Objectives

- Understand difference between external and internal curing
- Understand why the use of internal curing is needed today
- Understand the science of internal curing
- Understand which properties of concrete can be improved with internal curing
- Examine recent steps the industry is taking to implement internal curing

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
### Concrete Opportunities

- Reducing unwanted cracking in concrete, especially in higher performance concrete
- Improving construction schedule when long curing times are needed
- Improving rapid repairs and patches
- Making concrete less susceptible to thermal cracking at early ages

**VALUE ADDED PRODUCT**

### 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 reduces stress and cracking potential due to drying or temperature changes
- Important but frequently overlooked step

### External Curing

- Conventional curing works by treating the ‘outside’ of concrete after placement
  - Placing water (water curing) on the concrete surface
  - Placing a curing compound that helps to reduce water loss to evaporation
Challenges with External Curing

- External curing has worked for centuries, why is something different needed now?
- In an effort to make concrete less permeable (i.e., HPC) we use more low w/c systems with supplementary cement
- While reduced porosity is good for durability, it can limit water movement limiting the effectiveness of water curing
- Supplementary cementitious materials requires longer curing times (slower reactions) and have more chemical shrinkage with hydration

Internal Curing

- Internal curing - process by which the hydration of cement occurs when internal reservoirs provide additional water that is not part of the mixing water
- Allows curing to be well distributed
- Allows curing as needed

How Does Internal Curing Work?

- Water can be lost due to drying
- Water can be consumed by hydration resulting in self desiccation
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’

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

- RR intermodal facility
  – 250,000 yd³ of low slump IC material
- CRC Paving for TxDOT
  – 6 months 1 crack, 5.5 years minor drying or plastic shrinkage cracking
Internal Curing Applications

- Two bridge decks were cast in 2010 at the same time in Monroe Co (Bloomington) IN
- Internally cured bridge: similar workability, higher strength, lower transport and no cracking (3 cracks in the plain bridge)
- Additional bridges being constructed

Objectives
Concrete Problems
Defining Internal Curing
Science of Internal Curing
Internal Curing Applications

Building large slabs is complex
- Denver Water 10 Million Gallon Lone Tree Tank No. 2
- Negligible differences in placing & finishing
- Opinion – less cracking and maintenance

Summary
- US infrastructure is aging & deteriorating: IC offers one approach to extend the service life of concrete
- LWA can be used as a reservoir to ‘hide water’ throughout the cross section that can be used during hydration
- Internal curing can reduce shrinkage and shrinkage induced cracking
- Internal curing is being implemented, with examples shown, in practice and showing great potential
Objectives

- To understand what is meant by the term internal curing
- To understand the principles that are used to proportion internally cured mixtures:
  1) chemical shrinkage volume
  2) aggregate spacing
  3) aggregate properties
- To understand the tests that are used to quantify aggregate performance
What is Curing

- Describes the process by which hydraulic-cement concrete matures and develops hardened properties over time.
- Continued hydration of the cement in the presence of sufficient water and heat.

Conventional Curing (ACI 308)

- Measures taken to limit the loss of water, heat, or both, from the concrete, or by externally providing moisture and heat.
- 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.

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: Reduce Loss of Water to the Environment

Are There Other Options

- Exoskeleton vs Endoskeleton
- Can we look inside the concrete
- Can we supply water from inside

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
NPCA Precast Show – Internal Curing

**Where Do ‘Hide’ IC Water?**

- Porous Inclusions - a solid body that contains pores for gas or liquid to be enclosed within the mass of a mineral.
- Lightweight aggregate has pores that enable it to absorb water that can be released after setting

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**Why IC and Why Now?**

- HPC are ‘dense’ and remove and disconnect large pores
- While this is good for durability it makes it more difficult for curing water to move into concrete
- Concrete also self-desiccates (i.e., dries from inside without water loss)
- Self-desiccation increases in low w/c & with supplementary materials

---

**What is Self-Desiccation**

- Simply – it’s like internal drying without water loss
- A reduction in internal relative humidity (RH) occurs when pores are emptied
- What causes these pores to empty?
- Does the size of the pore matter?
Proportioning Principles

