile	208	225	ICC higher IRI
Cracked slabs, percent	4.7	6.6	ICC higher cracked slabs
Joint faulting, in	0.22	0.24	ICC higher faulting
Dowel LTE, percent	92	92	Same joint LTE

Maintenance and Rehabilitation

Two treatment options were specified, as summarized in Table 30. They included full-depth repair of cracked slabs and diamond grinding of the surface to restore texture and smoothness. Full-depth repairs were estimated based on the percent slabs cracked as predicted by the AASHTO ME Design procedure. Diamond grinding was specified at 40 years due to faulting and IRI magnitude. At the end of the 60-year analysis period, full-depth repairs were performed and an HMA overlay was placed on both alternatives due to the level of damage.

Table 30. Maintenance and rehabilitation activities and schedule for I-45 JPCP optimized designs with conventional concrete and ICC alternatives.

Conventional Concrete		ICC		Comment
Age	Percent Area Repair	Age	Percent Area Repair	
15	0.1	15	0.1	
25	0.2	25	0.2	
40	4.7	40	5.3	Add diamond grinding for full area
50	0.5	50	0.5	
60	0.5	60	1.0	Add overlay

Life Cycle Cost Analysis

A typical LCCA was conducted using the assumptions previously listed. The costs were calculated per directional mile length of the roadway with two lanes and a shoulder. Table 31 provides a summary of the LCCA comparison results for the JPCP optimized designs. Table 32 and Table 33 provide details of the calculations for costs reported in Table 31 for conventional and ICC CRCP alternatives, respectively.

The results in Table 31 indicate that the use of ICC for this project, which results in a JPCP slab reduction of 1 inch for a 30-year design life, can result in cost savings of about 1.7 percent in initial construction cost. However, the reduced thickness will tend to require increased M&R over time beyond 30 years. The cracking is marginally higher than in the conventional concrete and therefore will require a slightly higher level of M&R. The increase in maintenance activities results in an increased cost of 6.7 percent for M&R. However, the overall life cycle cost of the ICC JPCP project is estimated to result in a cost savings of 0.9 percent over the 60-year analysis period. An agency might consider cost savings of about 1 percent to be marginal, and therefore opt to use same thickness for ICC as control concrete, which will result in higher initial cost but reduced M&R costs for ICC.

Table 31. LCCA comparisons for I-45 optimized design alternatives with conventional concrete and ICC for an analysis period of 60 years.

Cost Item	Control – 11.5-inch JPCP		ICC – 10.5-inch JPCP	
	Total Cost, $	Net Present Worth, $	Total Cost, $	Net Present Worth, $
Total initial cost	2,006,690	2,006,690	1,972,659	1,972,659 (1.7% savings)
Total M&R costs year 1-60 years	859,656	206,524	913,996	220,322 (6.7% extra)
Net present value		2,213,214		2,192,982 (0.9% savings)
EUAC		79,970		79,239 (0.9% savings)

The other way to compare the conventional with ICC is to use the conventional design thickness for both (i.e., 11.5-inch thickness for both the conventional and ICC projects). An LCCA comparing the ICC and conventional concrete alternatives with identical thicknesses of 11.5 inches shows an overall increase in costs of 2 percent over the 60-year analysis period for the ICC, rather than a 0.9 percent reduction. This occurs due to the elimination of the benefit in initial construction cost.

The analysis presented in this section is based on the AASHTO ME Design performance predictions, which only account for structural characteristics of the materials. However, ICC has a potential to provide durability benefits by reducing shrinkage cracking and by reducing permeability and thereby reducing joint deterioration problems from freeze-thaw related mechanisms prevalent in the Midwest (Peshkin et al. 1990). As an example, based on pavement management expertise from the Illinois Tollway, about half their slab repairs may be the result of joint deterioration problems in conventional concrete. These types of slab repairs are not considered in the analysis presented in Table 31.

ICC has significant potential to reduce joint slab repairs and other maintenance activities due to freeze-thaw problems and spalling at the joints, among others. Validation of this concept needs field testing over a number of years through the construction of ICC projects using aggregate sources used on projects that have exhibited joint deterioration problems.

Table 32. LCCA for JPCP optimized design with conventional concrete.

I-45 Life Cycle Cost Evaluation - Conventional JPCP

Per Directional Mile

Section:	JPCP -Control		Analysis period, years	60	
Project Length, ft	5,280		Initial year of construction	2013	
Number of Lanes	2		Discount rate, %	3.0%	
Lane width, ft	12				
Median Shoulder width, ft	4		JPCP thickness	11.5	inch
Outer Shoulder width, ft	10		GB thickness	12	inch
Pavement area (traffic lanes), sq.yd	14,080	sq.yd	Subbase thickne	0	inch
Pavement area (shoulders), sq.yd	8,213	sq.yd			
Total pavement area (traffic lanes + shoulders), sq.yd	22,293	sq.yd			
Total base/subgrade area (1' extra on either side), sq.yd	23,467	sq.yd			

