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

Most Common Types of External Curing

- Water Ponding, Sprinkling, Burlap: Supply Additional Water
- Curing Membranes: Reduce Loss of Water to the Environment

http://express.howstuffworks.com/exp-exoskeleton.htm
Are There Other Options

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

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

Objective
Concept
Internal and External Curing
Proportioning Principles
Example
Aggregate Properties

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

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Where Do We ‘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
### 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
Proportioning Principles

- Aggregate Spacing – the LWA need to be well-spaced to allow water to reach all the paste
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Internal Curing Water Distribution

- Need paste to be within close proximity to LWA
- Fine aggregate protects more of the paste than the coarse lightweight aggregate
- Bentz from NIST has developed a HCSS model
- ESCS FLWA works well

Proportioning Principles
Chemical Shrinkage

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

Self Desiccation and Setting

Chemical Shrinkage vs. Time

- Chemical shrinkage occurs as cement hydrates
- Occurs in all cements
### 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

### Summary So Far

- **Curing** – provide or maintain water to enable the cement to hydrate
- Most curing is external – Here we will ‘hide’ water in the porous LWA
- IC is more important for low w/c mixtures with supplemental cement
- Self-desiccation occurs when water is consumed by the hydration reaction (CS) emptying pores

### Mixture Proportioning for IC

- Concept of proportioning mixtures for internal curing is simple
- 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 cementious
- 6 bag mixture – 564 lb/yd³
- IC Water = 7*564/100 = 39.5 lb/yd³
- Assume Aggregate with 15% Absorption
- Mass\textsubscript{LWA-OD} = 39.5/15% = 263 lb/yd³
- Very Good First Approximation

Conventional Concrete

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

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<th>Conventional</th>
<th>Density</th>
<th>Volume</th>
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<tr>
<td>Air</td>
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<td>1.62</td>
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</table>
Example for One Yard of Concrete With Internal Curing

- Mass_{LWA} = 263 lb
- Vol_{LWA} = 263/(1.52*62.4) = 2.78 ft^3
- Vol_{F. Agg} = 9.05 – 2.78 = 6.28 ft^3
- Mass_{F. Agg} = 6.28*2.68*62.4 = 1051 lb

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<th>Internally Cured</th>
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<tr>
<td>Cement</td>
<td>564.0 lb/yd^3</td>
<td>564.0 lb/yd^3</td>
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<td>Water</td>
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<tr>
<td>Coarse Aggregate</td>
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</tr>
<tr>
<td>Fine Aggregate</td>
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</tr>
<tr>
<td>Lightweight Aggregate</td>
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</table>

Objective

- Concept Internal and External Curing
- Proportioning Principles
- Example
- Aggregate Properties

Volume Proportions

- 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
  - 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)
    - $\alpha_{\text{Max}}$ 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.
  - The product of three terms
    - $M_{\text{LWA}}$ – 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/yd$^3$, Chemical shrinkage of 0.07 ml/g$\text{cem}$, and a LWA with 15% porosity (determined from 24 hr absorption)
  - Assume $\alpha_{\text{max}} = 1$ and $S = 1$
Mixture Proportioning for IC

- How much lightweight aggregate should we use?
- Three Basic Methods
  - Rule of Thumb
    7 lbs per 100 lbs cement
  - Simple Calculation: Supply vs Demand
  - More Complicated Features
    - Account for time dependent absorption
    - Account for desorption (water release)
    - Account for features other than CS

Mixture Proportion Equation

- Bentz Equation (1999)
  \[ M_{LPA} = \frac{C_f \times CS \times \alpha_{sat}}{S \times \phi_{LPA}} \]

- Castro modified the expression. While the concept is the same, accounts for time of saturation \( t^a \) and the desorption of the aggregate \( \psi \) (discussed later).

