Internal Curing – Ready, Set, Specify

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Concrete Problems

- American’s spend 4.2 billion hours a year stuck in traffic
- Bridges (>25%) are structurally deficient or functionally obsolete
- Highways (>33%) are in poor or mediocre condition
- Cracked and spalling concrete
- Corroding steel reinforcement

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Dream it Do it
Curing

- When concrete is placed it is sensitive and can be easily damaged if not treated properly
- We want to maintain appropriate temperature and moisture during the first few weeks
- Proper curing enables concrete to hydrate (chemically react) developing potential strength and durability
- Proper curing reduce stress and cracking potential due to drying or temperature changes
- Important but frequently overlooked step
• ACI–308: Action taken to maintain moisture and temperature conditions in a freshly placed cementitious mixture to allow hydraulic-cement hydration and, if applicable, pozzolanic reactions to occur.

http://science.howstuffworks.com/environmental/earth/geology/dinosaur-bone-age.htm
External Curing

- Conventional concrete is done to the outside of the concrete

- Can think of this a little like a crab/lobster exoskeleton

http://express.howstuffworks.com/exp-exoskeleton.htm
Most Common Types of External Curing

• Water Ponding, Sprinkling, Burlap: Supply Additional Water

• Curing Membranes: Only Reduce Loss of Water to the Environment
Internal Curing (IC)

- IC works from the inside of concrete
- IC uses reservoirs of water that hide water before set to get a dense structure and make the water available after set for hydration

Castro et al. 2010
Proportioning Principles

• How much LWA/water is needed – The majority of uses are performed based on replacing chemical shrinkage of the hydrating paste

• Aggregate Spacing – the LWA need to be well-spaced to allow water to reach all the paste

• Properties of the Aggregate – The aggregate needs to be able to absorb and release the water
Chemical Shrinkage

- Le Chatelier
- 1850-1936
- Volume of reactants larger than volume of the products

Chemical Shrinkage

\[
\begin{align*}
\text{Capillary Water} & \quad \text{Hydration Product Solid} \\
\text{Unhydrated Cement} & \quad \text{Hydration Ceases}
\end{align*}
\]
How Does Internal Curing Work?

- Porous lightweight aggregate is ‘prewetted’ before mixing
- Water moves from the ‘pores’ in LWA to the paste on demand as needed
- This movement is due to fact that smaller pores want to remain ‘water filled’

![Conceptual Model of Pores In Concrete](slide)

![Conventional Concrete](slide)

![Internally Cured Concrete](slide)

Radinska et al. 2007
Self Desiccation and Setting

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Sant et al.; Crouch et al. 2006
Chemical Shrinkage

• Occurs in all cements
• Strictly speaking only the difference between the external and internal change needs to be used however it is practical to just use the entire CS
• A good first number to use is 6.4 ml/g of cement (cementitious material) and while this varies depending on chemistry (6.4 to 7 ml/g is a good place to start)
• Concept of proportioning mixtures for internal curing is simple

• Demand – Space created by chemical shrinkage (or other loss)

• Supply – Water stored in the LWA
Why is this an Issue in Lower w/c

• Chemical Shrinkage (CS) is not very sensitive to w/c at early ages
• AS should decrease as w/c increases.....
• Do higher w/c have less self-desiccation ??
• Size of the voids:
  a) Capillary vs Gel
  b) Few/big voids
  c) Lower pressures
Mixture Proportioning for IC

- How much LWA should we use?
- Three Basic Methods
  - Rule of Thumb
    7 lbs per 100 lbs cementitious
  - Simple Calculation: Supply vs Demand
    \[ Supply = Demand \]
    \[ M_{LWA} \phi S = C_f \, CS \, \alpha_{Max} \]
  - More Complicated Features
    - time dependent absorption
    - desorption (water release)
    - Features other than CS

Supply = Demand

\[ M_{LWA} = \frac{C_f \times CS \times \alpha_{max}}{t^A \times \phi_{LWA 24h} \times \psi} \]
As Simple as Replacing a Volume of the Fine Aggregate Volume Proportions