CONSTRUCTION ITEMS			YEAR	QUANTITY	UNIT	UNIT PRICE	COST	2013 PRESENT WORTH
INITIAL CONSTRUCTION (year 0)								
Final subgrade preparation			0	23,467	sq. yd.	$2.50	$58,667	$58,667
12" Crushed stone aggregate base layer			0	15,629	cu. yd.	$22.00	$343,834	$343,834
11.5" JPCP- Control (2 lanes plus median & right shoulders)			0	22,293	sq. yd.	$47.05	$1,048,800	$1,048,800
						Subtotal	**$1,451,300**	**$1,451,300**
MOT at 5%			0	6	month	$20,000	$120,000	$120,000
Design Costs at 10%			0				$145,130	$145,130
Miscellaneous at 10%			0				$145,130	$145,130
CSE Services at 10%			0				$145,130	$145,130
						TOTAL INITIAL CONSTRUCTION COSTS	**$2,006,690**	**$2,006,690**
FUTURE REHABILITATION NEEDS								
Maintenance & Repair								
Diamond Grind Existing Surface			15	0	sq.yd	$5.60	$0	$0
Full-depth pavement repairs	% Repair =	0.1	15	22.3	sq.yd	$200.00	$4,459	$2,862
MOT at 5%			15				$223	$143
Design Costs at 10%			15				$446	$286
Construction Inspection Services at 10%			15				$446	$286
Major Maintenance								
Diamond Grind Existing JPCP Surface			25	0	sq.yd	$5.60	$0	$0
Full-depth pavement repairs	% Repair =	0.2	25	44.6	sq.yd	$200.00	$8,917	$4,259
MOT at 5%			25				$446	$213
Design Costs at 10%			25				$892	$426
Construction Inspection Services at 10%			25				$892	$426
Major Maintenance								
Diamond Grind Existing JPCP Surface			40	22,293	sq.yd	$5.60	$124,843	$38,271
Full-depth pavement repairs	% Repair =	4.7	40	1,047.8	sq.yd	$200.00	$209,557	$64,241
MOT at 5%			40				$10,478	$3,212
Design Costs at 10%			40				$20,956	$6,424
Construction Inspection Services at 10%			40				$20,956	$6,424
Major Maintenance								
Diamond Grind Existing JPCP Surface			50	0	sq.yd	$5.60	$0	$0
Full-depth pavement repairs	% Repair =	0.5	50	111.5	sq.yd	$200.00	$22,293	$5,085
Apply microsurfacing (lanes & shoulders)			50	0	sq.yd	$6.10	$0	$0
MOT at 5%			50				$1,115	$254
Design Costs at 10%			50				$2,229	$509
Construction Inspection Services at 10%			50				$2,229	$509
Major Rehabilitation								
Mill existing UTBHMWC			60	0	sq.yd	$3.50	$0	$0
Full-depth pavement repairs	% Repair =	0.5	60	111.5	sq.yd	$150.00	$16,720	$2,838
Place asphalt tack coat (9 sy/gal)			60	2,477	gallon	$1.70	$4,211	$715
2.0-in HMAC binder			60	2,475	tons	$65.00	$160,846	$27,301
2.0-in HMAC surface			60	2,475	tons	$65.00	$160,846	$27,301
MOT at 5%			60				$17,131	$2,908
Design Costs at 10%			60				$34,262	$5,815
Construction Inspection Services at 10%			60				$34,262	$5,815
						TOTAL INITIAL COST (year 0):	**$2,006,690**	**$2,006,690**
						TOTAL MAINTENANCE AND REHABILITATION COSTS (year 1 through 60):	**$859,656**	**$206,524**
						NET PRESENT WORTH:		**$2,213,214**
						EQUIVALENT UNIFORM ANNUAL COST:		**$79,970**

Table 33. LCCA for JPCP for optimized design with ICC.

I-45 Life Cycle Cost Evaluation - IC JPCP

Per Directional Mile

Section:	JPCP - IC		Analysis period, years			60
Project Length, ft	5,280		Initial year of construction			2013
Number of Lanes	2		Discount rate, %			3.0%
Lane width, ft	12					
Median Shoulder width, ft	4		JPCP thickness	10.5	inch	
Outer Shoulder width, ft	10		GB thickness	12	inch	
Pavement area (traffic lanes), sq.yd	14,080	sq.yd	Subbase thickne	0	inch	
Pavement area (shoulders), sq.yd	8,213	sq.yd				
Total pavement area (traffic lanes + shoulders), sq.yd	22,293	sq.yd				
Total base/subgrade area (1' extra on either side), sq.yd	23,467	sq.yd				