This may be needed for some aggregate but since \( \psi \) is high (>85%) for ESCS materials small correction likely not needed.
**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

**Lightweight Aggregates Have a Long History of Use in Concrete**

- 126 - Pantheon, Rome, Italy
- 1929 – First high rise “Haydite LWA”
- 1990’s Hibernia Offshore Platform – St. Johns, Newfoundland

**Manufacture of LWA**

- Expanded surface shale, clay or slate
- Bloat (expand) when heated, entrap gas
**Bloating**

- Depends on composition
- Occurs during heating
- Bricks – undesirable; heated so gases evolve before the brick becomes glassy
- Gas trapped in the process (CO₂, SO₂)
- May be improved with additives
- The secret - pores that are left behind are essential for internal curing

**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

**Which Aggregates to Use**

- Particle shape and surface texture influence the finished properties, the workability and other aspects
- Aggregates will have a different absorption capacity, density and other features
- Castro et al. (2010) however observed that after testing a wide range of expanded aggregate in North America that all worked for IC
### Aggregate Testing

**Objective**

- 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 Gravimetric Analyzer, Q5000

### Grading/Specific Gravity

**Objective**

- Grading of the LWA can be measured like a conventional sand
- Grading will influence workability and paste content
- In general a wide range of gradations will work for internal curing
- This can be similar to or improve existing sand gradings
- Specific gravity is used to determine the volume (mass) replacement of the fine aggregate with fine lightweight aggregate

### LWA Absorption as function of time

**Objective**

- The 14 most used fine LWA in the U.S. and a European LWA were tested
- Absorption test was developed to measure absorption as a function of time.
- The volume of water absorbed was monitored for 48 hours by determining the amount of water at each age needed that had been absorbed
LWA Absorption over time

- Rapid initial absorption, slows over time
- 24 hour absorption values between 6 to 30%
- Magnitude depends on the source

LWA Absorption Over Time

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

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).

Desorption: Vapor Sorption Testing

- The mass of the sample is recorded as the relative humidity around the sample is changed.
- Larger pores empty at higher relative humidity.

Ideal Desorption Behavior

- Blue line shows typical LWA with over 85% of the absorbed moisture given back to the matrix.
- Red line shows a less desirable porous material.
Desorption of Expanded LWA

Objective
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• 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

CASTRO ET AL. 2009

ASTM C1761 Desorption

Objective
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• 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

Characterizing LWA Porous Plate Apparatus

Objective
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Internal and
External Curing
Proportioning
Principles
Example
Aggregate
Properties

• An alternative to characterize LWA at high RH where desorption does not work very well
• Used in soil science
• Referred to as a pressure plate

POUR-GHAZ ET AL. 2010
Characterizing Available ESCS LWA Used in North America

**Objective**

- Aggregates release substantial moisture at high relative humidities

<table>
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<th>ESCS</th>
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</table>

**Proportioning Principles**

1. LWA properties - Gradation, specific gravity, absorption and desorption
2. Proportioning Principles - LWA (Supply); chemical shrinkage (Demand)
3. In general, 7lb of water is needed for every 100 lb of cement (good rule of thumb)
4. Desorption of aggregate is a ‘newer’ property but it is easy to measure with salt

**More Information**

- Internal Curing of High Performance Concretes - Laboratory and Field Experiences, ACI SP-256, Eds. D. Bentz and B. Mohr, American Concrete Institute, CD-ROM, 2008.
- Friggle, T., and Reeves, D., Internal Curing of Concrete Paving Laboratory and Field Experiences, ACI SP-256, Eds. D. Bentz and B. Mohr, American Concrete Institute, 71-80, CD-Rom, 2008.
- The Economics, Performance, and Sustainability of Internally Cured Concrete, ACI SP-290, Eds. A.K. Schlinder, J.G. Grygler, and W.J. Weiss, American Concrete Institute, CD-ROM, 2012 (papers by Bastes, Streeter, DiBella)

http://www.escsi.org/ContentPage.aspx?id=205&ekmensel=1b7c39fc_61_74_205_1

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 – Gradation, 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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