Internal Curing
Using Prewetted Lightweight Aggregates

Improving Concrete Durability and Sustainability Using Internal Curing

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Curing is one of seven essential procedures “that make concrete capable of providing decades of service with little or no maintenance.”

[ACI 201 2R-08, Guide to Durable Concrete]
INTERNAL CURING USING PREWETTED LIGHTWEIGHT AGGREGATE

ACI Definition (original): Internal Curing: “supplying water throughout a freshly placed cementitious mixture using reservoirs, via pre-wetted lightweight aggregates, that readily release water as needed for hydration or to replace moisture lost through evaporation or self-desiccation” [2010]

ACI CT-13 Definition: Internal Curing: “process by which the hydration of cement continues because of the availability of internal water that is not part of the mixing water”
What is LWA?

- Expanded shale, clay and slate (ESCS)
- Structural, ceramic aggregate produced in a rotary kiln
- Less than half the unit weight of ordinary aggregate
- Complies with ASTM C-330 and C-331
Expanded at 2000° F
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- Use fine aggregate to distribute water
- Help satisfy increased water demand from SCM’s
- Works even at moderate 0.40 – 0.48 w/cm
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It’s All About the Distribution

Henkensiefken (2008)
<table>
<thead>
<tr>
<th>Hydration Age</th>
<th>Estimated Travel Distance for Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1 day</td>
<td>20 mm</td>
</tr>
<tr>
<td>1 day to 3 days</td>
<td>5 mm</td>
</tr>
<tr>
<td>3 days to 7 days</td>
<td>1 mm</td>
</tr>
<tr>
<td>&gt; 28 days</td>
<td>0.25 mm</td>
</tr>
</tbody>
</table>

Clogging the Capillaries With Products of Hydration Restricts the Flow of Water

Bentz, D., Koenders, S., Monnig, S., Reinhardt, H., van Breugel, K., Ye, G.
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• **Benefits**
  - Less shrinkage, less cracking
  - Improved fluid transport properties
    - lower water absorption
    - lower chloride permeability & penetration
  - More hydration & SCM reaction
    - less cement or more strength

• **Results**
  - More durable structures achieving extended service life
    - Improved economics
    - Increased sustainability
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Extensive Lab Research

147 Citations as of September 2013
Stress Development Mechanisms

Why Does Concrete Crack?

Restraint + Volume Change = Stress

Cracking Occurs When Tensile Stress Exceeds Tensile Capacity
Stress Development Mechanisms

- Early-Age Volume Change Occurs Because of
  - Thermal effects
    - Temperature changes due to hydration
    - Coefficient of thermal expansion
  - Decrease of internal relative humidity
    - Drying due to atmospheric conditions
    - Self-desiccation (autogenous shrinkage)
Cement fineness has consistently increased from 1954 until the present. Finer cements have:

• Increased early age heat release
• Increased semi-adiabatic temperature (thermal cracking)
• Increased autogenous shrinkage
• Greater propensity for early age cracking
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Self-Desiccation

$t=0$, water meets cement

Auburn University
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Self-Desiccation

\[ t = \text{initial set, hydration products form skeleton} \]

Decrease in volume due to chemical shrinkage

Cement

Hydration Products

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Self-Desiccation

t=after set, hydration continues and cement consumes capillary pore water and induce capillary stresses

Additional decrease in absolute volume due to capillary stresses

Desiccating capillary pores
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Self-Desiccation

Water moves from LWA in to capillary pores, minimizes desiccation and promotes additional hydration.

- Shrinkage reduced by limiting capillary stresses
- Pre-Wetted Lightweight Aggregate
- Water-Filled Void
- Emptying Voids

Water can move \( \approx 0.12 \text{ in.} \)
Example of Chemical Shrinkage (CS)

Hydration of tricalcium silicate (major component of portland cement)

\[ C_3S + 5.3 \, H \rightarrow C_{1.7}SH_4 + 1.3 \, CH \]

Molar volumes

\[ 71.1 + 95.8 \rightarrow 107.8 + 43 \]

CS = \((150.8 - 166.9) / 166.9 = -0.096 \, \text{mL/mL} \) or

\(-0.0704 \, \text{mL/g cement} \)

For each g of tricalcium silicate that reacts completely, we need to supply 0.07 g of extra curing water to maintain saturation. Can think of this as 7 lbs of water per 100 lbs of cement in the concrete mixture.