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![Chart showing the comparison between Conventional and Internally Cured mixtures.](chart.png)
• Need paste to be within close proximity to LWA
• Fine aggregate protects more of the paste than the coarse LWA
Lightweight Aggregate Structure

- #8 agg images from x-ray tomography
- A large volume of pores can be seen
- These pores come in various sizes and connectivity
- Pore size related to RH at water release
Mixture Proportion Equation

- Prewetted surface dry aggregate over salt solution
- $\text{KNO}_3$ - salt at 94% RH for a saturated salt solution
- Weigh the sample originally, weigh the sample till it comes to near equilibrium (mass changes are small), then oven dry the sample

\[ M_{LWA} = \frac{C_f \times CS \times \alpha_{\text{max}}}{t^A \times \phi_{LWA \ 24h} \times \psi} \]
Summary So Far

• Internal Curing is Just Doing What We Should Be Doing Water Curing Concrete

• Proportion Based on Two Main Concepts
  – Provide water to replace chemical shrinkage volume (7 lb per 100 lbs cementitous)
  – Aggregate needs to be well spaced – Accomplished with the use fine aggregate

• Aggregate needs to desorb (i.e., release water when needed) occurs at high RH, ‘large pores’ and can simply be measured by mass with salt
Field Experiences (Monroe Co 2010)

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Plain and IC Bridge Decks (Monroe Co, Indiana 2010)

Plain concrete bridge deck was pumped

IC concrete bridge deck was placed by means of a bucket

<table>
<thead>
<tr>
<th></th>
<th>Cement Content (kg/m³)</th>
<th>W/C</th>
<th>Fine Agg. (kg/m³)</th>
<th>Fine LWA (kg/m³)</th>
<th>Coarse Agg (kg/m³)</th>
<th>Mixture Water (kg/m³)</th>
<th>Water in LWA (kg/m³)</th>
<th>WR (%)</th>
<th>AE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain</td>
<td>390</td>
<td>0.39</td>
<td>726</td>
<td>-</td>
<td>1046</td>
<td>152</td>
<td>-</td>
<td>0.22</td>
<td>0.08</td>
</tr>
<tr>
<td>Int. Cured</td>
<td>390</td>
<td>0.39</td>
<td>313</td>
<td>270</td>
<td>1046</td>
<td>152</td>
<td>25</td>
<td>0.22</td>
<td>0.08</td>
</tr>
</tbody>
</table>

^percentage referred to the cement weight
Internal Curing Applications

- NYDOT using internal curing in bridge decks (map showing bridges as of 2012)
- General experience is positive
- Reduced cracking with no problems to contractor or supplier

Streeter et al. 2012
Strength Results

- Similar or slightly higher compressive strength results in Bloomington IN (DiBella et al. 2011)
- Similar Strength and Fresh Properties in Tonowanda and Lisle (not Shown) NY (Wolfe et al 2012)

<table>
<thead>
<tr>
<th></th>
<th>Comp. Str. 7 day</th>
<th>Comp. Str. 28 day</th>
<th>Comp. Str. 56 day</th>
<th>Concrete Density</th>
<th>Air Content</th>
<th>Slump</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class HP</td>
<td>3,040 psi</td>
<td>4,677 psi</td>
<td>5,343 psi</td>
<td>140.2 pcf</td>
<td>5.5 %</td>
<td>5.0”</td>
</tr>
<tr>
<td>Class HP-IC</td>
<td>3,500 psi</td>
<td>4,683 psi</td>
<td>5,417 psi</td>
<td>135.2 pcf</td>
<td>6.0 %</td>
<td>4.5”</td>
</tr>
</tbody>
</table>
## Rapid Chloride Penetration Test