CONSTRUCTION ITEMS			YEAR	QUANTITY	UNIT	UNIT PRICE	COST	2013 PRESENT WORTH
INITIAL CONSTRUCTION (year 0)								
Final subgrade preparation			0	23,467	sq. yd.	$2.50	$58,667	$58,667
12" Crushed stone aggregate base layer			0	15,629	cu. yd.	$22.00	$343,834	$343,834
10.5" JPCP- IC (2 lanes plus median & right shoulders)			0	22,293	sq. yd.	$45.87	$1,022,622	$1,022,622
						Subtotal	**$1,425,122**	**$1,425,122**
MOT at 5%			0	6	month	$20,000	$120,000	$120,000
Design Costs at 10%			0				$142,512	$142,512
Miscellaneous at 10%			0				$142,512	$142,512
CSE Services at 10%			0				$142,512	$142,512
						TOTAL INITIAL CONSTRUCTION COSTS	**$1,972,659**	**$1,972,659**
FUTURE REHABILITATION NEEDS								
Maintenance & Repair								
Diamond Grind Existing Surface			15	0	sq.yd	$5.60	$0	$0
Full-depth pavement repairs	% Repair =	0.1	15	22.3	sq.yd	$200.00	$4,459	$2,862
MOT at 5%			15				$223	$143
Design Costs at 10%			15				$446	$286
Construction Inspection Services at 10%			15				$446	$286
Major Maintenance								
Diamond Grind Existing JPCP Surface			25	0	sq.yd	$5.60	$0	$0
Full-depth pavement repairs	% Repair =	0.2	25	44.6	sq.yd	$200.00	$8,917	$4,259
MOT at 5%			25				$446	$213
Design Costs at 10%			25				$892	$426
Construction Inspection Services at 10%			25				$892	$426
Major Maintenance								
Diamond Grind Existing JPCP Surface			40	22,293	sq.yd	$5.60	$124,843	$38,271
Full-depth pavement repairs	% Repair =	5.3	40	1,181.5	sq.yd	$200.00	$236,309	$72,442
MOT at 5%			40				$11,815	$3,622
Design Costs at 10%			40				$23,631	$7,244
Construction Inspection Services at 10%			40				$23,631	$7,244
Major Maintenance								
Diamond Grind Existing JPCP Surface			50	0	sq.yd	$5.60	$0	$0
Full-depth pavement repairs	% Repair =	0.5	50	111.5	sq.yd	$200.00	$22,293	$5,085
Apply microsurfacing (lanes & shoulders)			50	0	sq.yd	$6.10	$0	$0
MOT at 5%			50				$1,115	$254
Design Costs at 10%			50				$2,229	$509
Construction Inspection Services at 10%			50				$2,229	$509
Major Rehabilitation								
Mill existing UTBHMWC			60	0	sq.yd	$3.50	$0	$0
Full-depth pavement repairs	% Repair =	1.0	60	222.9	sq.yd	$150.00	$33,440	$5,676
Place asphalt tack coat (9 sy/gal)			60	2,477	gallon	$1.70	$4,211	$715
2.0-in HMAC binder			60	2,475	tons	$65.00	$160,846	$27,301
2.0-in HMAC surface			60	2,475	tons	$65.00	$160,846	$27,301
MOT at 5%			60				$17,967	$3,050
Design Costs at 10%			60				$35,934	$6,099
Construction Inspection Services at 10%			60				$35,934	$6,099
						TOTAL INITIAL COST (year 0):	**$1,972,659**	**$1,972,659**
						TOTAL MAINTENANCE AND REHABILITATION COSTS (year 1 through 60):	**$913,996**	**$220,322**
						NET PRESENT WORTH:		**$2,192,982**
						EQUIVALENT UNIFORM ANNUAL COST:		**$79,239**

To illustrate the potential impact on LCCA, an analysis was performed for a JPCP constructed in the Midwest (Chicago). The design thicknesses for the same level of traffic were 11 inches for ICC and 12 inches for conventional concrete. An HMA base layer was used in this design. In the LCCA, the maintenance activities were increased for the conventional concrete alternative by 50 percent and no changes were made to the maintenance activities of the ICC alternative. These results, in comparison to the results provided in Table 31, result in a cost savings of 16 percent in M&R net present costs (compared to -6.7 percent savings). The total savings over the life of the project is 2.6 percent, as shown in Table 34. This is more than twice the savings as when only structural distress was considered (0.9 percent).

Table 34. LCCA comparisons for JPCP in Midwest with increased maintenance in conventional concrete.

Cost Item	**Control – 12-inch JPCP**		**ICC – 11-inch JPCP**	
	Total cost, $	**Net Present Worth, $**	**Total Cost, $**	**Net Present Worth, $**
Total initial cost	2,113,601	2,113,601	2,083,595	2,083,595 (1.4% savings)
Total M&R costs year 1-60 years	2,113,601	2,113,601	704,996	164,157 (15.8% savings)
Net present value		2,308,524		2,247,753 (2.6% savings)
Equivalent Uniform Annual Cost		83,414		81,218 (2.6% savings)

SUMMARY OF LCCA

Two projects, previously analyzed with the AASHTO ME Design procedure, 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. M&R activities and schedules were established based on AASHTO ME Design performance predictions for both the alternatives. The results of the LCCA are as follows:

- The SH 121 CRCP project, which resulted a CRCP thickness reduction of 1 inch for ICC, provided the following cost impacts over the 60-year analysis period:
    - Reduction of 5.0 percent in initial construction cost.
    - Reduction of 21 percent in M&R costs.
    - Reduction of 7.6 percent in the overall life cycle cost.
- If the design thickness of the ICC construction is same as the conventional construction, then the following cost impacts were obtained over the 60-year analysis period:
    - Increase of 4.3 percent in initial construction cost.

  - Reduction of 24 percent in M&R costs.
  - Reduction of 1.3 percent in the overall life cycle cost.
- The I-45 JPCP project, which resulted a JPCP thickness reduction of 1 inch for ICC, provided the following cost impacts over the 60-year analysis period:
  - Reduction of 1.7 percent in initial construction cost.
  - Increase of 6.7 percent in M&R costs.
  - Reduction of 0.9 percent in the overall life cycle cost.
- The JPCP project when analyzed for the Midwest climate for the same traffic levels also resulted in 1-inch thickness reduction in the initial design. Assuming ICC can reduce the need for slab repairs due to freeze-thaw and joint spalling, the following cost impacts were determined:
  - Reduction of 1.4 percent in initial construction cost.
  - Reduction of 15.8 percent in M&R costs.
  - Reduction of 2.6 percent in the overall life cycle cost.