Chemical shrinkage of blended cements (fly ash, slag, or silica fume) is generally significantly higher than that of ordinary portland cement by itself.
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The “Bentz Equation”

\[ M_{LWA} = \frac{C_f \times CS \times \alpha_{max}}{S \times \phi_{LWA}} \]

\(~ 7 \text{ lb of internal curing water needed per 100 lb cement)~\)
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For Internal Curing Replace a Portion of Natural Sand With Lightweight Aggregate Sand (LWAS)

Mixture Proportions of the Fine Aggregate In a Yard of Concrete

- 10-25% LWAS
- 75-90% Natural Sand
Why can LWA be used for IC?

- Largest pores will empty first
- The saturated LWA provides water to the paste and keeps a large pore full
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Why can LWA be used for IC?

Absorption of LWA

Absorption of LWA
Why can LWA be used for IC?

Desorption of LWA

85 to 98% moisture released

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Desorption of LWA
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More Hydration

Degree of hydration (%)

Water / cement ratio

Degree of hydration of cement @ 90 days, cured @ 50% RH

Espinoza-Hajazin (2010)
Higher Compressive Strength
- Portland Cement Mortar @ 0.30 & 0.50 w/c

Sealed Curing

Golias (2011)
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Less Shrinkage; Less Cracking

Plain 0.30 Concrete
0.6 mm wide crack
observed @ 12 days

IC 0.30 Concrete
0.4 mm wide crack
observed @ 43 days

Schlitter (2010)
Delayed Cracking

- Summer curing temp. profile for expanded shale IC mix

Byard (2010)
Internal Curing Using Prewetted Lightweight Aggregate

Reduced Warping – 80% Reduction

Wet base, 7 day cure then 73°F @ 50% RH on slab surface

Wei (2008)
Lower Absorption

28 day curing

Henkensiefken (2009)
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Lower Chloride Permeability

Chloride ion permeability @ 90 days, cured @ 50% RH

Espinoza-Hajazin (2010)
Internal Curing vs. No Internal Curing
Denver Water Test Slabs – 92°F ambient, 20% RH

No conventional curing
DENVER WATER – 10 million gallon tank
– 1300 yard slab pour

Change Order to include walls and columns
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Denver Water – 10 million gallon tank – 1300 yard slab pour
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Denver Water – 10 million gallon tank – Contractor requested change order to use IC mix for ring girder, columns and walls
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Denver Water – 10 million gallon tank
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Denver Water – 10 million gallon tank
– 8” thick PT roof slab placed monolithically
Denver Water - Conclusions

• Using IC resulted in an 80% reduction in shrinkage cracks compared to similar size tanks built previously (squirts, spurts, and drips)

• Based on the Lonetree Basin project success, IC will be used for:
  • 2 more 10 MG tanks will be built this year
  • Three 15 MG tanks are planned for 2014
Paving in Texas

UP RR Intermodal Facility
Constructed 2005

250,000 yd³ IC project low slump pavement

Visual inspections
At 6 months one crack
At 5.5 yrs minuscule plastic or drying shrinkage cracks

Bridges in New York & Indiana

NY: 16 built or under construction as of 2012

IN: 33 bridges
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Indiana Bridges NE of Bloomington

• Replacement of two bridges ¼ mile apart
  • Prestressed concrete box beams
  • Composite RC deck
  • 8” thick at centerline, 4½” thick at edge
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Indiana Bridges NE of Bloomington
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Indiana Bridges NE of Bloomington

Standard External Curing (wet burlap) – Both Bridges
Internal Curing Using Prewetted Lightweight Aggregate

Indiana Bridges NE of Bloomington

Plain Concrete Deck at One Year
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Indiana Bridges NE of Bloomington

Plain Concrete Deck at One Year

Longitudinal and Transverse crack
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Indiana Bridges NE of Bloomington

IC Concrete Deck at One Year

No Cracks
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Texas State Highway 121
1300 CY, 5 miles of CRCP, Class P
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SR-121
Crack Spacing of IC Section at 10 months

500 ft section CRCP no joints
Crack Survey at 10m
Number of cracks:
IC 21 vs. 52 control
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SR-121
Crack Width (% of total at 10 months)
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UDOT Mountainview Corridor
INTERNAL CURING USING PREWETTED LIGHTWEIGHT AGGREGATE

UDOT Mountainview Corridor

Distress Maps at 1 Year, 8200 South

8200 South NB, Conventional

8200 South SB, Internally Cured
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Test Slab Big River Erwinville, LA

20’ X 40’ Slab Placed July 5, 2012
Photo Taken at 4.5 hours
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Test Slab Big River Erwinville, LA

