Types of Cracking and Influencing Causes

TRB Cracking Webinar May 25, 2016

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Many Potential Types of Cracks

- Plastic shrinkage
- Drying shrinkage
- Restrained thermal & drying
- Subsidence
- Delayed joint cuts
- Shear crack
- Cracks at kicker joints

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Volume Changes That Influence Cracking

1. Chemical/autogenous shrinkage
2. Plastic shrinkage, subsidence
3. Drying shrinkage
4. Thermal expansion/contraction
5. Creep

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Chemical Shrinkage of Hydrating Cement

- Chemical shrinkage occurs due to the reduction in absolute volume of solids and liquids in the hydrating paste.
- Chemical shrinkage continues to occur as long as cement hydrates.
- After initial set, the paste resists deformation, causing the formation of voids in the microstructure.

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Chemical Shrinkage is not just limited to cement hydration

- Occurs when the volume of the products of chemical reaction is smaller than the sum of the initial reactants.
- Eg. 0.50L of Ethanol mixed with 0.50L of water will only result in 0.96L of fluid (Wikipedia).
- Or 0.5L of cement mixed with 0.5L water, if well hydrated, will result in ~0.94L of hydrated solid material.
Autogenous Shrinkage

- Autogenous shrinkage is the dimensional change of concrete caused by chemical shrinkage.
- When internal relative humidity is reduced below a given threshold (i.e., extra water is not available), self-desiccation of the paste occurs, resulting in a uniform reduction of volume.
- Becomes significant at low water/cement ratios, less than about 0.42
Chemical and Autogenous Shrinkage of Cement Paste

ASTM C1608

Becomes significant at low w/cm typical of HPC mixtures

ASTM C1698

Figure from PCA Design & Control of Concrete Mixtures

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Volumetric Relationship Between — Subsidence, Bleed Water, Chemical and Autogenous Shrinkage

Before set

After set
Window of Finishability or Window of Plastic Shrinkage Cracking

Penetration Resistance

<table>
<thead>
<tr>
<th>Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4MPa (500 psi)</td>
</tr>
<tr>
<td>27.6MPa (4000 psi)</td>
</tr>
</tbody>
</table>

Figure from K. Hover

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From initial float until time of set and application of curing
Plastic Shrinkage Cracks on HPC Bridge Deck
(delayed set & lack of evaporation control)
Sprayed on Evaporation Retarder
Fog Misting from Upwind Edge

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One short plastic crack near edge of deck
Epoxy Repair of plastic shrinkage cracks on new bridge deck (~1991)

good concrete between the cracks
Drying Shrinkage and Cracking

Cracking results from restraint.

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Influence of Wet Curing on Shrinkage

More curing reduces on-set and rate of drying shrinkage

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Drying Shrinkage and Water Content

Specifying min. cement contents prevents producer from reducing unit water content of mixture.

Use of water reducers will reduce shrinkage.

Less shrinkage with more aggregate (better packing & larger max. size agg.).

Figure from PCA Design & Control of Concrete Mixtures.
Thermal Cracking

• Can result from excessive temperature gradients resulting from heat of hydration of cement.

• Can also result from restraint from adjacent cool temperature components preventing contraction on cooling (often seen on barrier walls dowelled into previously placed base slabs, with cracks starting from the bottom).
Heat Rise in Concrete Due to Hydration of Cement

As concrete heats up it swells, then it contracts on cooling back to ambient temperature----inducing tensile stresses

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Thermal Length Change

- Concrete contracts about $6 \times 10^{-6}/^\circ F$
- $(10 \times 10^{-6}/^\circ C)$ on cooling.
  (varies with volume and type of coarse aggregate)
- The outside cools faster than the core so tensile stresses can cause cracks if the thermal gradient $> 35^\circ F (20^\circ C)$
- With bridge decks, the substructure is cool and similar gradients will induce transverse cracking
Water Leaking Through New Bridge Deck Due to Transverse Cracks (thermal + shrinkage)

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Concrete Temperature development for different HPC Bridge Decks (MTO 2012)

MTO HPC is 50 MPa and <1000 coulombs at 28 days

High crack density

Low transverse crack density
Two HPC Bridge Decks with high and low crack density (MTO 2012)

We are developing a semi-adiabatic test for qualifying mixes that measures thermal and autogenous shrinkage.
Restrained thermal cracks in mass retaining wall
Saw Cuts 1/3 depth of 400 mm (16 inch) thick airport pavement
Causes of Random Cracks near saw-cut joints

- Crack follows and/or crosses joint. May be due to A or B, C or sawing joint late after crack had already formed.
- Crack ran ahead of sawing to slab edge due to late cutting.
- Infiltration of incompressible material from shoulder.
- Sealant reservoir (groove) or crack inducer not deep enough to form plane of weakness at desired joint location.
- Joints at intersection were not lined up. Crack occurs to complete omitted continuity.