- Aggregate Spacing – the LWA need to be well-spaced to allow water to reach all the paste
- How much LWA/water is needed – The majority of uses are performed based on replacing chemical shrinkage of the hydrating 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

Le Chatelier

1850-1936

Volume of reactants larger than volume of the products

Chemical Shrinkage
Mixture Proportioning for IC

- Concept of proportioning mixtures for internal curing is simple

Supply ▲ Demand

- Demand – Space created by chemical shrinkage (or other loss)
- Supply – Water stored in the LWA

Mixture Proportioning for IC

- How much lightweight aggregate should we use?
- Three Basic Methods
  - Rule of Thumb
    7 lbs per 100 lbs cementitious
  - Simple Calculation: Supply vs Demand
  - More Complicated Features

Simple Rule of Thumb

- 7 lbs water per 100 lbs cementitious
- 6 bag mixture – 564 lb/yd$^3$
- IC Water = 7*564/100 = 39.5 lb/yd$^3$
- Assume Aggregate with 15% Absorption
  - Mass$_{LWA-OD}$ = 39.5/15% = 263 lb/yd$^3$
- Very Good First Approximation
Conventional Concrete

- SG_{Cement} = 3.15; SG_{C. Agg} = 2.68
- SG_{F. Agg} = 2.75; SG_{LWA} = 1.52
- Density = SG * 62.4 lb/ft³
- Volume = Mass/Density

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Density</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>564.0 lb/yd³</td>
<td>196.6</td>
<td>2.87 ft³</td>
</tr>
<tr>
<td>Water</td>
<td>203.0 lb/yd³</td>
<td>62.4</td>
<td>3.25 ft³</td>
</tr>
<tr>
<td>Coarse Aggregate</td>
<td>1750.0 lb/yd³</td>
<td>171.6</td>
<td>10.20 ft³</td>
</tr>
<tr>
<td>Fine Aggregate</td>
<td>1514.9 lb/yd³</td>
<td>167.2</td>
<td>9.06 ft³</td>
</tr>
<tr>
<td>Lightweight Aggregate</td>
<td>~</td>
<td>94.8</td>
<td>~</td>
</tr>
<tr>
<td>Air</td>
<td>~</td>
<td>~</td>
<td>1.62 ft³</td>
</tr>
</tbody>
</table>

Example for One Yard of Concrete With Internal Curing

- Mass_{LWA} = 263 lb
- Vol_{LWA} = 263/(1.52*62.4) = 2.78 ft³
- Vol_{F. Agg} = 9.05 – 2.78 = 6.28 ft³
- Mass_{F. Agg} = 6.28*2.68*62.4 = 1051 lb

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Internally Cured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>564.0 lb/yd³</td>
<td>564.0 lb/yd³</td>
</tr>
<tr>
<td>Water</td>
<td>203.0 lb/yd³</td>
<td>203.0 lb/yd³</td>
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<tr>
<td>Coarse Aggregate</td>
<td>1750.0 lb/yd³</td>
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</tr>
<tr>
<td>Fine Aggregate</td>
<td>1514.9 lb/yd³</td>
<td>1050.8 lb/yd³</td>
</tr>
<tr>
<td>Lightweight Aggregate</td>
<td>~</td>
<td>263.2</td>
</tr>
</tbody>
</table>

Volume Proportions

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Internally Cured</th>
</tr>
</thead>
<tbody>
<tr>
<td>LWA</td>
<td>~</td>
<td>~</td>
</tr>
<tr>
<td>Fine</td>
<td>~</td>
<td>~</td>
</tr>
<tr>
<td>Air</td>
<td>~</td>
<td>~</td>
</tr>
<tr>
<td>Coarse</td>
<td>~</td>
<td>~</td>
</tr>
<tr>
<td>Water</td>
<td>~</td>
<td>~</td>
</tr>
<tr>
<td>Cement</td>
<td>~</td>
<td>~</td>
</tr>
</tbody>
</table>

[Image of volume proportions chart]
### Mixture Proportioning for IC

- **How much lightweight aggregate should we use?**
- **Three Basic Methods**
  - Rule of Thumb
    - 7 lbs per 100 lbs cementious
  - Simple Calculation: Supply vs Demand
- More Complicated Features

