Internal Curing with Lightweight Aggregate for Transportation Structures & Pavements

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Answering Questions about IC

- What is Internal Curing (IC)?
- Why use Lightweight Aggregate (LWA) for Internal Curing?
- What is Lightweight Aggregate?
- How much LWA is needed for Internal Curing?
- What are the Absorption and Desorption of LWA?
- So why use Internal Curing?
- What is the Cost of Concrete with Internal Curing?
- Where has Concrete with Internal Curing been used?
- How is Internal Curing Specified?

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What is Internal Curing?

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What is Internal Curing

"Internally cured concrete uses prewetted absorptive materials that contain moisture. The absorbed moisture is released … to enhance and maximize the hydration of cement."

Report on Internally Cured Concrete Using Prewetted Absorptive Lightweight Aggregate - ACI (308-213)R-13

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Why use Lightweight Aggregate for Internal Curing?

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Why use Lightweight Aggregate for Internal Curing?

LIGHTER WEIGHT is NOT the reason

INCREASED ABSORPTION is the reason

- Lightweight aggregate (LWA) has a higher absorption than normal weight aggregate (NWA)
- Absorbed water provides curing of the concrete from the inside out

LWA is a competent structural aggregate that can meet specifications for concrete aggregates

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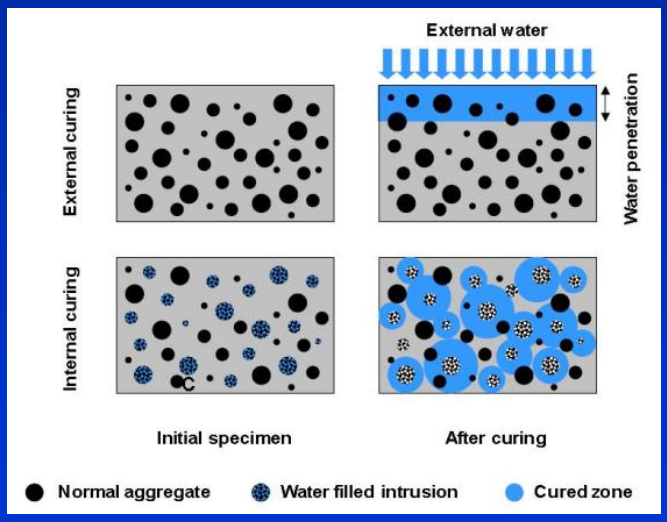
Internal Curing with LWA



From Jason Weiss, Purdue University

Conventional external curing - limited by permeability

Internal curing using LWA - NOT limited by permeability

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Internal Curing with LWA

ESCSI Guide Specifications for IC Concrete

Internal curing with LWA is simply:

… modifying a conventional NW concrete mixture

… by replacing a portion of the NW fine aggregate

… with prewetted fine or intermediate LWA.

- Prewetted LWA is used like an admixture
- Fine LWA is typically used to improve distribution of internal curing water

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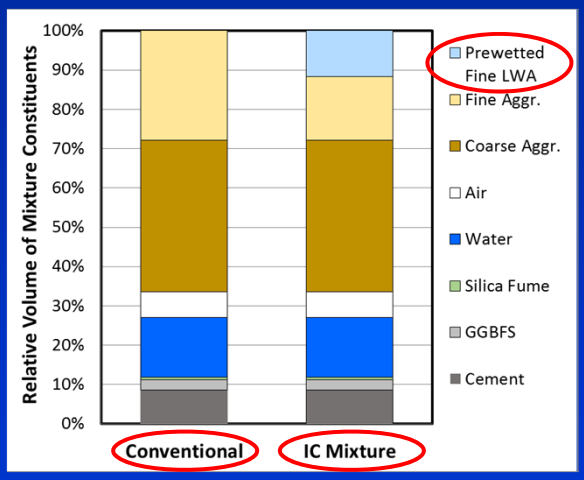
Internal Curing with LWA



Internal curing is

modifying a conventional concrete mixture

by replacing a portion of the fine aggregate with prewetted fine LWA

Figure shows relative volume of constituents in conventional and IC mixtures

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Internal Curing with LWA

Internal curing (IC) using prewetted LWA is

- Not a new concept
  - It has been recognized for years

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Internal Curing with LWA

Internal curing (IC) using prewetted LWA is:

- Not a new concept

For concrete made with lightweight aggregates [2], tests indicate that ponding was of no benefit. Lightweight aggregates absorb considerable water during mixing which apparently can transfer to the paste during hydration.

Klieger, P., **1957**, "Early High-Strength Concrete for Prestressing," *Proceedings of the World Conference on Prestressed Concrete*, San Francisco, CA, pp. A5-1 to A5-14, cited in ACI 213R-14.

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Internal Curing with LWA

Internal curing (IC) using prewetted LWA is:

- Not a new concept

presents no problem in the field when the characteristic is recognized and properly counteracted. The absorption of any part of the mixing water reduces the water-cement ratio and the absorbed water seems to act as a built-in curing system. The aggregates are angular, even to the minus 200 sieve sizes, and cause a harsh working mix

Jones, T. R., Jr., and Stephenson, H. K., **1957**, "Properties of Lightweight Concrete Related to Prestressing," *Proceedings of the World Conference on Prestressed Concrete*, San Francisco, CA, pp. A6-1 to A6-12.

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Internal Curing with LWA

Internal curing (IC) using prewetted LWA is:

- Not a new concept

> 2. The strength index of job cured cylinders under these comparatively favorable conditions at 28 days was about 91 percent for natural aggregate and 98 percent for lightweight. It appears that the absorbed moisture in the lightweight aggregate provides more internal curing.

