Internal Curing

Using Prewetted Lightweight Aggregates

Improving Concrete Durability and Sustainability Using Internal Curing

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Keith McCabe
Haydite
DiGeronimo Aggregates
Sustainability Is...

• Longevity... longer lasting is usually better.
• Balance...social, economical and environmental issues
• Planning... building a project right or is it more important to build the right project
Sustainability of Infrastructure

• Effect on our economy
• As population increases infrastructure needs increase
• Average age of bridges is 43 years*
• More than 26%, or one in four, of the nation’s bridges are either structurally deficient or functionally obsolete*
• How do we improve performance
• How do we improve sustainability

*ASCE Infrastructure Report Card 2009
Bridges
What is Sustainability?

The capacity to endure

— Wikipedia
Improve Sustainability of Concrete

- Increase service life
- Improve durability
- Reduce cracking
- Reduce chloride ingress
- Increase use of SCMs
HPC Survey

• 2003 FHWA Nationwide HPC survey – Most Common Pavement Distresses
  – Early-age deck cracking (57% responses were a 4 or 5=often)
  – Corrosion (42% - definitely linked to cracking)
  – Cracking of girders, etc. (31%)
  – Others (sulfate attack, ASR, F/T, overload, poor construction quality were all below 25% level)
Internal Curing

• Internal curing refers to the process where increased hydration of cement occurs because of the availability of additional internal water that is not part of the mixing water.

• Typically concrete has been cured from the outside in; IC is curing from the inside out. Internal water is supplied via internal reservoirs found in ESCS prewetted lightweight fine aggregates.

• IC is based on simple, sound fundamental principles
Why we need Internal Curing

• In HPC it is not easy to provide curing water from the top surface at the rate that is required to satisfy the ongoing chemical shrinkage, due to the low permeability of the concrete

• Recent research shows that IC provides benefits in even moderate w/c mixtures
Historical LWC Structures
Pantheon in Rome – 126 AD
Pantheon

Lightweight concrete dome.

Romans hauled LWA 35 mi with horses...
1929 - First high rise building using “Haydite” lightweight aggregate

Southwestern Bell Building
13th & Oak, Kansas City MO
Lightweight Concrete Ship
USS Selma, 1919
Sister Ship at Powell River, BC Canada
90 Years in Sea Water

Design 5000 psi, 106 pcf, Current strength 8700 psi
Hibernia

Offshore Platform
St. John’s Newfoundland
1990+
IC a side benefit
Internally Cured
126-155 pcf
10,000 -13,000 psi
Internal Curing Offers Benefits of

- improved hydration,
- reduced chloride ingress
- reduced early age cracking

– All of which helps extend the service life of concrete
Internal Curing Benefits

More durable and less permeable concrete –

• Improved Hydration and SCM Reaction Significantly Reduces Concrete Porosity

• Denser and more homogeneous interfacial transition zone (ITZ) between lightweight aggregates and hydrating cement paste

• Reduced Early Age and Long Term Shrinkage Cracking


Internal Curing Using
Prewetted Lightweight Aggregate

• From extensive lab research to full scale projects
• Use fine aggregate to distribute water
• Helps satisfy increased water demand from SCM
• Works even at moderate 0.40 – 0.48 w/cm
Internal Curing Using
Prewetted Lightweight Aggregate

• Benefits
  – Less shrinkage, less cracking
  – Improved transport
    • Lower water absorption
    • Lower chloride permeability & penetration
  – More hydration & SCM reaction
    • Less cement or more strength

• Result
  – More durable structures achieving extended service life
    • Improved Economics
    • Increased Sustainability
Basics of IC - Aggregate
First the LWA is Prewetted

- Done by sprinkling, soaking, vacuum saturation or thermal quenching
Aggregate Requirements for IC

• Aggregate needs to be able to hold sufficient amount of absorbed water
• Aggregate should not adversely effect the quality of concrete
• Aggregate needs to hold the water until needed and not effect w/c ratio
• Aggregate should give up water at high RH (desorption)
Prewetting Aggregate With Sprinklers
LWA Absorption Graphs