### Demand Equation

- **Demand** – Volume created when cement reacts (hydrates) – this is known as chemical shrinkage
  
  \[
  Supply = Demand \\
  M_{LWA} \phi S = C_f CS \alpha_{Max}
  \]

  - The product of three terms
    - \(C_f\) – Cement Factor – The amount of Cement in the concrete
    - \(CS\) – the chemical shrinkage of the cement
      (est 0.064 ml/g)
    - \(\alpha_{Max}\) is the expected maximum degree of hydration (0 to 1)

### Supply Equation

- **Supply** – the amount of water that is supplied by the lightweight aggregate. This is the water stored in the aggregate.
  
  \[
  Supply = Demand \\
  M_{LWA} \phi S = C_f CS \alpha_{Max}
  \]

  - The product of three terms
    - \(M_{LWA}\) – Mass of the lightweight aggregate
    - \(\phi\) – the volume of water absorbed by the lightweight aggregate (absorption) – refers to the water absorbed at a particular time
    - \(S\) – the saturation factor
Example

- Determine the mass of LWA for a cubic yard of concrete if one uses internal curing.
- The plain mixture has a cement content of 560 lb/yard$^3$, chemical shrinkage of 0.07 ml/g cement, and a LWA with 15% porosity (determined from 24 hr absorption)
- Assume $\alpha_{\text{max}} = 1$ and $S = 1$

\[
M_{\text{LWA}} = \frac{C_f \, CS \, S_{\text{Max}}}{\emptyset \, S} = \frac{560 \, \text{lb/yard}^3 \, (0.07) \, 1.0}{(15\%) \, 1.0} = 262 \, \text{lb/yard}^3
\]

Example of Spreadsheet

- Developed an automated spreadsheet to perform the calculations that you just did by hand
- The goal is to go from an existing mixture design to an internally cured mixture design using the properties of the lightweight aggregate

Step 1: Begin with Information from the Conventional Mixture

- This information can generally be obtained from the ready mix supplier as shown in orange cells

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight</th>
<th>SG (SSD)</th>
<th>Volume, ft$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>564</td>
<td>3.15</td>
<td>2.868</td>
</tr>
<tr>
<td>GGBFS</td>
<td>115</td>
<td>2.99</td>
<td>0.616</td>
</tr>
<tr>
<td>PAI</td>
<td>0</td>
<td>2.64</td>
<td>0.000</td>
</tr>
<tr>
<td>Silica Fume</td>
<td>25</td>
<td>2.2</td>
<td>0.182</td>
</tr>
<tr>
<td>Sand</td>
<td>1210</td>
<td>2.623</td>
<td>7.393</td>
</tr>
<tr>
<td>Coarse Ag 1</td>
<td>1700</td>
<td>2.763</td>
<td>9.860</td>
</tr>
<tr>
<td>Coarse Ag 2</td>
<td>0</td>
<td>2.763</td>
<td>0.000</td>
</tr>
<tr>
<td>Water</td>
<td>258</td>
<td>1</td>
<td>4.135</td>
</tr>
<tr>
<td>Air</td>
<td>0</td>
<td>0</td>
<td>1.755</td>
</tr>
<tr>
<td>Σ</td>
<td>3872</td>
<td>-</td>
<td>26.810</td>
</tr>
</tbody>
</table>

Legend

- Target Air, % 6.5%
- Ready Mix Input
  - w/c 0.366
  - LWA Input
  - Materials Weight
  - SG (SSD)
  - Volume, ft$^3$
Step 2: Add LWA Information

- We will now enter information about the LWA being used
- We will show how to obtain these values later today, for now assume they are known
- These are obtained experimentally for your LWA material
- As shown in the green cells

<table>
<thead>
<tr>
<th>Internal Curing Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>LWA Absorption: 15.0%</td>
</tr>
<tr>
<td>LWA Desorption: 85.0%</td>
</tr>
<tr>
<td>LWA Specific Gravity: 2.750</td>
</tr>
<tr>
<td>Cement Factor: 704</td>
</tr>
<tr>
<td>Chemical Shrinkage: 0.005</td>
</tr>
<tr>
<td>Degree of Hydration: 1</td>
</tr>
<tr>
<td>SSD LWA Replacement: 413</td>
</tr>
<tr>
<td>SSD Sand Replaced: 619</td>
</tr>
</tbody>
</table>