ACI C504

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Minimizing Cracks

a) Protect the fresh concrete from plastic shrinkage cracking

b) Do not specify minimum cement contents that increase unit water content of mixtures. Keep the concrete sufficiently moist after set to lower early drying shrinkage

c) Minimize thermal cracking due to temperature gradients (i.e. control heat evolution from concrete mixture & protect from cold temperatures or from the hot sun)

d) Proper timing and depth of joints
Reducing Shrinkage Cracking: Materials, Testing, and Specification

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Motivation

• Transverse cracking in 100,000+ bridges
• 62% of DOT’s consider cracking as a problem
• Cracks shorten service life, increase maintenance cost, and accelerate corrosion

Here we see cracks spaced at 0.8 m On the approaches to a bridge
Reality is a Bit More Complex

\[ d\varepsilon(t, \xi) = \frac{d\sigma(\xi)}{E_\sigma(\xi)} + d\varepsilon_{SHR}(\xi) \]

\[ d\varepsilon(t, \xi) = \frac{d\sigma(\xi)}{E_\sigma(\xi)} + d\varepsilon_{SHR}(\xi) + d\sigma(\xi) \left[ \frac{\phi(t, \xi)}{E_{28}} \right] \]

Weiss et al. 1998, JEM
Outline

• Materials Approaches to Reduce Cracking
  – Aggregate Volume
  – Shrinkage Reducing Admixtures
  – Internal Curing

• Tests to Evaluate Shrinkage and Cracking
  – New Shrinkage Tests
  – Dual Ring Test Has Merit and is Fast

• Performance Based Specifications
  – Model Based on Risk of Cracking
Shrinkage of Concrete Constituents

- Shrinkage - Volumetric Change Associated With A Loss Of Water
- Aggregate Generally Does Not Shrink (In the US)
- It’s the Paste That Shrinks
Shrinkage is a Paste Property

Shrinkage (% of Paste) vs Aggregate Volume (%)

Stiffer Aggregate More Effective In Restraining Paste Shrinkage

\[ \varepsilon_{Concrete} = \varepsilon_{Agg} \cdot V_{fAgg} + \varepsilon_{Paste} \cdot V_{fPaste} \]

\[ \varepsilon_{Concrete} = \varepsilon_{Paste} \cdot (1 - V_{fAgg})^n \]
Shrinkage and Paste Volume

- w/c = 0.42; No Air; 564 lb/yd³ Cement

5 to 6% Shrinkage Per 1% Paste Change

Assuming 2.3% Entrapped Air
Kelvin Young Laplace Theory

- Concrete is Made of Little Tiny Holes, Called Pores
- Size of the Pore Matters
- Pressure ($p_{\text{cap}}$) is related to surface tension ($\gamma$) and inversely related to radius of the meniscus that forms ($r$)
- Big Pores – Low Pressure, Low Shrinkage
- Water is a clingly material – High Shrinkage

\[ p_{\text{cap}} = -\frac{2\gamma \cdot \cos \theta}{r} \]
SRA and Surface Tension

• To reduce shrinkage we reduce pressure, this means we either... reduce surface tension

• 1983 – Japan
• 1997/99 – US
• US Product 1999

\[ P_{cap} = -\frac{2\gamma}{r} \]
Shrinkage Reducing Admixtures

The graph shows the age at which a crack first occurs for different w/c ratios and the use of SRA. For a w/c ratio of 0.50, the age at first crack is around 28 days without SRA and 14 days with SRA. For a w/c ratio of 0.30, the age at first crack is around 21 days without SRA and 7 days with SRA.
Internal Curing Approach

- To reduce shrinkage we reduce pressure, we can increase the size of the pore

\[ P_{\text{cap}} = -\frac{2\gamma}{r} \]

Castro et al. 2009
Shrinkage Cracking and IC

- Restrained tests results on IC concrete (explained in more detail later)
- Increasing the use of LWA leads to a great reduction in cracking
- 24% LWA is typ. des.

Henkensiefken et al. (2008)
Field Trials and Applications

• Becoming More Widely Used
• INDOT, NYDOT, IL Tollway Cities and Towns, Others
• Reducing Cracking
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Laboratory Tests to Measure Shrinkage

- ASTM C-157
- ASTM C-341

\[ \varepsilon = \frac{\Delta l}{l_0} \]
Measuring Shrinkage
Starting Time is Critical

![Graph showing shrinkage strain vs water to cement ratio for different aggregate volumes and autogenous shrinkage at 24 hours.]

- Constant Aggregate Volume (70%)
- Constant Aggregate Volume (65%)
- Autogenous Shrinkage at 24 Hours

New Test – ASTM C1698
Stress Development Approach

- 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

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

![Graph showing residual tensile stress and specimen temperature over age of specimen.]