<table>
<thead>
<tr>
<th>Time [day]</th>
<th>NY Lisle</th>
<th>NY Tonawanda</th>
<th>Monroe Co</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Charge passing [Coulombs]</td>
<td>Charge passing [Coulombs]</td>
<td>Charge passing [Coulombs]</td>
</tr>
<tr>
<td></td>
<td>Plain Concrete</td>
<td>IC Concrete</td>
<td>Plain Concrete</td>
</tr>
<tr>
<td>28</td>
<td>535</td>
<td>423</td>
<td>572</td>
</tr>
<tr>
<td>56</td>
<td>373</td>
<td>406</td>
<td>342</td>
</tr>
<tr>
<td>91</td>
<td>357</td>
<td>392</td>
<td>308</td>
</tr>
</tbody>
</table>
Here we see the predicted service life model results for the decks cast in 2010.

- Class C concrete 20 yrs, ICHPC 55-90 yr
- Model assumes no cracks
Visual Inspection of the Plain Bridge Decks after 20 Months

- Plain bridge deck several cracks
- Internally cured deck no cracks 20 mos later
- Monroe county is very happy

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Main Take Always – Cracking/Corrosion

Class C

Internally Cured Class C

Assumes No Cracks

Corrosion Limit
Special Thanks

Tommy Nantung

Tony Zander

and the team

Ron Walker

Contractors

Ready Mix

Producers

Tim Barrett and Albert Miller
Some Concepts from 2013

- Maximum paste volume of 25%
- Cement content >390lbs/cyd
- Fly ash at 20-25% by mass
  (or ggbfs at 15-20% by mass)
- Silica fume at 3-7% by mass
- w/cm of 0.36 – 0.43
- Air content of 6.5%
- Slump from 2.5 - 5.5”
- Comp. strength at 28 days >5000psi
- Charge passed in RCPT <1500C
• IC posed no real issues
• Some honeycombing on harsh/wrong mixture
• Conveyed not pumped
• Paste ‘too low’ IMHO
Low variability from trial to cast

Note: The first half of the deck was made with this mixture
Bridge #2 Paoli
US 150 over Lost River

- IC Comments: Contractor had to refill LWA bins during day
- Workability harder midway (we detected moisture change in the aggregate)
- Long haul with slow traffic on a hot day
- Mixture was hard to pump, was losing air and was sticky
Bridge #2 Paoli
US 150 over Lost River

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Compressive Strength (psi)

Resistivity (Ωm)

Age (d)

0 7 14 21 28 35 42 49 56

0 10000

6000

2000

100

Cross sections of the bridge and compressive strength and resistivity graphs are shown. The graphs demonstrate the development of compressive strength and resistivity over time for different materials.
• Contractor liked the mixture
• Did not know that it was an internally cured mixture until informed mid-cast
• Did not have continuous supply of concrete (Likely truck scheduling)
  – Wait time exceeded 20 minutes between trucks (7 trucks)
  – Pump re-cycled twice
Some variations in the mixture design between trial and actual batching
Bridge #4 South Bend
SR 933 Baugo Creek

- High levels of HRWRA
- Tallest LWA pile (variability from pile)
Summary of Main Findings from the Summer of 2013 (Documented All)

- IC has minimal impact on construction IC
- HPC outperforms Class C mixtures
- Quality control is crucial
- Minimize variation btw trial and field cast

![Graph showing total chloride vs. duration for different mixtures]
Discussion of Internal Curing, Cracking, and Corrosion

- IC increases hydration, reduces porosity,
- Reduces interfacial zones
- IC reduces absorption and reduces chloride diffusion

- Internal curing reduces the potential for cracking
  - Cracks accelerate fluid ingress and corrosion of reinforcing steel

Pease et al. 2008
Restrained Shrinkage

- Instrumented W12 × 210 beam – Widened steel beam restrains concrete from moving freely as the concrete shrinks.
- threaded rods used to anchor the specimen at ends
- wedges - 1.5mm (1/16in.) wide tip and widened to 10mm (3/8 in.)
- 15 ft long, 90% restraint
Cracking and Corrosion