Step 3: Obtain IC Mixture Proportions (Automatically)

<table>
<thead>
<tr>
<th>IC Mixture Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>Cement</td>
</tr>
<tr>
<td>GGBFS</td>
</tr>
<tr>
<td>Fly Ash</td>
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<tr>
<td>Silica Fume</td>
</tr>
<tr>
<td>Sand</td>
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<tr>
<td>Lightweight Aggregate</td>
</tr>
<tr>
<td>Coarse Aggregate 1</td>
</tr>
<tr>
<td>Coarse Aggregate 2</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>Air</td>
</tr>
<tr>
<td>Σ</td>
</tr>
</tbody>
</table>
**Step 3: What Happened**

- The equation is applied to determine the mass of LWA knowing absorption, desorption, cement factor (sum of cementitious materials), DOH, and chemical shrinkage.
- With this mass of LWA the volume of LWA is determined and an equal volume of sand is removed.
- That's all.

**Step 4: Mixture Design**

- This is likely a good place to start for your trial batch if they have made this concrete before.
- This will let you check the workability and the air content.
- Remember orange boxes likely come from the ready mix producer and the green properties are for the LWA you are using.

**Aggregate Testing**

- Gradation (spacing, paste content)
- Specific gravity (mixture proportioning)
- Absorption: how much water can be held
  - Absorption during the first 72 hours
  - 24 hour absorption, using cone and paper towel method
- Desorption: how much water will be released back to the mixture
  - Curve of desorption during drying
  - Thermo Gravimetrical Analyzer, Q5000
- Rapid initial absorption, slows over time
- 24 hour absorption values between 6 to 30%
- Magnitude depends on the source

- When absorption is normalized by 24 hour absorption, they show a relatively uniform behavior described by the power equation:

  \[ S = t^k \]

Surface Dry (SD) Condition: Paper Towel Method (ASTM 1761)

- LWA is oven dried, cooled, and soaked for 24 hours (or an alt. time, ASTM 72 hours)
- Excess water is removed
- Free moisture on the surface of LWA is dried by placing it under air current until it reaches surface dry (SD) condition
- Free moisture is monitored by placing a paper towel on LWA. If water is not seen on the towel and LWA did not stick to the paper towel, SD condition was reached.
Centrifuge Test

- Wetted aggregates were placed in the centrifuge
- The sample is spun to remove excess surface moisture
- The mass of the spun sample and the mass of the spun sample after oven drying are used to determine the absorbed moisture
- Good correlation with paper towel test (fast, less subjective, measures surface moisture)

Alternative to the Centrifuge is the Paper Towel Method

<table>
<thead>
<tr>
<th>Paper Towel Method</th>
<th>Centrifuge Method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Testing Method</strong></td>
<td><strong>Average Absorption (%)</strong></td>
</tr>
<tr>
<td>Paper Towel</td>
<td>21.26</td>
</tr>
<tr>
<td>Centrifuge</td>
<td>20.18</td>
</tr>
</tbody>
</table>

Pooled Standard Deviation (%) 4.51
Average Coefficient of Variation - 0.273

ASTM C1761 Desorption

- The previous slides show an approach that measures the mass loss for each RH
- ASTM C1761 measures the mass loss between prewetted surface dry (SD) aggregate and the aggregate when its stored over a specific saturated salt (94% RH)
- Benefit is it is a test that is easy to perform as a check step

\[
Desorption = \psi = 1 - \frac{M_{3D} - M_{936}}{M_{SD} - M_{OD}}
\]
• ESCS LWA release a large portion of their moisture at high humidities. Commercial materials shown. This is desirable for internal curing.