![Graph showing normalized water absorption over elapsed time for various aggregates.](image)

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<thead>
<tr>
<th>Aggregate</th>
<th>SG (OD)</th>
<th>Absorption</th>
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<td>Stalite</td>
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<td>Haydite AX</td>
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<tr>
<td>Solite #10</td>
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<tr>
<td>DiGeronimo - Haydite</td>
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<td>15.7%</td>
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<td>Fraiser Park</td>
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<td>19.3%</td>
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<td>Livelite</td>
<td>1.04</td>
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Castro (2011)
LWA Desorption Graph

Typical Desorption for LWA

Virtually all moisture available at 94% RH w/ ESCS lightweight aggregate

Castro (2011)
Visualization of Water Transport

Blue-ink corona in cement matrix around prewetted LWA

$w/c = 0.37$

Higher $w/c$ enlarges the corona to 2-4+ mm

Lura (2003)
IC Water Distribution Using Prewetted LWA

It’s All About Water Distribution
• White = ‘thirsty’ paste
• Blue = ‘happy’ hydrated paste

Henkensiefken (2008)
IC Water Distribution Using Prewetted LWA

3 x 3 mm (1/8")
IC Water Distribution Using Prewetted LWA

10 mm by 10 mm

Yellow – Saturated LWA
Red – Normal weight sand
Blues – Pastes within various distances of an LWA
IC Water Distribution Using Prewetted LWA

• Use fine aggregate to distribute water
• Help satisfy increased water demand from SCM’s
• Works even at moderate 0.40 – 0.48 w/cm

Bentz & Weiss (2011)
Basics of IC - Concrete
Improved Cement Paste Microstructure

Scanning Electron Microscope Observations:

• Fewer and smaller un-hydrated cement particles (indicating enhanced hydration)

• Fewer and smaller empty pores (indicating less self-desiccation)

• Denser and more homogeneous interfacial transition zone (ITZ) between lightweight aggregates and hydrating cement paste

Bentz & Weiss (2011)
RH Measurements - Without IC

Castro (2011)
RH Measurements - With IC

Castro (2011)
Internal Curing Increases Hydration

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

50% RH Curing

Golias (2010)
Large Scale Testing
Purdue University

Schlitter (2010)
Large Scale Testing
Purdue University

Test Slabs 15’ long with end restraint. 0.30 w/c
Curing: 2 days sealed, then 73° F @ 50% RH

Schlitter (2010)
Large Scale Testing
Purdue University

Plain Concrete
0.6 mm wide crack
observed @ 12 days

IC Concrete
0.4 mm wide crack
observed @ 43 days

Schlitter (2010)
Cracking Tendency of Lightweight Concrete
Auburn University

• Can you get too much IC?
• Studied 3 LWA (shale, clay, slate), with summer (95°) and fall (73°) curing conditions (total 20 mixes):
  – control
  – IC, fine LWA
  – LWC, coarse LWA
  – ALWA, all fine and coarse aggregate was LWA

Byard (2010)
## Cracking Tendency of Lightweight Concrete

Auburn University

<table>
<thead>
<tr>
<th>Item</th>
<th>CTRL</th>
<th>IC</th>
<th>LWC</th>
<th>ALWC</th>
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<td>LW C agg</td>
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<td>230</td>
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Auburn Mixture Designs (w/c .42)

Byard (2010)
Cracking Tendency of Lightweight Concrete
Auburn University

Less Shrinkage; Less Cracking

Byard (2010)
Cracking Tendency of Lightweight Concrete
Auburn University

Time to Cracking, hours

**Delayed Cracking**

Summer (95°) curing temp. profile for expanded shale IC mix

Byard (2010)
Chloride Permeability at Higher W/C and 50% RH Cure

- 10 concretes (w/c .40 .425 .450 .475 .50)
- Drying conditions, strip 24h, 23°C, 50% RH
- Mixtures with IC exhibit average of
  - 16% better hydration,
  - 19% higher compressive strength, and
  - 30% lower permeability
- IC very useful under poor curing conditions.