Campbell, R. H., and Tobin, R. E., **1967**, "Core and Cylinder Strengths of Natural and Lightweight Concrete," *ACI Journal Proceedings*, V. 64, No. 4, Apr., pp. 190-195, cited in ACI 213R-14.

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Internal Curing with LWA

Internal curing (IC) using prewetted LWA is

- Not a new concept
  - It has been recognized for years
- Not a new type of concrete
  - It is modified normal weight concrete (NWC)
- Not lightweight concrete (LWC)
  - Density is slightly reduced, but that is not the goal
- Not a replacement for conventional curing
  - But will improve tolerance for poor curing

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What is Lightweight Aggregate?

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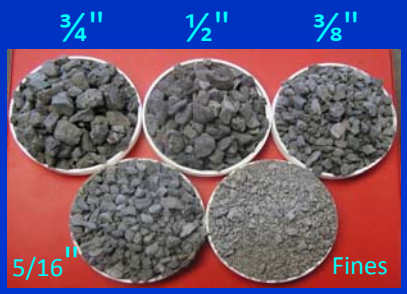
LWA is just a lighter rock

When LWA is used for internal curing in concrete

- Same aggregate requirements (except grading)
- Same batch plants and mixing procedures
- Same admixtures
- Can use same mix design procedures
- w/cm is not affected by water absorbed in LWA

LWA conforms to AASHTO M 195 gradings and other properties



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LWA is just a lighter rock

How much lighter?

Compared to normal weight aggregate, lightweight aggregate has approximately

- Twice the volume for the same mass
- Half the mass for the same volume

1 lb. of each aggregate

But again, for internal curing the density is not important, but rather the absorption

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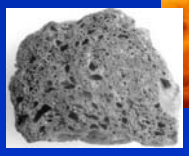
LWA is a manufactured product

Raw material is shale, clay or slate

Heated in rotary kiln to over 2000 deg. F

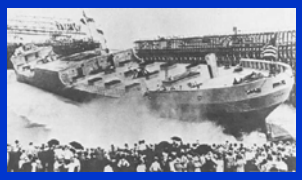
Softened material expands as bubbles form

After cooling, bubbles remain



Rotary kiln process was developed in early 1900s

First use was in 1918 for a LWC ship



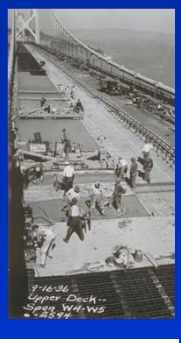
LWA is NOT a new material!

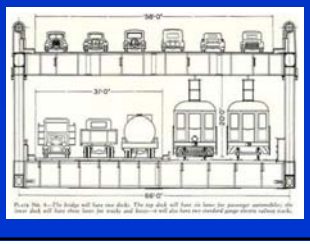
Early Use of LWA

Early use of LWA in concrete for a bridge project

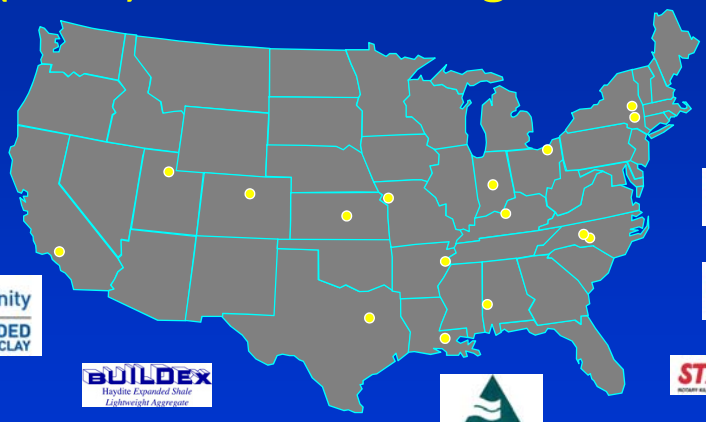
- San Francisco-Oakland Bay Bridge
- Built in 1936 using all LWC (95 pcf) for the upper deck of suspension spans
- Deck is still in service today

LWA is NOT a new material!





Expanded Shale, Clay and Slate (ESCS) Manufacturing Facilities



16 plants in the US

See www.escsi.org for locations of member companies

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Standard Specification for LWA for Internal Curing of Concrete

ASTM C1761/C1761M–13b

- Minimum requirements for LWA to be used to provide water for internal curing of concrete
- Test methods for absorption and desorption
- Procedure for computing required quantity of LWA

X1.3 Required Amount of Lightweight Aggregate

X1.3.1 The amount of lightweight aggregate required for internal curing per unit volume of concrete can be estimated using Eq X1.1.

$$M_{LWA} = \frac{C_f \times CS \times \alpha_{max}}{S\,W_{LWA}} \qquad \text{(X1.1)}$$

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How much LWA is needed for Internal Curing?

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Quantity of LWA for Internal Curing

Main variables (simplified and different notation)

- Total cementitious materials content (C_f)
- Chemical shrinkage (CS)
- Absorption (A) of LWA
- Desorption (D) of LWA

X1.3 Required Amount of Lightweight Aggregate

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$$M_{LWA} = \frac{C_f \times CS \times \alpha_{max}}{S\ W_{LWA}} \quad \text{(X1.1)}$$

Scientific basis for calculation

- Demand is based on C_f & CS
- Supply is based on A & D & quantity of LWA
- Set equal and solve for quantity of LWA

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Quantity of LWA for Internal Curing

Demand: C_f x CS

Supply: W_{LWA} x (A x D) / (1 + A)

Set the demand equal to the supply:

$$C_f \times CS = W_{LWA} \times (A \times D) / (1 + A)$$

Solve for the quantity of prewetted LWA:

$$W_{LWA} = C_f \times CS \times (1 + A) / (A \times D)$$

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Sample IC Calculation

Main variables (simplified and different notation)