85 to 98% moisture released

Aggregate Summary

• All the important properties for the lightweight aggregate are summarized on the summary tab

LWA Absorption:

LWA Desorption:

LWA Specific Gravity:

Surface Moisture:

Aggregate Properties (From Published Literature)

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

- Conventional
  - Prewet the lightweight aggregate for 24 to 48 hours with sprinkling

- Alternatively
  - Materials can be used without prewetting however very high level information is needed about the absorption
### Summary

- Internal curing uses porous inclusions (LWA) to supply curing water
- Aggregate needs to be well spaced, ESCS FLWA provides good spacing
- Important LWA properties – Grading, specific gravity, absorption and desorption
- Proportioning Principles - LWA (Supply); chemical shrinkage (Demand)
- In general, 7lb of water is needed for every 100 lb of cement (good rule of thumb)
- Desorption of aggregate is a ‘newer’ property but it is easy to measure with salt

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### Internal Curing Module: Shrinkage and Shrinkage Cracking

Influence of Low w/c & HSC
- Chemical and Autogenous Shrinkage
- Internal Curing (IC) Review
- IC and Shrinkage
- Plastic Shrinkage

Presented by Jason Weiss, jason.weiss@oregonstate.edu
Objectives

- To understand how shrinkage relates to stress development and how stress development relates to cracking
- To understand the different types of shrinkage and their causes
- To understand why low w/cm are prone to cracking
- To understand how IC can reduce the potential for cracking
- To review data that compares the cracking behavior of plain and IC concrete

Introduction

- Cracking frequently observed
- Transverse cracking in 100,000+ bridges
- 62% of DOT’s consider cracking as a problem (NCHRP)
- Cracks shorten service life, increase maintenance cost, and accelerate corrosion

Early Age Stress Development

- Concrete shrinks (reduces volume) due to moisture loss or temperature reduction
- If this volume reduction is not restrained, the sample will shrink and get smaller
- If restrained, tensile stresses develop that can result in cracking
Early Age Stress Development

- Fortunately, concrete is an aging viscoelastic material, stresses “relax” and reduce

<table>
<thead>
<tr>
<th>Causes of Shrinkage</th>
<th>Cracking</th>
<th>Influence of Low w/c &amp; HSC</th>
<th>Chemical and Autogenous Shrinkage</th>
<th>IC Review</th>
<th>IC and Shrinkage</th>
<th>Plastic Shrinkage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Specimen</td>
<td>Stress Based On Hooke’s Law</td>
<td>Stress Relaxation</td>
<td>Creep/Cracking Effect</td>
<td>Stress Relaxation</td>
<td>d\sigma(d) = -d\varepsilon(0)/E</td>
<td>d\varepsilon(0)/E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Final Stress State</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Autogenous Shrinkage

- As LWA replacement volume increases, autogenous shrinkage decreases
- 25.3% accounts for the CS volume

<table>
<thead>
<tr>
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<th>Influence of Low w/c &amp; HSC</th>
<th>Chemical and Autogenous Shrinkage</th>
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<th>Plastic Shrinkage</th>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Restained Shrinkage

- Using an Instrumented Ring
- Measure Strain that Develops in Steel
- Determine the Pressure Required to Obtain that Strain
- Apply Pressure to Concrete and Obtain Tensile Stress

Weiss and Ferguson 2001
Hossain and Weiss, 2002
Restrained Shrinkage Cracking (Sealed Samples)

- The age of cracking is plotted as a function of LWA addition
- As the volume approaches the CS replacement (25%) no cracking is observed

Henkensiefken et al. (2008)

Restrained Shrinkage Cracking (Unsealed Samples)

- As before we see that increasing the LWA volume decreases the potential for cracking
- Unsealed samples require a higher volume

Henkensiefken et al. (2008)

Thermal Effects

- Dual ring test used to capture expansion and contraction, Invar rings (low COTE)
- Coil system used to regulate sample temperature from 60°C to -10°C

Schlitter et al. 2010
Temperature Required to Crack

- Internally cured systems are more robust

Plain Mortar (w/c = 0.30) Internally Cured Mortar (w/c = 0.30)

\[ \Delta T \text{ crack} = 10.3^\circ C \]
\[ \Delta T \text{ crack} = 7.7^\circ C \]

Robustness at Early Ages

- IC has greater load or temp. capacity

Review of Main Topics

- Concrete is susceptible to cracking when it is restrained from shrinking
- The cracking potential increases with lower w/c higher strength concrete
- Chemical shrinkage occurs as cement hydrates, can result in autogenous shr.
- Internal curing is simply using LWA as a reservoir to ‘hide water’, reduce self-desc.
- Internal curing reduces shrinkage and shrinkage cracking
Review of Main Topics

