Toward Long Lasting, Durable Bridge Decks

Acknowledge Contributions from Ron Walker, Neal Carboneau, Tony Zander, Tommy Nantung

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Salt Usage Abounds

• Before 1940’s, removal of snow and ice used plowing, salt and cinders
• 1950-60’s bare pavement policy implemented
• 1970’s deicing salts become widely used to maintain clear pavements
• US - salt is the most widely used deicing material with 8-12 million annual tons
Durability Related to Transport

- Salt can be absorbed or can diffuse in the pores and when it reaches the rebar it can depasivate the steel and cause corrosion.
How Long Does 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

![Graph showing chloride migration over time](image)

- Chloride At the Bar
- Critical Value
- Time
Various Strategies to Extend Time

- Higher Strength
- Sealers
- Overlays
- Coated Bars
Reducing Transport

- Strength is related to w/c; transport properties are even more strongly influenced
- WRA, SCM, SF all densify concrete
- Why is this the case and what else may change

After ACI 318 From Hover 2003

Diagram showing the relationship between water/cementitious materials ratio and strength.
A Pore Structure Argument for Why We Want Higher Strength Concrete

- Concrete is a Porous Material
- Two Types of Pores
  - Capillary Porosity (Big Pores)
    Mix Water, Fill in Over Time
  - Gel Porosity (Small Pores - Hydration)
Transport in Large Pores, Shrinkage from Small Pores

- Transport occurs through capillary pores
- Capillary pores – large and connected
- Low w/c - smaller pores – improves strength and improves transport
- But what about the influence on other properties

Assumes 100% Hydration
What Can We Control

- We can control the capillary pores by controlling the w/c (SCM and WRA good)
- We should do this when we can
- Excess water leads to pores and increased transport
- Low w/c = HSC
Higher Strength
Why Do We Want It

• “High-strength concrete is one of the most significant new materials available to federal, state, and local highway agencies.......... With its improved impermeability, durability, and accelerated strength gain ........ an ideal material .....”

• HSC may be slightly more expensive than normal concrete initially, but its greater strength means that HSC bridges may require fewer supports, which could reduce overall costs.
Benefits of High Strength Concrete

**Advantages**
- Higher Strength
- Rapid Strength Gain
- Low Permeability
- Improved Durability
- Costs
- Less Members
- Ease of Placement
- Volume Stability
- Toughness
- Higher Modulus
- Lower Creep

**Disadvantages**
- Costs

It’ll knock your socks off..
And it’ll get’em whiter
True or False: Increasing Strength Improves Performance

.........Misconceptions of Using Lower W/C, Higher Strength Concrete
Is All High Strength Concrete Evil??

Obviously No
High Quality Concretes Can Be Made with High Strength, However Be Prepared for What You Ask For Additional Problems May Arise
Low Transport ...... Between the Cracks

High Strength/Low Permeability is Important If Uncracked

Not so Important once the Section has Cracks

28 Day Comp. Strength (MPa)

<table>
<thead>
<tr>
<th>Specimen Age at First Cracking (Days)</th>
<th>12</th>
<th>9</th>
<th>6</th>
<th>3</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>65% Agg. By Volume</td>
<td>+</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>+</td>
</tr>
<tr>
<td>Problem: Increased Cracking Potential</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Weiss 1997
Advantages

- Higher Strength
- Rapid Strength Gain
- Low Permeability
- Improved Durability
- Costs
- Less Members
- Ease of Placement
- **Volume Stability**
- Toughness
- Higher Modulus
- Lower Creep

**Misconception #1**

Higher Strength Concrete Has Significantly Lower Shrinkage

(Volume Stability)
Measuring Shrinkage
Starting Time is Critical

Weiss et al. 1999

After Aitcin 1999
Advantages

- Higher Strength
- Rapid Strength Gain
- Low Permeability
- Improved Durability
- Costs
- Less Members
- Ease of Placement
- Volume Stability
- Toughness
- Higher Modulus
- Lower Creep