- Total cementitious materials content (C_f) 564 lbs
- Chemical shrinkage (CS) 7 lbs / cwt
- Absorption (A) of LWA 15% of oven dry
- Desorption (D) of LWA 95% of absorbed water

ESCSI has a calculator on their website – www.escsi.org

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Sample IC Calculation

Weight of prewetted LWA required

- $W_{LWA} = C_f \times CS \times (1 + A) / (A \times D)$
- $W_{LWA} = C_f \times 7 \text{ lbs/cwt} \times (1 + 0.15) / (0.15 \times 0.95)$
- $W_{LWA} = C_f \times 56.5 \text{ lbs/cwt}$
- $W_{LWA} = 564 \text{ lbs}/100 \times 56.5 \text{ lbs/cwt}$
- $W_{LWA} = 319 \text{ lbs}$

Consider the quantity of prewetted LWA like an admixture dosage

- but it <u>replaces</u> an equal volume of NWA

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Sample IC Calculation

Volume of prewetted LWA

- Assume SG of prewetted LWA = 1.60
- $V_{LWA} = W_{LWA}$ / (62.4 pcf x SG)
- V_{LWA} = 319 lbs / (62.4 pcf x 1.60) = 3.20 ft^3

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Sample IC Calculation

Replace 3.20 ft^3 of NW sand in the conventional concrete mixture …

with the 3.20 ft^3 of prewetted LWA needed for IC

Assume 1800 lbs of NW sand with SG = 2.70

- Volume of NW sand in conventional mixture
- = 1800 lbs / (62.4 pcf x 2.70) = 10.68 ft^3

LWA replacement for IC = 3.20/10.68 = 30%

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Sample IC Calculation

Compare the effect of different LWA absorptions

Absorption	10.0%	15.0%	20.0%	25.0%	
Desorption	95.0%	95.0%	95.0%	95.0%	
Specific Grav.	1.60	1.60	1.60	1.60	
W_{LWA}/cwt	81.1	56.5	44.2	36.8	lbs/cwt
W_{LWA}	457	319	249	208	lbs
V_{LWA}	4.58	3.19	2.50	2.08	ft^3
% Repl	42.9%	29.9%	23.4%	19.5%	

Any ESCS LWA can be used for internal curing

- Adjust replacement for the LWA absorption

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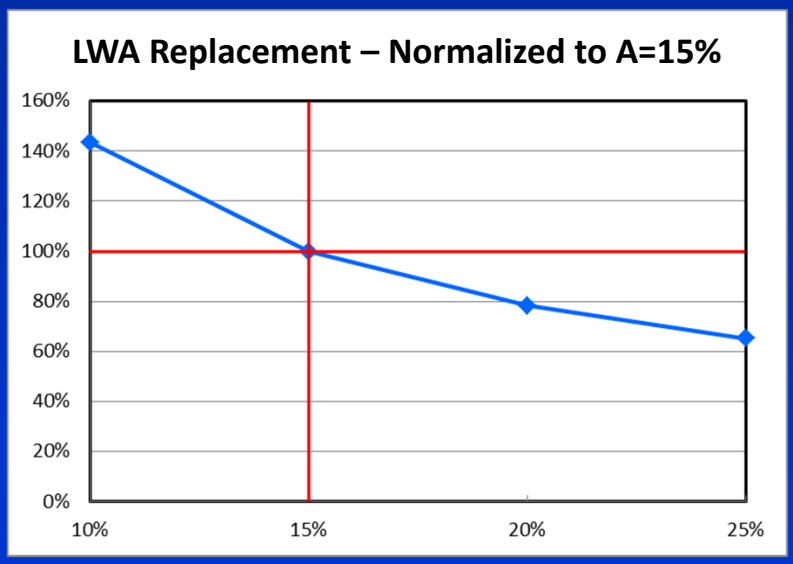
Sample IC Calculation



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What are the Absorption and Desorption of LWA?

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Absorption

Definition in ASTM C1761:

absorption, A_{72}, n – of lightweight aggregate, the increase in mass of a specimen of oven-dry LWA … after being submerged for 72 h, expressed as percentage of oven-dry mass.

This quantity is commonly measured for all types of aggregate

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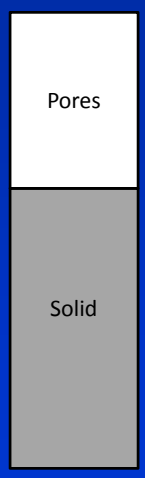
Schematic Image of LWA Particle



Oven Dry, M_{OD}

LWA particle at oven dry condition

Pores (voids) and solid fractions of the particle are concentrated into two volumes in this and following figures for illustration purposes

LWA has more pore volume than NWA

Relative volumes of solid and pores will vary for different types and sizes of LWA

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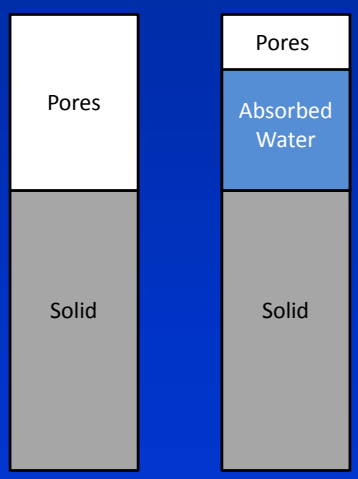
Absorption



Oven Dry, M_{OD}

Wetted Surface-Dry, M_{SD}

LWA particle after soaking for 72 hrs showing absorbed water in some of the pore volume

Only a portion of the pores are filled with water

Absorption as % of M_{OD} (C 1761)

$A_{72} = (M_{SD} - M_{OD}) / M_{OD} \times 100\%$

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Desorption

Definition in ASTM C1761:

desorption, n – the decrease in mass of LWA originally containing absorbed water due to water leaving the permeable pores as the aggregate attains moisture equilibrium ….