- Internally cured mixtures hide water in the LWA, this water is released after setting to increase the pore saturation
- If the pores are more full, the meniscus in the pore is larger & resulting shrinkage is smaller
- IC concrete is less susceptible to restrained shrinkage cracking than plain concrete
- Plastic shrinkage cracking can be reduced but stored water is used and not available

Objectives

Causes of Shrinkage Cracking

Influence of Low w/c & HSC

Chemical and Autogenous Shrinkage

IC Review

IC and Shrinkage

Plastic Shrinkage

Internal Curing Module:
Mechanical and Transport Properties

Presented by Jason Weiss, jason.weiss@oregonstate.edu
Objectives

- Review the concept of internal curing (IC)
- To understand changes that occur in concrete due to IC
- To understand the role of sample conditioning
- To understand the influence of IC on mechanical properties – strength, modulus, density, volume change
- To understand the influence of IC on durability - transport, FT, corrosion

Concrete Curing

- Before discussing internal curing, let’s review the basics of concrete curing
- ACI-308 – describes “curing” as action taken to maintain moisture & temperature in freshly placed cementitious mixture
- This allows hydraulic-cement hydration, and pozzolanic reactions to occur so potential properties of the mixture may develop
- Increase SCM reaction

Curing and Hydration

- Cement and SCM require water to react
- Initial water-filled pore space ‘fills in’
- Reduced porosity: strength ↑ transport ↓
- If water is not available, reaction stops
Review of Internal Curing

- The pores in a cementitious matrix have different sizes
- Water moves out of the biggest pores first
- Internal curing with LWA is based on two items
  1) water is stored in LWA pores
  2) most pores are larger than pores in paste
- This water can react

Objectives
Influence of Internal Curing
Sample Conditioning
Mechanical Properties
Durability
Case Studies

Review of Internal Curing

- Internal curing causes more cement to react (and more heat to be given off)
- At 3 days we see a difference between an internally cured and conventional mortar
- Internal curing increases reaction
- IC increases with curing time and increases at later ages for higher w/c

Sample Conditioning

- When additional water is not provided, the water activity (RH) decreases
- The water activity (RH) decreases the cement reaction slows or ceases

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March 2020
Curing and Strength

- Comparing the strength of a water cured and dried system
- Internal curing is similar for wet cured, much improved for drying

Mechanical Properties

- LWA concrete has been widely used for nearly a century
  - Hibernia – Offshore in Newfoundland
  - 10,000 - 13,000 psi concrete was used

Mechanical Properties

- Begin by considering that concrete is a composite that consists of three main phases at the ‘mm-scale’
  - Paste
  - Aggregate
  - Interfacial Transition Zone (ITZ)
Interfacial Transition Zone (ITZ)

- In conventional mixtures, the ITZ with LWA is better than with NWA (Holm 1984)
  - The alumina/silica surface of the LWA reacts with CH
  - The modulus between the LWA and the matrix is more similar, therefore there is less cracking
  - Less bleed water at surface of the aggregate
  - The surface is not as 'well defined' so CH can enter the aggregate

Objectives

Elastic Modulus of Concrete

- For paste with the same level degree of hydration, the influence of internal curing is shown below for a typical bridge deck mixture using a shale LWA
- IC mixtures have a lower modulus than a NWA
- Deformations in the LWA are more similar to paste

Elastic Modulus

- Elastic modulus is higher for all conventional mixtures
- Greater difference for the lower w/c mixtures since paste is stronger
Durability of LW Concrete

- USS Selma (1919) – 7,500 ton ship exposed to sea water
  - Low permeability, low corrosion
  - 28 day f’c greater than 4000 psi
  - Tested in the 1980s f’c in excess of 8000 psi
- Sister ship in Powell River, BC (5ksi, 8.7ksi)

Main Principles of Internal Curing

- Additional internal curing water reacts more binder to densify the system
- LWA has a reduce ITZ and reduces percolation
- At low w/c the capillary pores depercolate