These pavement design and life cycle cost analyses indicate that using ICC in JPCP and CRCP can provide the following:

- A small reduction (0.5-1.0 inch) in initial thickness design of JPCP and CRCP.
- This results in a small reduction in initial construction costs (1.7-5.0 percent) and in overall life cycle costs (0.9-7.6 percent).
- Alternatively, if the conventional concrete thickness design is used for the ICC pavement, a small increase in construction cost will occur (4.3 percent CRCP) but a significant reduction in M&R cost will occur over the long term (24 percent CRCP).

These LCCAs have limitations, as they are based on cost and life assumptions that are specific to a given location (e.g., the Dallas-Fort Worth area). The LCCA results may change if conducted in different locations, as illustrated for the JPCP example in the Midwest, where the overall long-term LCCA savings increased to 2.6 percent for ICC pavement because of the consideration of durability deterioration from freeze-thaw.

CHAPTER 7. ROAD MAP FOR INTERNALLY CURED CONCRETE PAVEMENTS

The "Road Map for Internally Cured Concrete Pavements" provides the industry and government with recommendations on how to proceed to achieve the goal of implementation of ICC in concrete pavement design and construction in North America where construction (e.g., curing), performance, and cost factors provide significant benefits.

The Road Map for ICC pavement follows the national Concrete Pavement Road Map (Second Generation): Volume II, Tracks. Publication FHWA-HRT-11-070 July 2012 (CP Road Map http://www.cproadmap.org/) developed by the Iowa-State University led team. For example: *Track 1. Materials and Mixes for Concrete Pavements.* This track includes many items related to ICC pavement including mix design and specifications, materials selection and testing, innovative materials, materials proportioning, mixture evaluation, and post-construction pavement materials evaluation. Sub-track 1-3. Innovative Materials already includes section 1-3-10, Advancements in Internal Curing of Concrete, and 1-3-11, Self-Curing Concrete

The ICC road map identifies "gaps" in the technology, knowledge base, construction, testing, standards, and education that are needed to inform government and industry engineers and managers about ICC. The road map will serve as a guide to the industry in their future promotion and technical activities with the goal of making ICC an optional mixture adjustment that will become a sustainability standard across North America for concrete pavement.

The concrete slab inputs for ICC are typically not more than a few percentage points change from those of a conventional concrete slab, and in fact, the range of ICC inputs falls well within the national calibration efforts for the AASHTO ME Design procedure. The changes aren't outside of the realm of our typical consideration for inputs but it's the cumulative effect they have that makes them of such value. Minor tweak in the mixture create a potential for major performance benefits.

The road map includes the following "tracks" that address a specific focus of activity:

1. Educational and technology transfer materials and outreach seminars.
2. Guidelines for the design and construction of ICC pavements.
3. Construction of ICC experimental pavement sections.
4. Research and development to improve ICC mixtures, design, and construction.

TRACK 1. EDUCATIONAL AND TECHNOLOGY TRANSFER MATERIALS AND OUTREACH SEMINARS

There is a great need to develop a series of educational materials for technical presentations and communications with key staff in various highway agencies (local, State, Tollway, Federal, etc.).

The ESCSI should pursue a cooperative agreement with the FHWA to conduct a series of technology transfer seminars on ICC pavements at selected State highway agencies. This could be combined with the use of ICC in bridge decks. ARA personnel have taken part in similar seminars for CRCP technology transfer under a cooperative agreement between the Concrete Reinforcing Steel Institute (CRSI) and the FHWA over the past several years. The FHWA provided funds to cover several experts to present professional seminars on CRCP at a dozen State highway agencies. The CRSI provided organization and other support in arranging the seminars and reimbursing the instructors. The participating States co-sponsored the seminar, in which 10 to 40 engineering and construction staff plus contractors and others participated in each State. Evaluation comments from the participants in these seminars were very positive. There were always a number of good discussions and questions and answers during the seminars.

The ESCSI should also pursue working with ACPA and its local chapter workshops. This would be in the form of presentations at conferences, ACPA webinars, CP magazine articles, and the development of 4-8 page technical documents.

TRACK 2. GUIDELINES FOR THE DESIGN AND CONSTRUCTION OF ICC PAVEMENTS

AASHTO ME Design already has the capability to design ICC pavements, both JPCP and CRCP, including overlays. There are a few deficiencies in the procedures and lack of knowledge for proper input selection, but overall the results obtained from inputting ICC properties for several key projects provided reasonable concrete pavement designs. The concrete slab inputs for ICC are typically not more than a few percentage points change from those of a conventional concrete slab, and in fact, the range of ICC inputs falls well within the national calibration efforts for the AASHTO ME Design procedure.

There is a strong need for improved guidelines to select appropriate design inputs for ICC mixtures. Some work on this has been done and documented in this report, but additional work is need on some inputs.

The construction of ICC pavement also needs some additional guidelines. These guidelines should include how to obtain an optimized mixture design, as well as field recommendations on batching, placement and curing.

TRACK 3. CONSTRUCTION OF EXPERIMENTAL ICC TEST PAVEMENT SECTIONS

Perhaps the most efficient and effective approach to encouraging the use of ICC in paving is the construction of ICC experimental projects around the country. An experimental ICC pavement project can be constructed and an open house can be held for interested engineers, contractors, and managers to attend. The open house also includes expert presentations on ICC and its use in concrete pavements. In addition, the projects will remain in place for many years to demonstrate the performance of ICC on real-world projects. Several papers and presentations can come out of these experimental projects that can be presented at research and training seminars. The FHWA and State highway agencies are often looking for innovative and high potential experimental projects such as this to construct.