Misconception #2

Higher Strength Has Higher Stiffness and That’s Always Good
Modulus Development

\[ E = 57000 \sqrt{f'_c} \]
Using Hooke’s Law to Compute Stress

\[ \sigma = E \varepsilon \]

Assumed Shrinkage

\[ \sigma = 57000 \sqrt{f'_{c}} \cdot [800 \mu \varepsilon] \]

Weiss et al. 1999
Misconception #3

Higher Strength Has Lower Creep and That’s Always Good

Advantages

• Higher Strength
• Rapid Strength Gain
• Low Permeability
• Improved Durability
• Costs
• Less Members
• Ease of Placement
• Volume Stability
• Toughness
• Higher Modulus
• Lower Creep
Misconception: Lower Creep is Always Beneficial to Performance

Specimen with Lower Creep

Weiss et al. 1999
Misconception #4

Higher Strength is Tougher Than Conventional Concrete

Advantages

• Higher Strength
• Rapid Strength Gain
• Low Permeability
• Improved Durability
• Costs
• Less Members
• Ease of Placement
• Volume Stability
• **Toughness**
• Higher Modulus
• Lower Creep
Strength Versus Toughness

Arnold Strong

Clint Tough
Higher Strength Concrete is More Brittle

Higher Strength is More Like Glass

Weiss et al. 1999
Misconception #5

Higher Early Strength, More Rapid Strength Gain is Always Better

Advantages

- Higher Strength
- **Rapid Strength Gain**
- Low Permeability
- Improved Durability
- Costs
- Less Members
- Ease of Placement
- Volume Stability
- Toughness
- Higher Modulus
- Lower Creep
Reducing Stress to Reduce the Potential for Shrinkage Cracking

Weiss et al. 1999

Normalized Strain Ratio (SRA/Plain) - W/C=0.3

3-Day
7-Day
28-Day
90-Day

Normalized Strain Ratio (SRA/Plain) - W/C=0.3

Drying
Autogenous
Total

Tensile Stress

Strength

Stress Developed

Time of Drying

Reduce Rate
Let's Collect our Thoughts

- People want HSC due to low transport
- HSC can lead to increased cracking
  - Increased shrinkage (typically not measured)
  - No substantial improvement in toughness
  - Reduced ‘creep’ (VE mtl) (reduced relaxation)
  - Increased stiffness
  - Rapid strength gain
- What do we want? low transport and low shrinkage and cracking
- How do we get it? – MP, SRA, Internal curing
Conventional and Internal Curing

External curing

Internal curing

Initial specimen

After curing

- Normal aggregate
- Water filled inclusion
- Cured zone

External water

Water penetration
Internal Curing and Pore Size

- Prewetted LWA provides water to the paste and keeps a large pore full.
- As a result, the pore size that remains full is larger.

A Similar Volume of Water is Depleted

\[ \sigma = \frac{2\gamma \cos \theta}{r} \]
Effect of Internal Curing on Shrinkage

- Remaining water will fill in pores
- LWA Pores > Paste Pores

\[ \varepsilon_p = \frac{S}{3} \left( \frac{2\gamma}{r} \right) \left( \frac{1}{K_p} - \frac{1}{K_s} \right) \]

- Modified version of Mackenzie’s equation
- Larger pores remain saturated - less shrinkage
Quantifying Stress with the Ring Test

\[ \sigma_{Concrete}(t) \bigg|_{r=R_{IC}} = \varepsilon_{Steel}(t)E_s \left( \frac{R_{OS}^2 - R_{IS}^2}{2R_{OS}^2} \right) \left( \frac{R_{OC}^2 + R_{IC}^2}{R_{OC}^2 - R_{IC}^2} \right) \]

Top & Bottom Drying or Perfectly Sealed

Weiss and Furgeson 2001, Hossain and Weiss, 2002
Restrained Shrinkage

• We can see that cracking is more likely than in the sealed case
• Appears logical
• Shrinkage rate decreases and can improve crack resistance
Benefit of Internal Curing