BSE/SEM Plain (top) and Internally Cured (bot) (Bentz and Stutzman 2008)
Frequent Question

- But LWA particles are porous, do they not lead to increased transport (permeability)?
- Zhang and Gjorv (1991) reported permeability of high-strength LWC is more dependent on cement paste than LWA
- Pyc et al. (2008) data suggests that once the pores in LWA empty they are not easily resaturated, even upon complete immersion of the specimen
- Henkensiefken et al. (2009) confirmed it is difficult to resaturate low w/c IC except for high vacuum

Transport Tests

- Ionic diffusion — concentration driven, diffusion of ionic species
- Capillary sorption — filling of a dry material mainly due to capillary effects
- Permeation — driven by pressure gradient
- Wick action — drying on one side of element

Water Absorption

- The plots below show how internal curing reduces absorption for several w/c
- 100% LWA has enough water to be equiv. to the chemical shrinkage volume

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Objectives

Influence of Internal Curing
Sample Conditioning
Mechanical Properties
Durability
Case Studies

Water Absorption

- The IC with a w/c of 0.3 behaves like a w/c of 0.23
- This can be explained by the increase in hydration and reduction in porosity

![Water Absorption Graph](image)

Durability Related to Transport

- Salt can be absorbed or can diffuse in the pores
- When chloride reaches the rebar (at sufficient concentration) it can depassivate the steel and leads to corrosion

![Durability Graph](image)

How Long Does it Take for Corrosion to Start?

- The chloride will migrate to the bar over time
- How long does it take to reach a critical level
- Depends on the quality of the concrete and the depth of the reinforcement

![Corrosion Time Graph](image)
Reduced Chloride Ingress

Transport Properties: Electrical Conductivity in Low w/c Mortars

Objectives

Influence of Internal Curing
Sample Conditioning
Mechanical Properties
Durability
Case Studies

Freeze-Thaw Behavior

Objectives

Influence of Internal Curing
Sample Conditioning
Mechanical Properties
Durability
Case Studies

- IC reduces the overall conductivity
- An IC with a w/c of 0.30 behaves like a w/c of 0.23
- As observed with absorption this is due to hydration and reduced porosity

- Prior studies have shown that drying can be beneficial for saturated LWC
- Recall, IC with a sufficiently low w/c, where self-desiccation occurs, pulls water from LWA
- Exposure to F/T at very early ages maybe a concern but over time the LWA empties

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March 2020
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
- Use a sufficiently low w/c where self-desiccation will pull water out of the LWA

Typical FT Behavior

- Studies on IC mixtures made with expanded aggregate are durable with proper air systems (Jones et al. 2013)

Alkali-Silica Reactivity (ASR)
The Mechanisms

\[ 2\text{NaOH} + \text{SiO}_2 + \text{H}_2\text{O} \rightarrow \text{Na}_2\text{SiO}_3 + \text{H}_2\text{O} \]

Gel Will Not Swell If Water Is Not Available In Concrete

Stresses Result In Cracking and Spalling

Alkali Silica Gel

Absorbing Water
Alkali Silica Reaction

- Shin et al. 2010 reported results for 5 systems (reactive, 15 & 28% reactive sand (m), 15 & 28% non reactive sand (N))
- Internal Curing Pros
  - decreases porosity through hydration
  - accommodation space allows gel to form without developing pressure
  - dilution (replaces reactive aggregates)
- Internal Curing Cons
  - Higher RH/moisture in paste would enable more ASR reaction to occur

Objectives

- Influence of Internal Curing
- Sample Conditioning
- Mechanical Properties
- Durability
- Case Studies

Alkali Silica Reaction

- Shin et al. 2010 reported on 5 systems
  - Reactive (R) – Most reactive and expansive
  - Non Reactive Aggregate Replacement at 15 & 28% (m) – Reduces expansion due to dilution
  - Internal Curing – LWA Replacement at 15 & 28% (N) – more effective even than non-reactive aggregate
  - LWA provides space for expansive gel to form
  - 15% replacement is CS volume

Bloomington Indiana

- Implemented in Monroe County Bridges in 2010
- Bridges cast using conventional ready mix concrete and conventional procedures
- Shows that this is a “very off the shelf technology” – replace some FA with LWA
**Strength Results**