One of the main goals of FHWA's Every Day Counts program is to accelerate the implementation of innovative technologies into mainstream practice. This program is in line with an earlier FHWA program, Highways for LIFE, within which State agencies were provided a significant level of project support for adopting technologies that had demonstrated success in improving safety, mobility (reduced congestion), performance, and cost-effectiveness. Under the Highways for LIFE program, agencies incorporated new technologies that satisfied the aforementioned goals. In addition, they were required to provide project information to the FHWA team that monitored the project, evaluated how well the goals were met, and reported details of the success stories for other agencies to adopt these technologies in future. Similar activities are planned under the Every Day Counts program. Examples of innovative technologies used in State demonstration projects include precast pavements, self-consolidating concrete, accelerated bridge construction, and roundabouts.

ICC may also be extended to airfield pavement projects. Airfield pavements will benefit from reduced permeability and reduced pavement distress, especially when deicers and anti-icing products are used. This technology does not require more experimentation and 10+ yrs of watch-and-see. It is proven that with a minor mix design tweak, ICC will either reduce thickness or extend performance, or both, and that it is ready-to-implement and is justifiable by ME design.

The ESCSI should reach out to contractors, FAA and State and toll highway agencies that are interested in exploring the ICC pavement alternative and offer technical guidance, as needed, so that agencies can request FHWA support for demonstration projects under the Every Day Counts program.

One specific ICC potential application bears comment. Premature failures are a major concern in full-depth repairs using fast-setting concrete mixes, including those with Type III cements or rapid set cements. High shrinkage and high effective built-in gradients resulting from elevated heat of hydration, combined with high shrinkage, are typically identified as causes for early age cracking. ICC has a remarkable potential for applications in mixes with high early strength requirements or projects with critical opening time requirements. ESCSI should consider promoting the use of ICC for rapid slab repairs and replacements and evaluate its performance in lab and field trials.

TRACK 4. RESEARCH AND DEVELOPMENT OF ICC MIXTURES AND DESIGN AND CONSTRUCTION GAPS IN KNOWLEDGE

ICC mixtures have been used very successfully in bridge decks. One estimate was there are over 30 bridge decks in New York, Virginia, Indiana, Utah, North Carolina, and Georgia built with ICC that are showing very low shrinkage cracking (Streeter, Wolfe, and Vaughn, 2012; Schlitter et al., 2010; Ozyildirim, 2011; ESCSI, 2012a; Delatte and Crowl, 2012). This effort has provided a great deal of research into ICC that has greatly moved the technology forward (ACI 308-13; ACI 213R-13). However, the application of this technology to pavements still demands additional knowledge. The examination of the literature and the interviews of experts during this project have identified some key gaps in knowledge that need to be filled with factual data and information relative to ICC pavements. A summary of these gaps is as follows for JPCP and CRCP:

- The primary gap is the lack of sufficient knowledge in how ICC pavement will reduce the long-term upward curling of concrete slabs. Excessive upward curling of slabs results in early and often excessive longitudinal and transverse cracking of JPCP slabs and edge punchouts of CRCP. Ya and Hansen (2008) showed a 70 percent reduction in moisture warping in 16 days of drying using ICC, but additional data are needed to confirm these findings (ACI(308-213)R-13) over the long-term. If it can be shown that ICC pavement slabs placed under varying climate conditions reduce long-term upward curling (primarily by reducing the moisture gradient through the slab) and quantify the difference, then this information can be used to greatly improve design. Top-down cracking has caused rapid premature cracking of some JPCP and CRCP placed during critical climatic conditions (e.g., sunny mornings) and critical mixture properties (e.g., high shrinkage). If upward curling is reduced, it can lead to much longer life for JPCP and CRCP. Field curling measurement data from this study for the three JPCP Dallas-Fort Worth ICC projects provided evidence of less-than-typical (low) curling (there were no comparable control sections however). Considerable additional data is needed to validate the reduction of short term and long term upward curling-related parameters in pavement analysis and design.
- The second gap is the lack of knowledge regarding potential long-term durability performance benefits of ICC pavement. The AASHTO ME Design software deals mostly with structural capacity and does not deal much with durability. Filling this gap would involve studies to examine various forms of durability issues that occur in conventional concrete pavements around the country that may be reduced with ICC mixtures. For example:

  - Plastic shrinkage cracking. This may result in deterioration of the surface over time and may contribute to top-down crack fatigue by providing small cracks that are easily extended with load repetition over time. Reducing plastic shrinkage cracking would also be very beneficial to contractors and the construction process since the early presence of this form of cracking is very problematic for judging the acceptance of the work. Many slabs have been replaced on some construction projects due to the presence of plastic shrinkage cracking.
  - Random cracking under harsh placement and weather conditions.
  - Joint disintegration of the lower portion of the concrete slab which eventually works its way through the slab and requires costly full-depth repair. This is a critical problem in the Midwest particularly.
  - Joint spalling due to inadequate freeze-thaw resistance in pavement concrete, which may be reduced in ICC because of dense matrix/low permeability.