20’ X 40’ Slab Placed July 5, 2012
Plain Section First crack July 27, 2012
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Test Slab Big River Erwinville, LA
20' X 40' Slab Placed July 5, 2012

Plain Section First crack July 27, 2012
Conclusions

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- The use of saturated LWA for internal curing delays the occurrence of early-age cracking in bridge deck and pavement applications.
  - This is because the use of LWA for IC:
    - Decreases or eliminates stresses due to autogenous shrinkage effects.
    - Decreases the modulus of elasticity.
    - Decreases the coefficient of thermal expansion.
  - This improved cracking performance may be in the form of: reduced number of cracks and/or decreased crack widths.
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Test Slab Big River Erwinville, LA

20’ X 40’ Slab Placed July 5, 2012
IC Section Crack-free June 27, 2013
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Test Slab Big River Erwinville, LA
20’ X 40’ Slab Placed July 5, 2012
IC Section First Crack July 16, 2013
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Illinois Tollway
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- 15 yr, $12B Capital Program
- Sustainability Focused
- Creates 120,000 Jobs
- Traffic – 66,000/day in 1958, 1.4M Today
- Expand Capacity & Save Time
- Concrete Types
- FRAP (Fractionated Reclaimed Asphalt Pavement)
- HPC using Internal Curing on bridge decks
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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
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Illinois Tollway Bridges Decks

- 100 Year Life Span
- Stainless Steel Re-bar
- Jointless
- Load Limit Increased
  - 80,000 lbs to 120,000 lbs
- Performance Based Concrete Spec
  - Includes IC as an option
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Illinois Tollway Bridges Decks - Specs

Time to Cracking

Net time to cracking shall not be less than 28 days when determined in accordance with ASTM C1581. Prior to batching for a test sample, all coarse aggregate particles exceeding ¾-inch shall be removed and replaced with an equal volume of minus ¾-inch graded material. This test shall be waived if the concrete mixture contains 605 lb/yd³ or less total cementitious material and a minimum dosage of 1.5 gal/yd³ of approved shrinkage reducing admixture (SRA).

Length Change

Measured shrinkage shall not be greater than 0.030 percent after 21 days of air drying when determined in accordance with AASHTO T 160. Specimens shall be wet cured for 7 days prior to air-drying. The initial reading for calculation of shrinkage shall be taken at the initiation of drying.
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Illinois Tollway Bridges – First Deck Placed
August 1, 2013

Hwy 20 bridge on the Jane Addams (I-90) Tollway
Hampshire, IL
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Illinois Tollway Bridges – First Deck
Photographed August 28, 2013

No visible cracks
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Illinois Tollway Bridges Decks

- Hwy 20 Bridge Deck Mix Design
  - Cement – 380
  - Fly Ash – 165
  - LWAF – 143 → 5 lb IC H2O, not 7 lb
  - SRA
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MoDOT – Highway Rapid Repair

- First Use of IC - Bridge Deck New Construction
- Next Use – Rapid Repair Patches on Interstate Highways
  - Very high w/cm
  - High early strength
  - Prone to early cracking, short service life. Repeat repairs
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Cost of Internal Curing

Say premium for IC is $10/CY (assumption)

Assume 9” deck

Compute premium per SF of bridge deck:

$10/CY (0.75 CF/SF) (1CY/27CF) = $0.28/SF

Compare to Fed Aid unit costs for entire bridge:

Avg = $156/SF ⇒ 0.28/156 = 0.18%
Max = $558/SF ⇒ 0.28/558 = 0.05%
Min = $57/SF ⇒ 0.28/57 = 0.49%

The cost of IC, compared to total bridge cost, is very minor – less than ½ of 1%, at worst!
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New Standards

Report on Internally Cured Concrete Using Prewetted Absorptive Lightweight Aggregate

Reported by ACI Committee 308 and ACI Committee 213

American Concrete Institute®
Internal Curing: A 2010 State-of-the-Art Review

Dale P. Bentz
W. Jason Weiss
EVALUATION OF INTERNALLY CURED CONCRETE FOR PAVING APPLICATIONS

PREPARED BY
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September 2013
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:
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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.
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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 7pcf 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.
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New Standards

Designation: C1761/C1761M – 12

Standard Specification for Lightweight Aggregate for Internal Curing of Concrete

1. Scope

1.1 This specification covers lightweight aggregate intended to provide water for internal curing of concrete. It includes test methods for determining the absorption and desorption properties of lightweight aggregate.

Norm 1—Internal curing provides an additional source of water to sustain hydration and substantially reduce the early-age autogenous shrinkage and self-desiccation that can be significant contributors to early-age cracking. Appendix X1 provides guidance on calculating the quantity of lightweight aggregate for internal curing.