Espinoza-Hajazin (2010)
Lower Chloride Permeability
Chloride ion permeability @ 90 days, cured @ 50% RH

Espinoza-Hajazin (2010)
Reduced Chloride Ingress

Bentz (2008)
Reduced Chloride Ingress

- Silver Creek Overpass, UT
- LWC Deck - Built in 1968
- Chloride content after 23½ years in service

**Note:** LWC not IC normal weight

<table>
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<tr>
<th>Depth</th>
<th>LWC Deck</th>
<th>NWC Appr. Slab</th>
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<td>0&quot; to ½&quot;</td>
<td>36.7 lbs / CY</td>
<td>20.5 lbs / CY</td>
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<tr>
<td>½&quot; to 1&quot;</td>
<td>18.0 lbs / CY</td>
<td>18.0 lbs / CY</td>
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<tr>
<td>1&quot; to 1½&quot;</td>
<td>7.7 lbs / CY</td>
<td>15.7 lbs / CY</td>
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<tr>
<td>1½&quot; to 2&quot;</td>
<td>0.5 lbs / CY</td>
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ESCSI (2001)
Lower Conductivity
Reduced 66% at 1 Year at w/c 0.42

Saturated Condition

Castro (2011)
Lower Conductivity
Reduced 66% at 1 Year at w/c 0.42

Unsaturated Condition

Castro (2011)
Plastic Shrinkage Cracking with IC

- IC reduces the width of the crack
- Can prevent cracking from occurring all together

Henkensiefken (2010)
Effect on Modulus of Elasticity

LWA Replacement lbs/cy

kg/m³

10⁶ psi

Normal weight (4.78)

NIST (needs details)
Reduced Curling & Warping

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

Wei (2008)
Mixture Design & Specification
IC Mixture Design Basics

- How much IC water is needed
- LWA absorption
- LWA rate of desorption
- Total aggregate grading of the mixture
- Size of the IC aggregate (fines or intermediate)
How Much LWA is Needed for IC

Typically replace ~400 lbs of concrete sand with an equal absolute volume of lightweight fines.
Simple IC Mixture Design

- Need 7 lbs of IC water per 100 lbs of cementitious

- 600 lbs cementitious = 42 lbs of IC water
- Assume 18% LWA absorption in the field
- Assume LWA at 55 lbs/cf
- \( 55 \times 0.18 = 9.9 \text{ lb/cf water at 90% desorption} \)
- Need 42 lbs IC water / 8.9 = 4.7 cf of LWA
- \( 4.7 \text{ cf} \times 55 \text{ lb/cf} = 259 \text{ lbs of LWA aggregate} \)
Batching Prewetted LWA

- Calculate absorbed and surface moisture
- Utilize paper towel test, NY 703-19E Moisture Content of Lightweight Fine Aggregate (Aug 2008) on ESCSI Website
- Adjust pull weights by absorbed moisture only
- Absorbed water not included in w/c
- Reduce mix water by surface moisture
Natural Sand Replacement

Replace about 30% of the Fine LWA

Mixture Proportions of the Fine Aggregate In a Yard of Concrete
NY State DOT Specifications

• Proper amount of water
• 30% replacement of fine aggregate
• Minimum 15% absorbed moisture
• Place under sprinkler for minimum of 48 hours
• Allow stockpiles to drain for 12 to 15 hours immediately prior to use
NY State DOT Specifications

- Calculate absorbed and surface moisture
- Utilize paper towel test
- Adjust pull weights by absorbed moisture only
- Absorbed water does not effect w/c
- Reduce mix water by surface moisture
Projects / Case Studies IC
Real World IC Projects

UP RR Intermodal Facility
Constructed 2005

250,000 yd³ IC project low slump pavement

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

Paving in Texas

Bridges in New York State

16 built or under construction
Internal Curing vs. No Internal Curing – 1 day after placement
Highlands Ranch, CO – 92°F ambient, 20% RH. (no conventional curing)
Indiana DOT Test in 2010