  There is an extensive amount of research that shows ICC will improve durability and concrete performance; therefore, there is solid evidence to suggest ICC will help to reduce some, if not all, of these problems.
- The third gap is the lack of knowledge about the reduction of long-term shrinkage of ICC compared to conventional concrete. Reduction in shrinkage is critical to several benefits of ICC, including tighter cracks (CRCP) and joints (JPCP) and curling of slabs. Limited field data on ICC indicate fewer and tighter long-term cracks, but additional field projects are needed to confirm this in several parts of the country and different mixtures.
- The fourth gap relates to use of ICC for high early strength and early opening concrete repairs and slab replacements. These projects often result in early random cracking from high shrinkage or thermal gradients. Research is needed into the best mixture design that will provide sufficient strength, but will have reduced shrinkage and other improvements that will minimize early cracking of these repairs. One project examined in this study showed promising results.
- Finally, better understanding of the true impact of both reduced elastic modulus and concrete CTE in ICC would enable more accurate calculation of critical stresses and subsequent fatigue damage in pavements. PCC elastic modulus is a sensitive parameter in calculating pavement response. There exists a vast amount of laboratory data from various studies conducted by several researchers in this area. A compilation of such data, limited to ICC, and an examination of mix design variables including unit weight and other mix design index properties, would be immensely useful for future pavement designs. Likewise, a focused examination of PCC CTE data, another critical ICC input, would be meaningful.

CHAPTER 8. SUMMARY

ICC is a concrete mixture in which a portion of the coarse, intermediate, and/or fine aggregates (for example, 30 percent of sand) is replaced with similar sized prewetted LWA. IC is a means to provide hydrating concrete adequate moisture from within the mixture to replace chemical shrinkage water. Additional prewetted LWA may also be added to restore, at least partially, the moisture that escapes through evaporation.

IC, which naturally takes place in lightweight aggregate concrete, has specifically been designed into normal weight concrete by the substitution of a relatively small portion of prewetted LWA that continue to release moisture well after placement and into the hydration process (Bentz and Weiss, 2011; Weiss et al., 2012). The LWA fraction is prewetted and maintained at a wetted surface dry condition during batching. After placement, as the paste starts to lose moisture during hydration, the absorbed water in the LWA is released into the paste to assist with continuing the hydration of the cementitious materials. In a fundamental sense, IC meets the time-dependent moisture needs of hydration to produce concrete with desired properties.

ESCSI LWAs are manufactured using naturally mined slate, shale, or clays (ESCSI, 2012a). The raw materials are sized in a standard process and fed through a rotary kiln, where they are subjected to temperature levels of approximately 2,000 °F. This heating process releases gases from the materials, causing the formation of pores and an expansion of the material. This expansion in volume is what gives the aggregate a lower unit weight

ICC has been used on bridge decks in recent years in several States with great success, reducing dramatically the amount of plastic shrinkage cracking and other random cracking particularly in high performance concrete bridge decks (Streeter, Wolfe, and Vaughn, 2012; Schlitter et al., 2010; Ozyildirim, 2011; ESCSI, 2012a; Delatte and Crowl, 2012). In fact, the use of ICC for bridge decks is rapidly expanding, given the remarkable effect on reducing cracking and the accompanying potential benefits. ICC has only been used on a few concrete pavement projects in the United States to date, but the results from these pavement projects have shown very favorable results.

The objective of this report was to evaluate the use of ICC in concrete pavement design and construction. In addition, chapter 7 presented a "Road Map for Internally Cured Concrete Pavements" to provide industry and government with recommendations on how to proceed to achieve the goal of implementation of ICC in concrete pavement design and construction. Evaluations were conducted for construction, performance, and life cycle costs of ICC for concrete pavements.

ICC LITERATURE AND EXPERT REVIEW

Extensive research has been done on IC to date, with over 120 research reports published.

In doing this study, four reference documents stand out as practical overall tools that cover the benefits, design, and use of ICC in detail:

- ACI (308-213)R-13, *Report on Internally Cured Concrete Using Prewetted Absorptive Lightweight Aggregate*
- ACI 213R-13, *Guide for Structural Lightweight-Aggregate Concrete.* This document has passed all committee approvals and will be published later this year
- Bentz, D.P., and Weiss, W.J., *Internal Curing: A 2010 State-of-the-Art Review, NISTIR 7765, U.S. Department of Commerce,* February 2011
- ASTM C1761/C1761M-12, *Standard Specification for Lightweight Aggregate for Internal Curing of Concrete*

Literature review performed under this study (see Chapter 2) suggests that the following are average changes to concrete material properties from internal curing:

- Compressive strength increase of 5 to 10 percent, or up to 20 percent if test data are available
- Flexural strength increase of 5 percent
- Splitting tensile strength increase by 5 percent
- Elastic modulus reduction by 5 percent
- CTE reduction by 5 percent, or up to 10 percent if test data are available
- Unit weight reduced by 7 pcf (for about 5 ft^3 of LWA inclusion)
- Zero-stress temperature reduction by 5 percent
- Reductions in shrinkage crack width in CRCP by as much as 50 percent. A conservative value of 20 percent reduction is acceptable in the absence of field test results
- Reduction in permeability of 10 percent or more are typical

ICC PAVEMENT PERFORMANCE

The only known ICC pavement projects are located in the Dallas-Fort Worth area. These include a major CRCP freeway, a large JPCP intermodal terminal, a high strength early opening off ramp with CRCP, and many residential and collector streets with JPCP. As of 2007, over 550,000 cubic yards of ICC had been placed in pavements in this region.