1.2 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance. Some values have only SI units because the inch-pound equivalents are not used in practice.
7.4 Water Absorption—The lightweight aggregate shall have a 72-h absorption not less than 5% when tested in accordance with Section 10.

7.5 Desorption Properties—The lightweight aggregate shall release at least 85% of its absorbed water at 94% relative humidity when tested in accordance with Section 11; that is, the following condition shall be satisfied:

\[ W_{100} \geq 0.85 \frac{A_{72}}{100} \]
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New Standards – ASTM C1761

- Section 10 – Absorption and Relative Density
- Section 11 – Desorption at 94% Relative Humidity
Specifying Internal Curing

- Water **IN, ON & OUT** of lightweight aggregate
  - **Absorbed** moisture **IN** LWA not part of w/c calculation
  - Surface moisture **ON** LWA needs to be determined and included in w/c calculation just like it is with conventional aggregates
  - Degree of **Desorption** of water **OUT** of LWA provides IC
    - Minimum 85% required by ASTM C1761 Specification for Lightweight Aggregate for Internal Curing of Concrete
    - Conservative value is 90% of absorbed moisture; most data exceeds 90%; contact LWA producer for details.
    - Specify use of tested value of particular LWA in mix proportioning
Specifying Internal Curing

- NW concrete with IC is still normal weight concrete
- Air content can still be determined using pressure meter
- Density is reduced by 3-5 lb / cu ft
  - Design using ACI 318 for NWC
  - No strength modifiers required
Other Topics
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Internal Curing Research – Zero Slump Concrete

No Internal Curing
- Poorer Cement Hydration
- Less Uniform
- More & Larger Unhydrated Cement Particles

With Internal Curing
- Better Cement Hydration
- More Uniform
- Fewer & Smaller Unhydrated Cement Particles
Internal Curing Research – Pervious Concrete

- Internal Curing (IC) Research for pervious concrete is underway at UMKC
Five mixes tested

- Mix 1: Control – All NWA
- Mix 2: NWCA, LWFA (Expanded Slate)
- Mix 2: NWCA, LWFA (Expanded Shale)
- Mix 2: NWCA, LWFA (Expanded Clay)
- Mix 5: All LWA (Expanded Shale)

Strength: Mix 1 Strongest, 2 next, then, 3, 4 and 5 was the lowest.
Internal Curing Research – Pervious Concrete

- **Strength Gain**
  - **Mix 1**: Control – No strength gain after 7 days
  - **Mixes 2 thru 5**: All continued to gain strength thru 56 days

- **Freeze-thaw**
  - **Mix 1**: Poor
  - **Mix 2**: better (at least 2X the performance of Mix 1)
  - **Mix 3**: better than Mix 2
  - **Mix 4**: Better than Mix 3
  - **Mix 5**: Test is still going with no signs of damage.
Research on mitigating ASR using LWAF is underway at Oregon State.

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ASR Research – ASR Mitigation Using LWAF

Limestone B (Non-reactive CA)-Siliceous Sand (Highly-reactive FA)
Length Change based on ASTM C 1293

![Graph showing length change over age](image-url)
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ASR Research – ASR Mitigation Using LWAF

Limestone B (Non-reactive CA)-Siliceous Sand (Highly-reactive FA)
Length Change based on ASTM C 1293
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ASR Research – ASR Mitigation Using LWAF

Spratt CA (reactive) – Martin Marietta (non-reactive)
Length Change based on ASTM C 1293

- B01-Control
- B02-25% Shale
- B03-25% Clay
- B04-25% Slate
- B05-50% Shale
- B06-50% Clay
- B07-50% Slate

Expansion limit
Preliminary findings

- Expansion decreased with higher absorption FLWA.
- Expansion decreased with the increase of replacement level.
- More alkali was consumed when reactive fine aggregates were partially replaced by FLWAs.
- Preliminary pore solution analysis showed pH reduction when reactive fine aggregates were partially replaced by FLWAs.
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Summary:

- Less shrinkage, less cracking
- More hydration & SCM reaction
- Improved transport properties
  - Lower water absorption
  - Lower chloride permeability & penetration
  - Increased durability
- Significant increase in service life
- Significant life cycle cost reduction
- Increased sustainability
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In the words of Jason Weiss

IC is “ready to go, NOW!”
“The research has been done; it’s time to stop talking about it and start making use of it.”

— Jason Weiss at TRB, January, 2013
Questions?

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