Relative quantity of absorbed water that prewetted LWA can release for internal curing

The desorption provides indication of

- How much absorbed water can be released
- Pore size in the LWA

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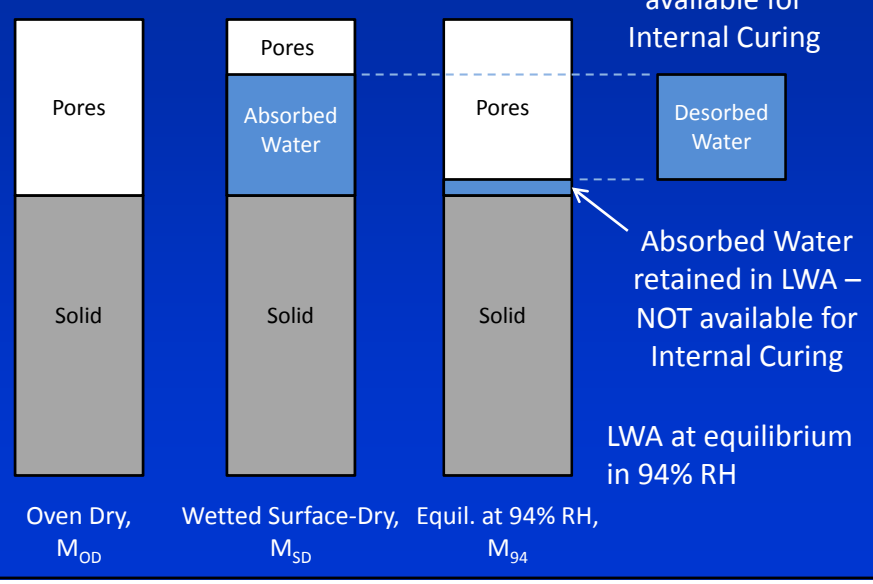
Desorption



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Desorption

Desorption is less than absorption

- For ESCS LWAs, desorption is 85 – 98% of absorption

ASTM C1761 requires desorption to be at least 85% of absorption for aggregates used for IC, i.e., D ≥ 0.85 A

- All ESCS LWAs meet this requirement
- Some other types of aggregate also meet this requirement

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Measured LWA Properties

LWA name	24 h centrifuge absorption, %	24 h centrifuge desorption, %	24 h PSD Relative Density (SG)
Gravelite (Riverlite LA)	16.4	92.4	1.502
Livlite (Riverlite AL)	30.0	97.5	1.430
TXI (Trinity) Frazier Park	17.5	95.2	1.633
Buildex Marquette	18.8	96.2	1.723
Buildex New Market	14.9	98.3	1.724
Haydite AX	12.4	97.5	1.753
Haydite A	13.5	98.7	1.743
Haydite DiGeronimo	17.1	97.3	1.639
Hydrocure	17.3	96.4	1.771
Norlite	17.4	95.7	1.620
TXI (Trinity) Boulder	19.0	89.8	1.737
TXI (Trinity) Streetman	20.1	88.0	1.777
Utelite	19.7	90.6	1.784
Solite LLC	16.4	97.1	1.886
Stalite	9.1	97.5	1.647

From several references – compiled by Jason Weiss, Purdue University

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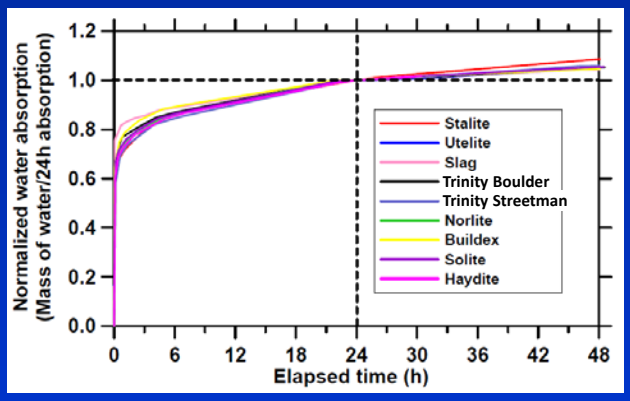
Absorption Characteristics of LWA



Preliminary data from an ESCSI-funded study at Purdue Univ.

- All LWAs tested have similar absorption behavior
- Desorption behavior for LWAs were also similar

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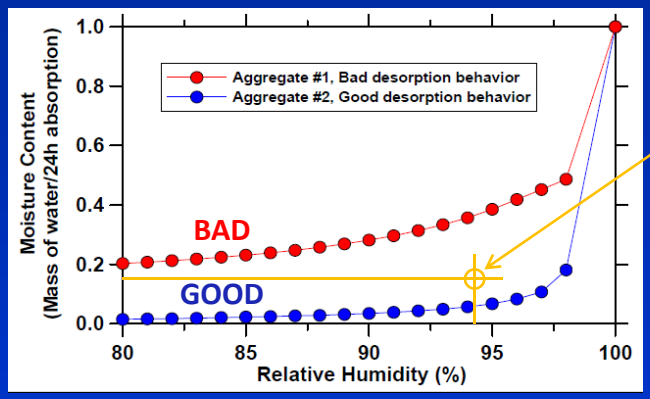
Desorption Characteristics of LWA



Min. desorption requirement in ASTM C1761 – D ≥ 0.85 A @ 94% RH

Preliminary data from an ESCSI-funded study at Purdue Univ.