Five of these projects were surveyed in February 2013 and their performance evaluated. All projects have been in service for 7 to 8 years since construction, except the high early strength off ramp, which was just 1 year old. The projects carry a wide range of traffic, from just 10 trucks a day in the residential pavements, to 240 trailer trucks per day at the intermodal terminal, to over 5,000 trucks per day on the freeway section.

Visual surveys were performed to assess the performance of these pavements. In general, the pavements were found to be in very good condition after 7 to 8 years of service. None of the five ICC projects exhibited any structural distress or showed any significant shrinkage cracks (other than normal CRCP cracks), spalling, or other non-traffic related durability distresses. Of course, these pavements are only 7 to 8 years old, and a much longer time period is needed to fully demonstrate their potential for improved durability. The conventional concrete freeway and the residential subdivision did not exhibit durability problems either during the visual surveys.

APPLICABILITY OF THE AASHTO ME DESIGN PROCEDURE FOR ICC PAVEMENT

Applicability of the AAHSTO ME design procedure to ICC pavement was evaluated. Key items of discussion are the following:

- **Are key ICC inputs within the range of normal concrete inputs?** Laboratory testing has shown that the substitution of a small fraction of LWA into a normal concrete mixture has a relatively small effect on the value of ICC properties. Four key ICC properties which are also AASHTO ME Design inputs are concrete strength, modulus of elasticity, CTE, and unit weight. The substitution of a small fraction of LWA results in relatively small beneficial changes to these key mixture properties. Appropriate ICC/AASHTO ME Design inputs for these factors are well within the range of the national calibration data for each input.

  IC in concrete also indirectly affects two other properties of concrete pavements that are considered in the AASHTO ME Design. These are zero-stress temperature and permanent curl/warp equivalent temperature gradient. Additional research is needed to assess how ICC affects these inputs.

  What about other ICC benefits that are not considered in the AASHTO ME Design procedure? There are at least two benefits of ICC that fall in this category: improved curing and permeability. These two factors are related to durability of the ICC pavement in the field.

- **Are there any limitations in the models and algorithms of AASHTO ME Design that would preclude or limit use of AASHTO ME Design for JPCP and CRCP design using ICC?** A review of the AASHTO ME Design models and algorithms does not indicate there are any potential problems in the design and analysis of either JPCP or CRCP using ICC.

ICC PERFORMANCE PREDICTION WITH THE AASHTO ME DESIGN PROCEDURE

The AASHTO ME Design procedure was used to predict the performance of the SH 121 CRCP project, the UP Intermodal Terminal, and the residential streets in Fort Worth. Performance was predicted for these projects using ICC and conventional concrete. In addition, the same comparative analysis was conducted for LTPP sections located in four different climate zones and regions. All design inputs were the same except concrete strength, CTE, unit weight, and modulus of elasticity. The results from these comparative studies are as follows:

- SH 121, Dallas: Performance of the CRCP freeway was predicted over many years into the future for conventional concrete and ICC. Results showed the conventional concrete CRCP would perform with no punchouts for just over 50 years and the ICC pavement would perform with no punchouts for just over 70 years. This was due to the tighter cracks for the ICC pavement due to expected reduced shrinkage.
- UP Intermodal Terminal, Dallas: Performance of the JPCP terminal entrance JPCP was predicted over many years into the future including both conventional concrete and ICC. Results showed the conventional concrete JPCP would perform (within the 95 percent reliability) over a 40 year period before fatigue cracking exceeded the performance criteria. The ICC JPCP would perform (within the 95 percent reliability) over 60 years before fatigue cracking exceeded the performance criteria.
- Fort Worth Residential Streets: Performance of the JPCP residential streets in Fort Worth was predicted over many years into the future including both conventional concrete and ICC. Results showed the conventional concrete JPCP would perform (within the 95 percent reliability) over a 25 year period before fatigue cracking exceeded the performance criteria. The ICC JPCP would perform (within the 95 percent reliability) over a 40 year period before fatigue cracking exceeded the performance criteria.
- LTPP SPS-2 Sections: JPCP sections were selected from the SPS-2 experiment with all of their measured input data and run over a long time period with conventional concrete inputs and with estimated ICC inputs. The ICC inputs were estimated as follows: flexural strength 5 percent lower than conventional, modulus of elasticity 5 percent lower, coefficient of expansion 5 percent lower, and unit weight 7 pcf lower (all within the range of test data comparing conventional and ICC). Results showed that at each of the sites the ICC JPCP would perform from 8 to 21 years longer than the conventional concrete JPCP until the cracking reached 10 percent slabs.

OPTIMIZED DESIGN THICKNESS

The AASHTO ME design was used to determine the optimum design thickness for ICC and for conventional concrete pavement for the SH 121 site and a close by site on I-45 where a comparative design was performed.

- The SH 121 project optimization for conventional design inputs and ICC design inputs showed a reduction in the design thickness by 1 inch while still providing similar performance and reliability. The increase in material costs incurred in a project with the use of LWA may be offset by the savings in design thickness.
- The UP Intermodal Terminal ICC concrete properties were used for a demonstration design of a JPCP on nearby I-45 with heavy truck traffic. The results showed that the structural slab thickness for ICC could be reduced by 1 inch from the conventional design.

Alternatively, ICC pavement of equal thickness to a conventional concrete pavement can increase the pavement life and reduce the need for M&R. These findings are based on the results from the AASHTO ME Design analysis predictions.