- Internally cured concrete looks the same
Indiana DOT Test in 2010
Indiana DOT Test
Conventional Deck @ 2 Months
Indiana DOT Test
Internal Curing Deck @ 1 Year– No Cracks
Interstate 81 - Whitney Point, NY
NY 353 - Salamanca, NY
Case Studies - New York State

Spencer and Court Street Overpass, Syracuse, NY
Court Street Overpass I-81
September 2009
HPC Mixture Design (w/cm 0.42)
Spencer and Court Street Overpass, Syracuse, NY

<table>
<thead>
<tr>
<th>Batch weights in pounds</th>
<th>Spencer St Standard Mix</th>
<th>Court St IC mix</th>
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<tbody>
<tr>
<td>Cement</td>
<td>500</td>
<td>500</td>
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<tr>
<td>Fly ASH</td>
<td>135</td>
<td>135</td>
</tr>
<tr>
<td>Microsilica</td>
<td>40</td>
<td>40</td>
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<tr>
<td>Fine LWA</td>
<td>0</td>
<td>196</td>
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<tr>
<td>Fine Aggregate</td>
<td>1130</td>
<td>782</td>
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<tr>
<td>Coarse Aggregate</td>
<td>1720</td>
<td>1720</td>
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<tr>
<td>Water</td>
<td>270</td>
<td>262</td>
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## HPC Mixture Design (w/cm 0.42)

**Spencer Street Overpass, Syracuse, NY**

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<th>Batch weights in pounds</th>
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<td>1720</td>
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<tr>
<td>Water</td>
<td>270</td>
</tr>
</tbody>
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HPC – IC Mixture Design (w/cm 0.42)
Court Street Overpass, Syracuse, NY

<table>
<thead>
<tr>
<th>Batch weights in pounds</th>
<th>Court St IC mix</th>
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<tbody>
<tr>
<td>Cement</td>
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<td><strong>Fine Aggregate</strong></td>
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<td>Coarse Aggregate</td>
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<tr>
<td>Water</td>
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IC Aggregate Grading

IC Fine Aggregate

% Retained

Screen Size

1/2  NO.4  NO.16  NO.50  PAN
Court Street Bridge
Court Street Bridge
## Syracuse, NY Bridge Comparison

<table>
<thead>
<tr>
<th>Bridge Projects</th>
<th>Concrete Type</th>
<th>7 day Compressive Strength (MPa)</th>
<th>14 day Compressive Strength (MPa)</th>
<th>21 day Compressive Strength (MPa)</th>
<th>28 day Compressive Strength (MPa)</th>
<th>Percent Improvement</th>
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</thead>
<tbody>
<tr>
<td>Spencer and Butternut Street</td>
<td>HPC</td>
<td>32.6</td>
<td>40.8</td>
<td>41.9</td>
<td>43.5</td>
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<td>Court Street</td>
<td>HPC-IC</td>
<td>33.5</td>
<td>42.9</td>
<td>45.3</td>
<td>48.1</td>
<td>5.1%</td>
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<tr>
<td>Percent Improvement</td>
<td></td>
<td>2.8%</td>
<td>5.1%</td>
<td>8.1%</td>
<td>10.6%</td>
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Bartell Road Overpass I-81
Cicero, NY

May 2010
Bartell Road Overpass I-81
Cicero, NY
Bartell Road Overpass I-81
Cicero, NY
HPC – IC Mixture Design
Bartell Road Cicero, NY

<table>
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<th>Batch weights in pounds</th>
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<td><strong>Fine Aggregate – Natural Sand</strong></td>
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<td><strong>Fine Aggregate – Expanded Shale</strong></td>
<td>194</td>
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<td>Coarse Aggregate -1&amp; 2 blend</td>
<td>1726</td>
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<tr>
<td>Water</td>
<td>273</td>
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w/cm 0.40
# Bartell Road Bridge Comparison