- Similar or slightly higher compressive strength results in Bloomington IN (DiBella et al. 2011)
- Similar strength and fresh properties in Tonowanda NY (shown); Lisle NY (Wolfe et al. 2012)

<table>
<thead>
<tr>
<th></th>
<th>Class HP</th>
<th>Class HP-IC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comp. Str. 7 day</td>
<td>3,040 psi</td>
<td>3,500 psi</td>
</tr>
<tr>
<td>Comp. Str. 28 day</td>
<td>4,677 psi</td>
<td>4,683 psi</td>
</tr>
<tr>
<td>Comp. Str. 56 day</td>
<td>5,043 psi</td>
<td>5,417 psi</td>
</tr>
<tr>
<td>Concrete Density</td>
<td>140.2 pcf</td>
<td>135.2 pcf</td>
</tr>
<tr>
<td>Air Content</td>
<td>5.5 %</td>
<td>6.0 %</td>
</tr>
<tr>
<td>Slump</td>
<td>5.0”</td>
<td>4.5”</td>
</tr>
</tbody>
</table>

**Transport Properties**

*Plain and IC Bridge Decks (Indiana)*

<table>
<thead>
<tr>
<th></th>
<th>W/C</th>
<th>Fine</th>
<th>Coarse</th>
<th>Water</th>
<th>WR</th>
<th>AE</th>
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</thead>
<tbody>
<tr>
<td>Plain</td>
<td>380</td>
<td>0.39</td>
<td>726</td>
<td>152</td>
<td>6.22</td>
<td>0.68</td>
</tr>
<tr>
<td>Int. Cured</td>
<td>380</td>
<td>0.39</td>
<td>313</td>
<td>152</td>
<td>25</td>
<td>0.22</td>
</tr>
</tbody>
</table>

*percentage referred to the cement weight*

**Rapid Chloride Penetration Test**

<table>
<thead>
<tr>
<th></th>
<th>Lisle, NY</th>
<th>NY Tonawanda</th>
<th>Menneou Cc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (day)</td>
<td>Charge (Cadmium)</td>
<td>Charge (Cadmium)</td>
<td>Charge (Cadmium)</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>
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<tr>
<td>91</td>
<td>357</td>
<td>362</td>
<td>308</td>
</tr>
</tbody>
</table>
Visual Inspection of the Plain Bridge Decks after 20 Months

• Plain bridge deck exhibited several cracks

Visual Inspection of the IC Bridge Decks after 20 Months

• The internally cured bridge deck mixture resulted in no visible cracks.

Review of Main Topics

• Internal curing is simply using LWA as a reservoir to ‘hide’ water
• Internal curing hydrates more cementitous materials
• Internal curing reduces porosity (due to hydration) and percolated ITZ
• In general, similar compressive strength observed (coarse aggregate same, part of fine aggregate replaced)
• Internal curing reduces fluid transport (absorption/diffusion) reducing corrosion
• Internal curing is being implemented
Conclusions

- Strength - Generally similar due to increased hydration counteracting potentially lower strength aggregate
- Modulus - Lower, but beneficial, as it allows restrained concrete to stretch easier
- Freeze-Thaw - Generally similar to a plain concrete with proper air entrainment
- ASR can be reduced due to dilution
- ASR and sulfate attack reduced due to space accommodation
- Reduced cracks - Cracks are the Achilles heal of corrosion

Conclusions

- Transport Properties – Similar or improved since porosity decreases/ITZ depercolates
  - Lower absorption
  - Similar or lower diffusivity (Cl−)
  - RCPT & electrical properties are similar or up to 30% better
  - Artifacts associated with current testing methods such as cut surfaces in samples, vacuum saturation, conductive aggregate
- IC concrete has the ability to reduce the chloride transport which has implications on the time to corrosion and service life.

Acknowledgements/Disclaimer

- These slides were developed as a part of a series for the Expanded Shale, Clay and Slate Institute by Jason Weiss.
- These materials are provided as general information and do not constitute legal or other professional advice.
- Any use of this information in the design or selection of materials for practice should be approved by the project owner and engineer-of-record.