- All ESCS LWAs tested have GOOD desorption behavior

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Wetted Surface-Dry Condition

From ASTM C1761 Section 10.2.2

LWA is in the wetted surface-dry condition (WSD) after:

- the prescribed soaking period (72 hrs) and
- the removal of surface moisture

Analogous to the saturated surface-dry condition (SSD) for normal weight aggregate

LWA particles do not reach saturation (maximum absorption) even after soaking for 72 hours

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Wetted Surface-Dry Condition

Consistently getting LWA fines to the wetted surface-dry condition can be challenging

Currently available methods

- NYS DOT Test Method No.: NY 703-19 E
  - Brown paper towel method
  - Can be done in field, but some variability
- Centrifuge method – "new" approach
  - ACI 211.2 Appendix B
  - More consistent – more operator independent
  - INDOT & Purdue are working on std method

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Wetted Surface-Dry Condition

Surface moisture on the LWA must be known to make corrections when batching

Absorption of LWA must be known to compute the weight of WSD LWA required to provide the desired quantity of water for IC

- Absorbed water DOES NOT affect mixing water
- Absorbed water is released from the LWA only after hydration has begun

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So why use Internal Curing?

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Benefits of Internal Curing

- Reduced permeability and chloride penetration
  - Significant delay to onset of corrosion
- Reduced shrinkage
  - Reduced cracking tendency
  - Reduced curling and warping of pavements
- More efficient use of cementitious materials
  - Increased strength or reduced cement content

Bottom line

- Increased service life
- Reduced life-cycle cost

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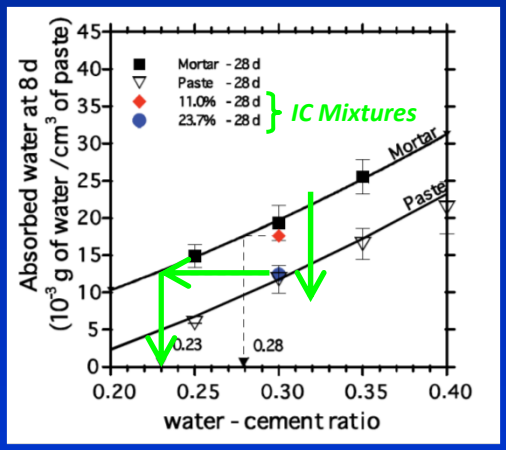
IC Reduces Permeability



Henkensiefken, et al., *Concrete In Focus*, NRMCA, Sept./Oct. 2009

For w/c = 0.30

- IC mortars have lower absorption
- Greater replace-ment provides greater reduction

IC mortar with w/c = 0.30 and 23.7% repl.

- Behaves like mortar with w/c = 0.23

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IC Reduces Shrinkage

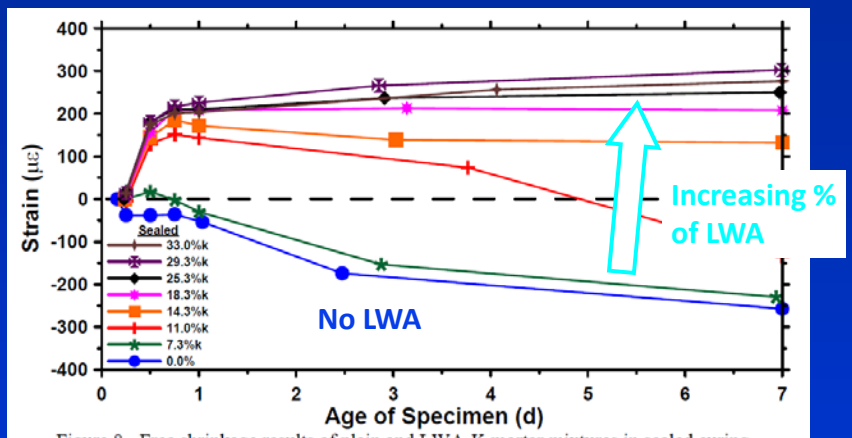

Figure 8 - Free shrinkage results of plain and LWA-K mortar mixtures in sealed curing conditions during the first 7 d

Henkensiefken, et al., *Cement & Concrete Composites*, 2009

Unrestrained shrinkage in sealed mortar mixtures

- IC reduces or eliminates shrinkage

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IC Reduces Shrinkage

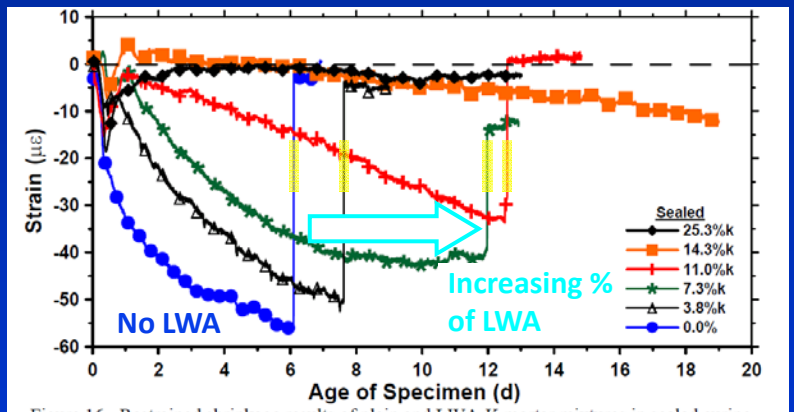

Figure 16 - Restrained shrinkage results of plain and LWA-K mortar mixtures in sealed curing conditions (In each case, a typical response is shown from the three samples tested). Sharp vertical rise in strain curve indicates occurrence of cracking in the specimen.