<table>
<thead>
<tr>
<th>Concrete Type</th>
<th>7 day Strength (MPa)</th>
<th>14 day Strength (MPa)</th>
<th>21 day Strength (MPa)</th>
<th>28 day Strength (MPa)</th>
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<tr>
<td>Bartell Road HPC</td>
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<td>17.3</td>
<td>-</td>
<td>30.2</td>
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<td>Bartell Road HPC-IC</td>
<td>21.0</td>
<td>25.9</td>
<td>29.4</td>
<td>34.8</td>
</tr>
</tbody>
</table>

**Percent Improvement**

- Bartell Road HPC: -5.4%
- Bartell Road HPC-IC: 49.7%
- 28 day: 15.2%

Source: NYSDOT
NYSDOT Study - Variety of Conditions

- Bridge type
- Number of spans
- Regions
- Climates
- De-icing chemicals
- Traffic loading
- Time when poured
NY Projects Built or Under Construction

- NY Route 9W over Vineyard Avenue
- NY Route 96 over Owego Creek
- Interstate 81 at Whitney Point Southbound
- Interstate 81 at Whitney Point Northbound
- Court Street over Interstate 81
- Bartell Road over Interstate 81
- Interstate 86 over NY Route 415
- Interstate 84 over Route 6
- Interstate 290 Ramp B over Interstate 190
NY Projects Built or Under Construction

- Interstate 81 over East Hill Road
- NY Route 17 Exit 90 Ramp over East Branch Delaware River
- NY Route 38B over Crocker Creek
- NY Route 353 over Allegheny River
- Interstate 290 Ramp D Over Interstate 190
- Interstate 87 over Route 9 and Trout Brook
- Interstate 81 Connectors near Fort Drum
Highway 121 Mainline Paving

- State Highway 121, Dallas, Texas
- 1300 cubic yards, 5 miles
- Continuously Reinforced Concrete Pavement (CRCP)
- November 16, 2006
- Class P (3500 psi or 570 psi flex at 7d)

Friggle & Reeves (2008)
Highway 121 Mainline Paving

Mixture Used
300 lbs (5 cu ft bulk)
Intermediate LWA per Cu Yd Concrete

Friggle & Reeves (2008)

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Coarse agg. 1</th>
<th>Coarse agg. 2</th>
<th>Lightweight agg.</th>
<th>Fine agg.</th>
<th>Combined</th>
<th>Combined % Retained</th>
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Highway 121 Mainline Paving

4000 psi @ 4 days

6000+ psi @ 28 days

Friggle & Reeves (2008)
Highway 121 Mainline Paving
Crack Spacing of IC section

500 ft section, no joints

Survey: 2/1 and 9/11/2007

Survey: 76d old, Average IC Crack Spacing: 31ft

Survey: 10m old, Number of cracks, IC 21 vs. 52 control

Friggle & Reeves (2008)
Highway 121 Mainline Paving
Crack Width (% of total at 10 months old)

Crack distribution %

Crack width (mm)

Less than 0.10

0.10

0.15

IC

LWA Section

Control Section

Friggle & Reeves (2008)
Union Pacific Intermodal Facility
Hutchins, Texas  January 2005

250,000 yd³  IC project low slump pavement
Visual inspection at 6 months found one crack
At 6 years minuscule plastic or drying shrinkage cracks
Union Pacific Intermodal Facility
Hutchins, Texas January 2005

• Low Slump IC Mixtures
  • Enhanced Workability
  • Better Consolidation
  • Flexural Strengths 650 – 700 psi @ 28 days
Better Pavements in Texas

• Since 2003, TXI placed 2,000,000 cy IC mixtures with 1.3 million in low slump pavements
• IC Mitigates or eliminates plastic and drying shrinkage cracks
• Average 1000 psi strength gain with IC
• 5 bulk cu ft of IC LWA reduces weight by 200 lbs/cy
  – 10yd load = 2000 lbs or .5 cy per load or
  – 5% fewer truck loads
Life Cycle Cost Analysis
Life Cycle Cost Analysis