- 0.3 w/c - plain
- 0.3 w/c – internal curing
- No. 6 rebar (hollowed)
- 28 corrosion sensors
- Notch at mid-span to control the location of first crack
- Strain gages monitor stress development and cracking in concrete
Restrained Shrinkage Behavior

- Multiple cracks along the reinforcing bar
- Each crack caused others to close slightly
- Cracking resulted in substantial debonding
• corrosion potential was greatly influenced by crack proximity of the crack around at the steel-mortar interface.
• Sensors #1, 3, 5, 15, 17, 21, 25, and 27 on the top surface of the rebar and started to corrode immediately.
Life Cycle Cost Analysis

- Cusson et al. 2010 reported results of a case study that compared a convention, high performance and high performance internally cured deck
- 200-mm (8 in) thick bridge deck
- 75 mm (3 in) cover
- Canadian exposure conditions

Cusson (2010)
Cusson et al. 2010 Service Life Model

- Schematic of life cycle model used

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Cusson et al. 2010 Service Life Model

- Internal curing improved service life
- 38% lower life cycle cost (5 year recovery)
Temperature Required to Crack

• Internally cured systems are more robust

Plain Mortar (w/c = 0.30)  
Not Internally Cured

Interally Cured Mortar  
(w/c = 0.30)

\[ \Delta T \text{ crack} = 10.3^\circ C \]  
\[ \Delta T \text{ crack} = 27.1^\circ C \]
Here we can see IC HES patching in West Lafayette, premature cracking was observed in many cases for plain HES.

Performed using IC in the standard HES patching and the benefit is reduced cracking and curling and increased hydration of the cement/opening.
Summary of Field Aspects and Cracking Aspects So Far

- First, IC has minimal impact on practice when done properly.
- Second, the main thing to watch for is the aggregate moisture (surface/absorbed).
- Third, IC HPC is a great use of this as it provides dense concrete with a low potential for cracking (improvement to C).
- Fourth, cracks occur not only at the surface but along the bar which can be problematic as a large section corrodes.
- NY – Only issue is researchers asking Q’s.
Discussion of Quality Control

Two Components of Water

- Absorbed water
  - varies with LWA material, soaking time, storage, and mixing time
  - Does not change volumetrics
  - Does not change the w/c

- Free water
  - Controls the slump
  - Is related to changes in w/c and strength
SSD and the Fallacy

- SSD – Saturated Surface Dry
  - Air-Dry
  - Saturated Surface Dry (SSD)
  - Wet

- In Reality – Not Really Saturated

- Better to say pre-wetted and surface dry
Determining Absorption

• Generally soak the aggregate for 24 hours (or 72 hours if you follow ASTM C 1761) then do one of the following methods to get the aggregate in prewetted surface dry condition
  – ASTM C 128 (Sand Castle Method)
  – Cobalt Chloride
  – Paper Towel Method
How to Prepare the Aggregate

- Drying a bit at a time – test each stage

- Centrifuge method “give it a whirl”
Paper Towel and Absorption

- Commercial grade, folded or roll paper towel
- Force is not specified
- Commercial grade paper towels - a capillary radius from 25 µm to 30 µm (testing Purdue paper towels and in a Georgia Tech Thesis and 3rd Grade Canadian Science fair)

\[ R_{cap} = \frac{2\gamma}{L_c \rho g} \]
Effect of Sample Size and Speed

Miller et al. 2014

*Centrifugal Force*

\[ F_{\text{cent}} = \frac{m \omega^2}{R} \]

*Capillary Pressure*

\[ F_{\text{cap}} = \frac{2 \gamma \cos \theta}{r} \frac{2 \pi r^2}{\rho \omega^2} \]

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Effect Spinning Speed and Time

Miller et al. 2014

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Freeze-Thaw Behavior

- Performance of lightweight bridge concrete bridge decks is at least as good as normal density concrete (Brown et al. 1985).
- Experiments have shown that plain and internally cured concrete behave similarly if they are properly air entrained.
- Want to be careful at early ages, and use a sufficiently low w/c where self-desiccation will pull water out of the LWA.
Freeze-Thaw Behavior