Henkensiefken, et al., *Cement & Concrete Composites*, 2009

Restrained shrinkage in sealed mortar mixtures

- IC delays or eliminates cracking

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IC Reduces Cracking Tendency

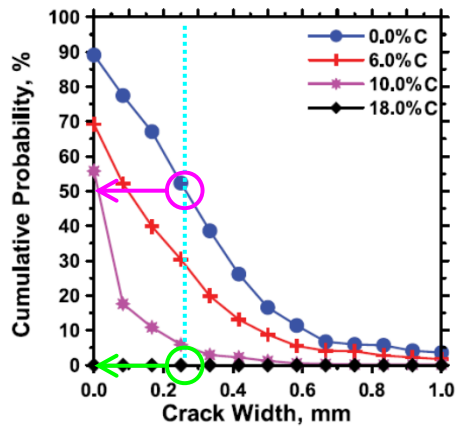

Fig. 4: Cumulative distribution of crack width occurrences in concretes with different replacement volumes of LWA (25.4 mm = 1 in.)

Henkensiefken, et al., *Concrete International*, Feb. 2010

0% replacement of fines with LWA (no IC) – 50% probability of 0.010 in. crack

18% replacement of fines with LWA – concrete did not crack

0.254 mm = 0.010 in.

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IC Decreases Warping

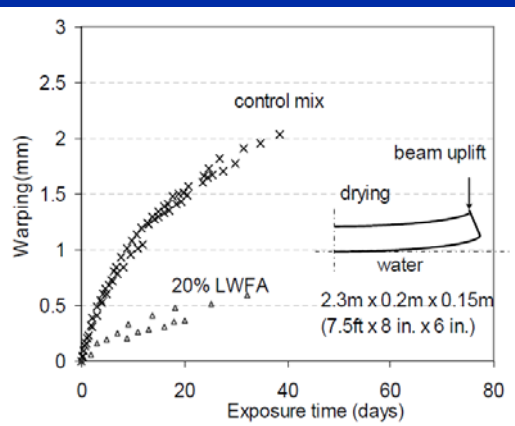
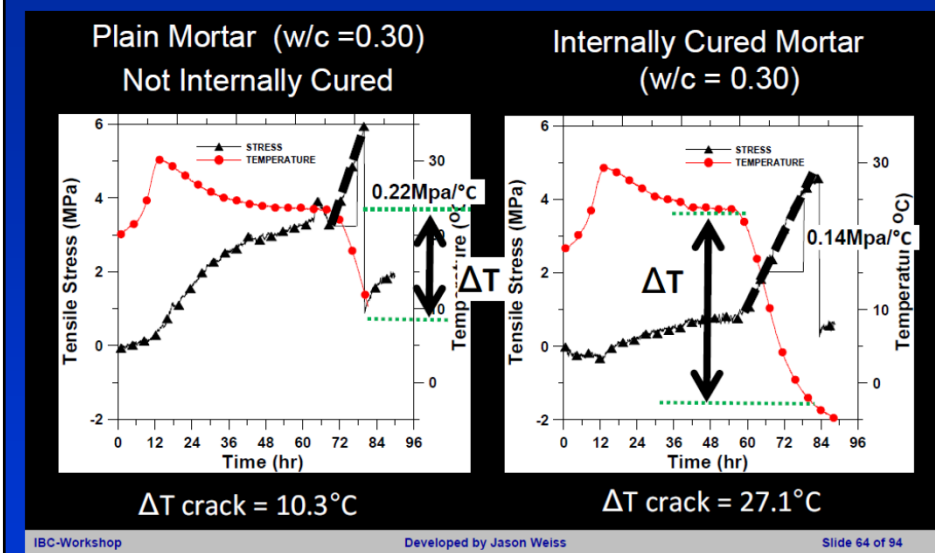


Figure 7.4 Measured development of beam warping (internal curing vs. no internal curing) for *w/cm*=0.45 concrete

Wei, Univ. of Michigan (2008)

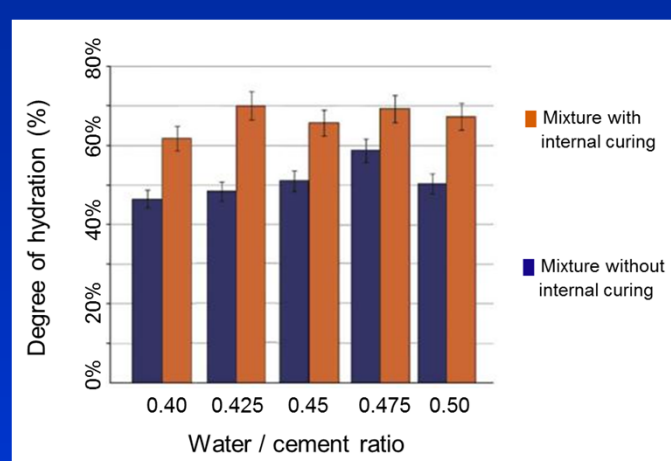
Measured curling was significantly reduced

IC Improves Construction Robustness



IC can tolerate larger temperature drops before cracking

IC Increases Hydration



Espinoza-Hijazin & Lopez, *Construction and Building Materials* (2010)

Degree of hydration is improved with IC

- Even for higher w/cm

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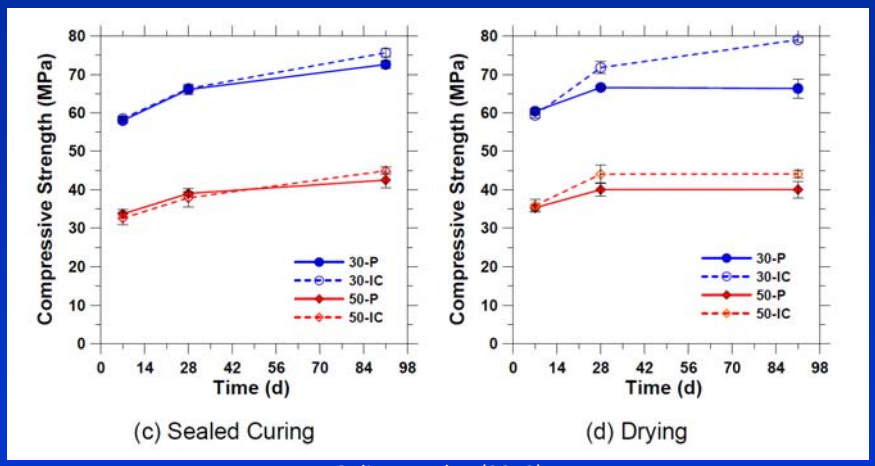
IC Increases Compressive Strength