Cusson (2010)
Life Cycle Cost Analysis

National Research Council Canada Study Compared Three Concrete Bridge Deck Options:

NC = Normal Concrete with No Supplementary Cementitious Materials (SCM)

HPC = High Performance Concrete with 25% SCM

HPC-IC = High Performance Concrete with 25% SCM and Internal Curing

Cusson (2010)
## Life Cycle Cost Analysis
### Mixture Designs

<table>
<thead>
<tr>
<th>Deck Option</th>
<th>Cracking</th>
<th>Initial (kg/cu m)</th>
<th>Water (kg/cu m)</th>
<th>Cement (kg/cu m)</th>
<th>W/C Ratio</th>
<th>SCM (%)</th>
<th>LWA (kg/cu m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td>No</td>
<td>140</td>
<td>350</td>
<td>0.40</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HPC</td>
<td>Yes</td>
<td>160</td>
<td>450</td>
<td>0.36</td>
<td>25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HPC-IC</td>
<td>No</td>
<td>160</td>
<td>450</td>
<td>0.36</td>
<td>25</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

Cusson (2010)
# Life Cycle Cost Analysis

## Impact of IC on Mixture Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>HPC Concrete w/c = 0.35</th>
<th>HPC-IC Concrete w/c = 0.35</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC water provided (kg/kg)</td>
<td>0</td>
<td>0.075</td>
<td></td>
</tr>
<tr>
<td>C-S-H content at 28 days (Hydration)</td>
<td>10.2</td>
<td>12.3</td>
<td>21</td>
</tr>
<tr>
<td>Compressive Strength at 7 days (MPa)</td>
<td>45</td>
<td>50</td>
<td>11</td>
</tr>
<tr>
<td>Compressive Strength at 28 days (MPa)</td>
<td>60</td>
<td>65</td>
<td>8</td>
</tr>
<tr>
<td>Water Permeability (m/s)</td>
<td>2.10E-11</td>
<td>1.70E-11</td>
<td>19</td>
</tr>
<tr>
<td>Chloride Permeability (coulomb)</td>
<td>553</td>
<td>415</td>
<td>25</td>
</tr>
<tr>
<td>Freeze/Thaw Resistance (% mass loss)</td>
<td>0.60</td>
<td>0.26</td>
<td>56 less</td>
</tr>
<tr>
<td>Salt Scaling Resistance (% mass loss)</td>
<td>0.46</td>
<td>0.30</td>
<td>35 less</td>
</tr>
</tbody>
</table>

Cusson (2010)
Life Cycle Cost Analysis
Service Life Predictions

Cusson (2010)
Life Cycle Cost Analysis
Service Life Prediction

Cusson (2010)
Life Cycle Cost Analysis
Initial vs. Life Cycle Costs

Cusson (2010)
Life Cycle Cost Analysis
Initial vs. Life Cycle Costs

Cusson (2010)
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Conclusions

- Prewetted LWA fines can be used to improve concrete properties
- IC material should have proper moisture
- IC material should have proper desorption characteristics
- Addition of IC materials do not affect the finishability of concrete
- IC will improve the durability of HPC
In Summary

More durable and less permeable concrete –

• Improved Hydration and SCM Reaction Significantly Reduces Concrete Porosity

• Denser and more homogeneous interfacial transition zone (ITZ) between lightweight aggregates and hydrating cement paste

• Reduced Early Age and Long Term Shrinkage Cracking

In Summary – Other Benefits

• Enables ‘greener’ concrete as OPC can be replaced (limestone, ash, slag)
• Longer life and use of SCMs lower carbon footprint
• More efficient use of cement and SCM
• Increase strength
• Increases ‘reserve capacity’ for temperature effects during construction
• Lower modulus of elasticity...less cracks
• Helps offset poor curing – improves good curing
• Reduced curling / warping
In Summary - Sustainability

- Taking a holistic approach from the beginning. Plan the right project and design it right
- Think long term
- We can’t solve our problems with the same mindset that we created them
- We must be more aware of the way we relate to each other, our environment and the way we do business
Questions?

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