- Class H Concrete Colorado
  - 0.42 w/c
  - 74% Aggregate
  - 570 lb/yd$^3$ cement

<table>
<thead>
<tr>
<th>Standard Class H Mixture</th>
<th>Amount (kg/m$^3$)</th>
<th>Amount (lbs/yd$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>270</td>
<td>456</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>68</td>
<td>114</td>
</tr>
<tr>
<td>Water</td>
<td>142</td>
<td>239</td>
</tr>
<tr>
<td>FA</td>
<td>885</td>
<td>1493</td>
</tr>
<tr>
<td>CA</td>
<td>1091</td>
<td>1840</td>
</tr>
</tbody>
</table>

Note: Agg in SSD Condition

Mix 1: Standard Class H
Mix 2: LWFA 1 x CS
Mix 3: LWFA 2 x CS
Mix 4: CLWA 1 x CS
Mix 5: 100% CLWA Replacement
Mix 6: IC Buildex
Mix 7: IC Utelite
Mix 8: Standard Class D
Mix 9: IC Class D

Jones et al. 2013
Freeze-Thaw Behavior

- Here we can see the ASTM C 666 data
- The conventional concrete is fine as is the LWA with the water in the LWA = CS (Mix 2, 4)
- The 2x CS will leave water in the LWA and the LWCA has excess water

Jones et al. 2013
Freeze-Thaw Behavior

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Jones et al. 2013
Influence of w/c

- High w/c will not draw water from the LWA as fast as low w/c since the suction is higher low w/c
- May be susceptible to damage at early ages

Jones et al. 2013
Potential Approach for Sustainability

• Reduce the cement (clinker) content of concrete used in transportation structures
• Current limits of 20-25% fly ash
• Can higher volumes of ash be used?
  – Contractors and agencies are concerned with slow strength development
  – Other concerns: slow set time, admixture incompatibilities, scaling, freeze-thaw damage, extended times for moist curing
• de la Varga et al. examined potential use of high volume fly ash mixtures (HVFA)
• Typical w/cm 0.42 concrete bridge deck mixture modified using HVFA to obtain similar early age strengths

• Similar paste volume
• Similar workability obtained with chemical admixtures

<table>
<thead>
<tr>
<th></th>
<th>0%</th>
<th>20%</th>
<th>40%</th>
<th>60%</th>
<th>80%</th>
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<tbody>
<tr>
<td>0.45</td>
<td></td>
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<td>0.42</td>
<td></td>
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<td>0.36</td>
<td></td>
<td></td>
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<tr>
<td>0.30</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

• Reference Mixture (INDOT – BASE CASE) >> 0.42
• Constant Paste Volume, Volume Replacements
Early Age Compressive Strength

• As the w/c is reduced and the fly ash volume is increased similar strengths can be obtained at early ages

• Transport properties were also greatly improved

• However, as the w/c is reduced, the autogenous shrinkage and cracking potential can increase
Internal curing can improve the strength, especially at later ages due to enhanced hydration.

Internal curing has a residual stress that was much lower than the plain mixture, being similar or less than the 0.42 mixture with benefits of 60% less cement, improved strength, and transport.
Water Absorption with HVFA

- Conventional mixture shown in blue
- Replacing 60% of the cement with fly ash and using a lower w/c reduces transport
- Internal curing beneficial
Electrical resistivity

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Internal Curing
Restrained Shrinkage

SCM – Rate; Shrinkage Rate
If We Dream It, We Can Cure It

- Crack Free (Reduced Bridge Deck Cracks)
- Lower Curling/Cracking in Pavements
- Reduced Cracking in High Early Strength Pavement Patches
- Enhanced Reactions with SCM
- Lower Cost CRCP? (steel)
- Longer Joint Spacing (cost, ride) ?
- Durability Tighter Microstructure
- Slipforming on Decks Nice Lower $\sigma$
- Reduced Plastic and Thermal Cracking

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