Golias, Purdue (2010)

Compressive strength is improved with IC when drying

- Greater effect for lower w/cm

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IC Increases Service Life

Preliminary analysis of data from NYS DOT projects by Purdue University indicates that IC can provide a significant increase in service life for bridge decks compared to conventional concrete

- Based only on diffusion properties
- Does not consider additional benefit from reduced cracking potential

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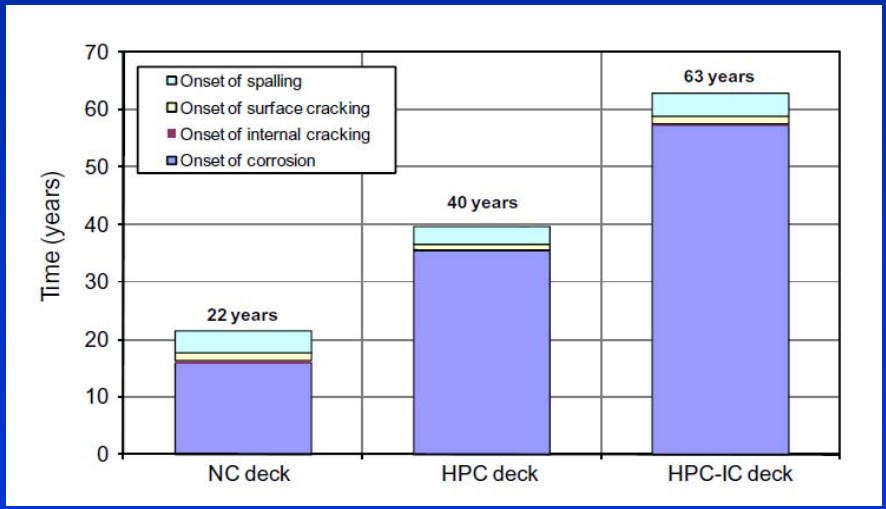
IC Increases Service Life

Service Life Prediction for Bridge Decks – NRC Canada



Cusson, et al. (2010)

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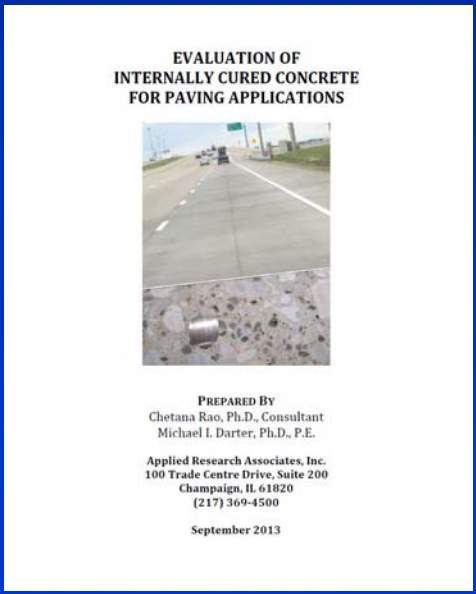
IC for Concrete Pavements



EVALUATION OF
INTERNALLY CURED CONCRETE
FOR PAVING APPLICATIONS

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September 2013

Rao & Darter conducted a preliminary study of IC for pavements for ESCSI in 2013

Found that IC may improve performance of concrete pavements

- Improved curing
- Reduced modulus of elasticity and CTE
- Potential for reduced curling and warping

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IC for Concrete Pavements

The study identified the following benefits

- Improved curing
- Reduced modulus of elasticity and CTE
- Potential for reduced curling and warping

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IC for Concrete Pavements

Recognized reduced modulus of elasticity & CTE

Modulus of Elasticity (ksi)	Control	Internal Curing	Sand LWC	All LWC
Control	4650	--	--	--
Slate	--	4350	3525	2550
Clay	--	4275	2825	2025
Shale	--	4300	3300	2250

7.5% average reduction with IC

Coefficient of Thermal Expansion (με/°F)	Control	Internal Curing	Sand LWC	All LWC
Control	6.2	--	--	--
Slate	--	5.9	5.1	4.3
Clay	--	5.8	5.1	4.0
Shale	--	6.0	5.2	4.0

4.8% average reduction with IC

From Byard & Schindler, ESCSI (2010)

These mixtures did not use full replacement of LWA for IC

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IC Increases Service Life

Rao & Darter report includes prediction of pavement performance using AASHTO ME Design Procedure

SH 121, Dallas, TX – CRCP Freeway

- Conventional – no punchouts for just over 50 yrs
- IC – no punchouts for just over 70 yrs

UP Intermodal Terminal, Dallas, TX – JPCP entrance road

- Conventional – 40 yrs before fatigue cracking
- IC – 60 yrs before fatigue cracking

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IC Increases Service Life

Rao & Darter report (ESCSI 2013) includes prediction of pavement performance using AASHTO ME Design Procedure

LTPP SPS-2 Sections – JPCP

- ICC would be expected to perform 8 to 21 years longer than conventional concrete

Residential streets, Fort Worth, TX

- Conv. – 25 yrs before fatigue cracking
- ICC – 40 yrs before fatigue cracking

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What is the Cost of Concrete with Internal Curing?