Absorbed water at 8 days (10^-3 gram of water / cm³ of paste)

- Plain - 28 d
- 11.0%k - 28 d
- 25.3%k - 28 d
- Paste w/c = 0.30 - 28 d

Total porosity excluding gel porosity

- 55/0.25 - 28 d
- 55/0.30 - 28 d
- 55/0.35 - 28 d
- 11.0%k - 28 d
- 25.3%k - 28 d
Two Benefits

- Reduced porosity due to increased hydration
- Reduced connectivity of interfacial transition zones
Internal Curing (Best Estimate)

- Started Research
- Planning
- Toll Way option
- 2/2
- Planning
- LTP 2 (in)
- Plan 4
- 3
- 1-2
- Private Intermodal State Pavement

Legend:
- Thinking/Planning
- Bridges in Place
- Pavement in Place
- Repair/Research
Indiana Field Trials - Conventional and IC mixtures in Sister Bridges

- 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 FLWA
Monroe County IN (DiBella et al. 2012)

• Simple Change in Mixture Proportions

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

• IN - Plain Slabs Cracked; IC did not crack

• IC has lower transport properties
Field comparison (Monroe Co In)

Plain bridge deck (Monroe Co.)
1 year after casting.

Internally cured bridge deck (Monroe Co.)
“Crack Free 18+ mos after Casting”
Use by NYDOT (Wolfe et al. 2012)
Comments from the Field

- Lanny Kipp, C&C Ready-Mix, NY
- Didn’t see any issues batching, pumping, or finishing
- Soaking the stockpile for several days, mixing and blending is important for uniform moisture
- Remove the water source the day before to allow free water to drain
- Once the LWA is in the bins, loss to evaporation would be minimal
- LWA weighed first to insure proper amt
- Loading slowed slightly due to the addition of a 4th aggregate
Comments from the Field

- Jeff Jones, Buffalo Redi Mix, NY
- I saw no problems from the producer’s, pumper’s and even the contractor’s perspective
- Air was not an issue pumping
- LWA worked fine in the plant. We ran 200 to 300 yards at a time.
- No issues with it hanging up
- I’ve worked with other low cement mixes and think that this is by far the best option
- I wouldn’t hesitate to do it again
- Manual moisture, cooked 20 mins
Tonwanda (190/I290) NY Results

- Similar RCPT results (DiBella et al 2011) *note cond. LWA in test

<table>
<thead>
<tr>
<th>Time [day]</th>
<th>NY Lisle</th>
<th>NY Tonawanda</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Charge passing</td>
<td>Charge passing</td>
</tr>
<tr>
<td></td>
<td>[Coulombs]</td>
<td>[Coulombs]</td>
</tr>
<tr>
<td></td>
<td>Plain Concrete</td>
<td>IC Concrete</td>
</tr>
<tr>
<td>28</td>
<td>535</td>
<td>423</td>
</tr>
<tr>
<td>56</td>
<td>373</td>
<td>406</td>
</tr>
<tr>
<td>91</td>
<td>357</td>
<td>392</td>
</tr>
</tbody>
</table>

- Similar fresh properties

- Similar Strength (Wolfe et al 2012)
ICHPC Coming to a County Near You for Full Scale Experiments (Carboneau)

- B-30498 SR 933, St. Joseph County, LaPorte District, October 2012
- B-33379 I-69, Grant County, Fort Wayne District, January 2013
- B-34199 US 150, Orange County, Vincennes District, February 2013
Summary

- People want HSC due to low transport
- HSC can lead to increased cracking
- To reduce the potential for shrinkage cracking we can reduce paste volume, use a surface tension modifier (SRA) or use internal curing
- Internal curing – uses prewetted LWA
- Internal curing use is starting to increase
- There are 4 experimental projects occurring across Indiana (other states as well)