All of the above benefits are related to the structural performance of the pavement. There may be other significant benefits of ICC on the durability side, including the following:

- Greatly reduced plastic and drying shrinkage cracking.
- Reduced permeability that may reduce the freeze-thaw damage to lower portions of slabs in the Midwest.
- Reduced permanent upward curling of slabs that would reduce the potential for top-of-slab transverse and longitudinal cracking.

LIFE CYCLE COST ANALYSIS OF ICC PAVEMENT

LCCA of ICC and conventional concrete alternatives were conducted to determine the cost-effectiveness, if any, of using ICC in paving applications. Two projects, previously analyzed with the AASHTO ME Design procedure, 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. M&R activities and schedules were established based on AASHTO ME Design performance predictions for both the alternatives. The results of the LCCA are as follows:

- The SH 121 CRCP project, which resulted a CRCP thickness reduction of 1 inch for ICC, provided the following cost impacts over the 60-year analysis period:
    - Reduction of 5.0 percent in initial construction cost.
    - Reduction of 21 percent in M&R costs.
    - Reduction of 7.6 percent in the overall life cycle cost.
- If the design thickness of the ICC construction is same as the conventional construction, then the following cost impacts were obtained over the 60-year analysis period:
    - Increase of 4.3 percent in initial construction cost.
    - Reduction of 24 percent in M&R costs.
    - Reduction of 1.3 percent in the overall life cycle cost.
- The I-45 JPCP project, which resulted a JPCP thickness reduction of 1 inch for ICC, provided the following cost impacts over the 60-year analysis period:
    - Reduction of 1.7 percent in initial construction cost.
    - Increase of 6.7 percent in M&R costs.
    - Reduction of 0.9 percent in the overall life cycle cost.
- The JPCP project, when analyzed for Midwest climate for the same traffic levels, also resulted in 1-inch thickness reduction in the initial design. Assuming ICC can reduce the need for slab repairs due to freeze-thaw and joint spalling, the following cost impacts were determined:
    - Reduction of 1.4 percent in initial construction cost.

    - Reduction of 15.8 percent in M&R costs.
    - Reduction of 2.6 percent in the overall life cycle cost.

These pavement design and life cycle cost analyses indicate that the use of ICC in JPCP and CRCP pavements can provide the following:

- A small reduction (1 inch) in initial thickness design of JPCP and CRCP.
- This results in a small reduction in initial construction costs (1.7-5.0 percent) and in overall life cycle costs (0.9-7.6 percent).
- Alternatively, if the conventional concrete thickness design is used for the ICC pavement, a small increase in construction cost will occur (4.3 percent CRCP), but a significant reduction in M&R cost will occur over the long term (24 percent CRCP).

These LCCAs have limitations, as they are based on cost and life assumptions that are specific to a given location. The LCCA results may change if conducted in different locations, as illustrated for the JPCP example in the Midwest, where the overall long-term LCCA savings increased from 0.9 percent (Dallas) to 2.6 percent (Chicago) for ICC pavement through the inclusion of durability deterioration from freeze-thaw.

POTENTIAL BENEFITS OF ICC

ICC used in both JPCP and CRCP provides benefits in terms of structural and durability longevity as well as sustainability:

- **Structural longevity:** The benefits of ICC can be included in the structural design of the JPCP or CRCP when using the AASHTOWare ME design procedure. This involves selection of appropriate inputs for concrete strength, modulus of elasticity, coefficient of thermal expansion, and unit weight. ICC typically provides values for these inputs that are beneficial to the structural longevity of JPCP and CRCP. Standard AASHTO and ASTM tests are available for each of these concrete inputs.
- **Durability longevity:** The durability benefits of ICC vary by climatic region. The reduction of plastic shrinkage cracking and other early age random cracking is a major benefit in all climates, but perhaps especially in hot and dry regions. ICC used in bridge decks has demonstrated a significant reduction in plastic shrinkage and drying shrinkage cracking. Another key durability benefit comes from the reduction in permeability of the concrete. The lower portion of a concrete pavement slab is subjected to free moisture year around in many areas and low permeable base courses. A reduction in the amount of moisture that can infiltrate into the lower portions of the slab may help to reduce any moisture related damage from the many freeze-thaw cycles that often occur in freeze areas.
- **Sustainability:** The increase in JPCP and CRCP longevity represents the single greatest benefit of ICC from a sustainability point of view. Longer lasting pavement means less natural materials resources are needed, less lane closures for M&R over

decades of time, lower user related congestion effects such as less fuel consumed, etc.

ROAD MAP FOR ICC

The "Road Map for Internally Cured Concrete Pavements" provides the industry and government with recommendations on how to proceed to achieve the goal of implementation of ICC in concrete pavement design and construction in North America where construction, performance, and cost factors provide significant benefits.

The road map identifies the few gaps in technology, knowledge base, construction, testing, standards, and education that need to be filled to inform government and industry engineers and managers about ICC. The road map will serve as a guide to helping ICC become an accepted alternative standard across North America for concrete pavement. The road map includes the following tracks that address a specific focus of activity:

1. Educational and technology transfer materials and outreach seminars.
2. Guidelines for the design and construction of ICC pavements.
3. Construction of ICC experimental pavement sections.
4. Research and development to improve ICC mixtures, design, and construction.

This road map is not static and must be constantly updated to keep it applicable to the state of the art and practice for ICC pavements.

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