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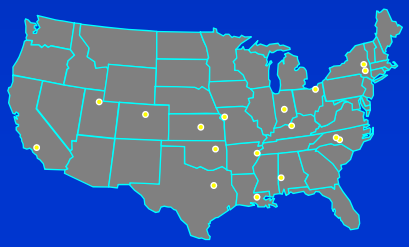
Cost of IC

Increased cost of LWA

- Additional processing

- Shipping from the manufacturing plant



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Cost of IC

Material cost premium over conventional concrete is usually about $10/cy

- For a 9” thick deck or pavement, this equates to $0.28/sf or $2.50/sy
- Delivered cost of concrete with IC will be higher to cover supplier’s other costs of prewetting, testing, etc.

Compared to total project cost, this is a small increment to obtain the increased service life and other performance benefits of IC concrete

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Where has Concrete with Internal Curing been used?

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Transp. Agencies that have used IC

- Illinois (Tollway)
  - Bridge decks
- Indiana
  - Bridge decks
  - HESC pavement repair
- Iowa
  - Bridge decks
- Kansas
  - Bridge decks
  - Pavement
- New York
  - Bridge decks
- Texas
  - Pavements
  - Bridge deck
- Utah
  - Bridge decks
- Virginia
  - Bridge decks & overlays
- Ontario, Canada
  - Bridge decks

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NYS DOT IC Projects

27 Projects as of 2012

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Field Experience with Internal Curing

Demonstration project in Indiana built in 2010

- Two county bridges located ¼ mile apart were replaced in same contract by same contractor
- Adjacent PS box bridges with composite deck
  - 8” thick at centerline; 4 ½” thick at edges; 27’-8” wide
  - Conventional mix was used for 59 ft long bridge (21” x 48” boxes)
  - IC mix was used for 39 ft long bridge (17“ x 48” boxes)

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IC Project in Indiana

Two county bridges built in Indiana in 2010

- Conventional deck & IC deck
- Same contractor & concrete supplier
- No difference in finishing was reported
- Slab without IC cracked after a few months
- Slab with IC still has no visible cracks

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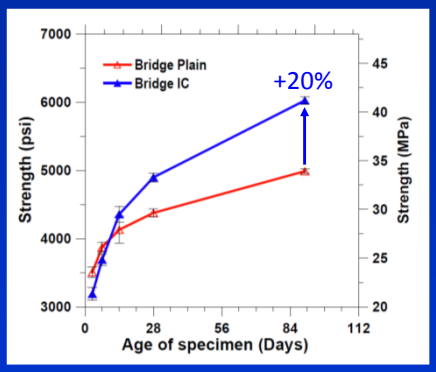
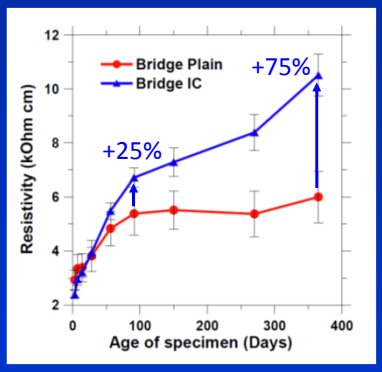
IC Project in Indiana

IC improved strength and reduced permeability





Di Bella, et al., "Documenting the Construction of a Plain Concrete Bridge Deck and an Internally Cured Bridge Deck," Report TR-1-2012, IN LTAP Center, June 2012

INDOT has now constructed several projects

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IC for Water Storage Tank in CO

Denver Water Company – Lonetree Basin Tank #2

- 10 M gallon Concrete Water Storage Tank
- 1300 CY slab placed in one pour

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IC for Water Storage Tank in CO

Test pour for water tank - Highlands Ranch, CO

- Internal Curing vs. No Internal Curing
- Concrete placed at 92°F air temp. & 20% RH
- No conventional curing

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IC for Water Storage Tank in CO

Denver Water Company – Lonetree Basin Tank #2

- After success with slab, contractor requested to use IC mix for ring girder, columns and walls
- Using IC reduced shrinkage cracks 80% compared to similar size tanks built previously
- Several more large tanks have been planned using IC

IC Projects for IL Tollway

Jane Addams Memorial Tollway (I-90)

- **I-90 West Corridor Overview**
  - Reconstruction and widening of a 54-year-old, 37-mile stretch of I-90 between Elgin and Rockford
  - Existing four lanes / PCC base / HMA overlay
  - Proposed six-lane composite JPC (11.25”- 13”)
  - 19 crossroad bridges

IC Projects for IL Tollway

Bridge decks for Illinois Tollway

- 100 year life span
- Stainless steel deck reinforcement
- Jointless bridges
- Load limit increased from 80 kips to 120 kips
- Performance based concrete specifications
  - High quality concrete with reduced shrinkage potential
  - IC was included as an option

IC Projects for IL Tollway

First IC deck - Hwy 20 bridge, Hampshire, IL

Deck placed 8/1/2013

No visible cracks on 8/28/2013

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Pavement Projects with IC

Large railway transit yard in TX

- Increased compressive strength by 15%
- Eliminated plastic & drying shrinkage cracking

Continuously reinf. concrete pavement for TxDOT

- Crack survey revealed "an overwhelming reduction in the number of cracks"
  - 21 vs. 52 in a comparable section of normal concrete
- Significant reduction in width of cracks

From Weiss, et al., *STRUCTURE Magazine*, Jan. 2012

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How is Internal Curing Specified?

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Special Provisions & Guide Specs

A simple approach has been used by several DOTs including NYS DOT, INDOT & WVDOH

- NYS DOT: 15% min. absorption & 30% replacement of NW sand with prewetted fine LWA
- Does not make provision for LWA with different absorptions
- Does not account for varying cement content

ESCSI has a guide specification

- Uses a general approach

LWA suppliers can provide additional guidance

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Thank you

For more information on
Internal Curing using ESCS LWA

www.escsi.org

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