Restrained Shrinkage Cracking: Self-Curing Concrete Made using Saturated Lightweight Aggregate

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Outline

• Cracking in Bridge Decks
• Causes of Autogenous Shrinkage
• How LWA helps Mitigate the Problem
• Objectives
• Difference between Sealed and Unsealed Curing Conditions as it relates to autogenous shrinkage
• Experimental Measurements
• Experimental Results
• Conclusion
Cracking in Bridge Decks

- Increase in the use of high-performance concrete in bridge decks because of improved durability
- HPC tends to have increased autogenous shrinkage in sealed conditions

<table>
<thead>
<tr>
<th>Initial Specimen</th>
<th>Initial Bridge Deck Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autogenous Shrinkage Effect</td>
<td>Disconnect Deck</td>
</tr>
<tr>
<td>Restraint Effect</td>
<td>Reconnect Deck</td>
</tr>
</tbody>
</table>
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Causes of Autogenous Shrinkage

- Hydration product volume is smaller than cement and water volume
- Not problematic with higher w/c mixtures
Causes of Autogenous Shrinkage

- Chemical Shrinkage creates vapor filled space
- Pressure Difference between fluid and vapor
- Pressure Difference is the cause of shrinkage

Jensen, 2005
Causes of Autogenous Shrinkage

- Autogenous shrinkage is the shrinkage of the bulk system
- Before set - No stress development due to autogenous shrinkage
- After set - Can have significant stress development due to autogenous shrinkage

Jensen, 2005
Causes of Autogenous Shrinkage

- Chemical Shrinkage
- Autogenous Shrinkage

Pore Volume (ml/g_cem)

Open Void Space

Time (Days)
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How LWA helps Mitigate the Problem

- Water is given up at high relative humidities
- Water leaves the largest pore first
- Pores of the LWA are larger than the pores of the paste

Radlinska et al, 2007
How LWA helps Mitigate the Problem

- Initial consumption of water
- Replenish system with water from LWA

Jensen, 2005
How LWA helps Mitigate the Problem

![Graph showing time (days) vs. pore volume (ml/g_cem) with open void space.]

- Chemical Shrinkage
- Autogenous Shrinkage

Pore Volume (ml/g_cem)

Time (Days)

Open Void Space
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Objectives

• Discuss the difference between sealed and unsealed curing conditions
• Provide experimental measurement of shrinkage performance of mortars with varying LWA volume replacements.
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Sealed and Unsealed Curing Conditions

- Interior Voids are created due to self-desiccation
- Surface Voids are created due to drying
- Sealed curing experiences internal voids only
- Unsealed curing experiences both internal and external voids

(a) Sealed  (b) External Drying Only  (c) Unsealed

Radlinska et al, 2007
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## Experimental Measurements

<table>
<thead>
<tr>
<th>LWA (%)</th>
<th>Cement (kg/m³)</th>
<th>Water (kg/m³)</th>
<th>Fine Aggregate (kg/m³)</th>
<th>LWA (kg/m³)</th>
<th>Additional Water Provided by LWA (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>728</td>
<td>218</td>
<td>1418</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3.8%</td>
<td>728</td>
<td>218</td>
<td>1319</td>
<td>60</td>
<td>6</td>
</tr>
<tr>
<td>7.3%</td>
<td>728</td>
<td>218</td>
<td>1230</td>
<td>114</td>
<td>12</td>
</tr>
<tr>
<td>11.0%</td>
<td>728</td>
<td>218</td>
<td>1135</td>
<td>172</td>
<td>18</td>
</tr>
<tr>
<td>14.3%</td>
<td>728</td>
<td>218</td>
<td>1050</td>
<td>223</td>
<td>23</td>
</tr>
<tr>
<td>18.3%</td>
<td>728</td>
<td>218</td>
<td>950</td>
<td>283</td>
<td>30</td>
</tr>
<tr>
<td>25.3%</td>
<td>728</td>
<td>218</td>
<td>808</td>
<td>369</td>
<td>39</td>
</tr>
<tr>
<td>29.3%</td>
<td>728</td>
<td>218</td>
<td>667</td>
<td>455</td>
<td>48</td>
</tr>
<tr>
<td>33.0%</td>
<td>728</td>
<td>218</td>
<td>567</td>
<td>525</td>
<td>54</td>
</tr>
</tbody>
</table>

- As more LWA is added more water is available
- Aggregate volume remained constant at 55%
Experimental measurements

- Internal Relative Humidity
- Free Shrinkage C157 with first 24 hours
- Restrained Shrinkage C1581

Sant, 2007
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Internal Relative Humidity

- Equation relating RH to pore size
- Equation relating pore size to shrinkage

\[
r = \frac{-2\gamma \cos(\theta)}{\ln(RH)} \cdot \frac{V_m}{RT}
\]

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

Henkensiefken et al., 2008
Sealed Free Shrinkage

Henkensiefken et al., 2008
Sealed Restrained Shrinkage

Henkensiefken et al., 2008
Unsealed Free Shrinkage

Henkensiefken et al., 2008
Unsealed Restrained Shrinkage

Henkensiefken et al., 2008
Conclusions

• Specimens with a larger replacement volume of LWA maintained a higher internal humidity

• Specimens with a larger volume of LWA showed a reduction in rate of shrinkage and absolute shrinkage

• The time to cracking is prolonged for mixtures with an increasing replacement volume of LWA
Acknowledgements

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Questions