- IC HPC 3
- IC HPC 3 - Temp.
- HPC 3
- HPC 3 - Temp.
Outline

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  – Internal Curing

• Tests to Evaluate Shrinkage and Cracking
  – New Shrinkage Tests
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  – Model Based on Risk of Cracking
Including ‘Random Variation’

Graph showing the relationship between stress or strength (MPa) and specimen age (days). The graph includes a region labeled 'Predicted Age of Cracking'.
Results Of An Alternative Approach to Consider Variability in Shrinkage

- Plotted the percentage of specimens cracked by a specific age
- Results of 10,000 simulations
- Can quantify risk or total probability

![Graph showing Specimens Cracked (%) vs. Age of the Specimen (Days)]

- Deterministic Age of Cracking
- $P_{\text{CRACK}}$
- 5% Probability
Toward a Shrinkage Specification

- Shrinkage can be related to cracking potential and this simple approach begins to relate a simple test to performance.
A Summary of Thoughts

• Concrete Shrinks but We Have Three Defenses
  – Aggregate Volume – Change Shrinking Proportion
  – Shrinkage Reducing Admixtures – Change Fluid
  – Internal Curing – Change Pore Emptying

• Current Tests are Lacking However
  – Dual Ring Test Has Merit and is Fast

• Specifications can Be Performance Based
  – Model Based on Risk of Cracking
Thank you
Are There Any Questions

Jason Weiss, Edwards Distinguished Professor
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Practical Applications to Minimize Cracking

Donald Streeter, P.E.
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
- ASCE 2013 report D+
- Colbert Report
  - “Tiny Triumphs”
Constraints

- Maintenance / preservation vs. Reconstruction?
- Accelerated construction / traffic demands?
- Durability / Service life expectations?
  - Band-aid fix
  - Moderate service extension
  - Longer term service

What is your goal???
How will you achieve your goal???
Cracking - Design

- Flexure
  - simple vs. continuous
  - span length
- Beam type
- Geometry, skew
Cracking - Materials

- Materials
  - water demand / characteristics
- Mixtures
  - interactions
Cracking - Construction

- Construction
  - Time of placement, environmental conditions
  - Rate of placement
  - Curing
    - timing, duration
Where do we see cracking

- Large elements / Mass placements
- Accelerated construction
- Multi-span continuous decks
- Large surface areas / flatwork
- Long / thin placements

Potentially everywhere!

Causes

- Shrinkage, Autogenous, Thermal
- Result of: design, materials, batching, environment, placing, finishing, curing
Crack mitigation practices as seen around the country...
Performance specification

- Owner defined parameters
  - Life cycle analysis
  - Consider permeability, strength, cracking
- QC Plan
  - Contractor defines
    - process, materials, mixtures
    - crack repair / treatment plan
    - Maintenance schedule
Mass Concrete

- Treating more placements as “Mass”
Mass Concrete

- Means to minimize cracking:
  - Mixture design
    - High pozzolan content
    - 30% – 70% SCM’s
  - Low heat cements
  - Placement size / shape
Mass Concrete

- Means to minimize cracking (con’t):
  - Cooling methods
    - Plastic PCC temp
    - Internal cooling
  - Environmental “controls”
  - Temperature monitoring
    - Max temp 160F
    - Max temp differential 35F
Mass Concrete

- Thermal Control Plan requirements
  - Mixture dependant
    - changes in mix = new TCP development
  - Method / duration of curing
  - Thermal development analysis
  - Temperature monitoring
    - sensor type / locations
    - Monitoring system plan / recording / reporting
  - Corrective action plan to control temp
Accelerated Concrete

- Precast / accelerated closures
- CIP accelerated PCC

- Shrinkage requirements
- Use longest set period allowed by work schedule
Superstructures

- HPC initiative in 1990’s
  - Placing under improved environmental controls
  - Mix controls – strength, temps, etc…
  - Immediate wet curing – 30 minutes from placement
  - Extended wet curing – 14 days

- Internal curing
  - Use of l-w fine aggregates as a replacement for sand
  - 30% substitution by volume
IC Specification - construction

- Stockpile establishment
- SSD condition –
  - minimum 15% absorbed moisture
  - presoak minimum of 48 hours
  - Requires additional bin
- Handling, delivery, placement
  - Follows traditional practice
  - Similar characteristics
I-87 / Route 9 and Trout Brook
## Comparison – I-87

<table>
<thead>
<tr>
<th>Concrete Type</th>
<th>7 day (psi)</th>
<th>14 day (psi)</th>
<th>28 day (psi)</th>
<th>28 day Strength (psi)</th>
<th>RCP Coulombs</th>
<th>F/T % loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPC</td>
<td>4420</td>
<td>5215</td>
<td>5910</td>
<td>569</td>
<td>1000</td>
<td>1.0</td>
</tr>
<tr>
<td>HPC-IC</td>
<td>4590</td>
<td>5790</td>
<td>6750</td>
<td>672</td>
<td>383</td>
<td>1.1</td>
</tr>
</tbody>
</table>

**% Improvement**
- 3.8%
- 11.0%
- 14.2%

*Cracking – no transverse cracking, map cracking SB Barriers – used HPC NB, HPC-IC SB, both show cracking*
Geometry

- Large surface areas
  - Construction practices
- Long – thin placements
  - SRA’s
  - Fibers
Minimizing cracking

- Consider design:
  - Size, geometry, staging
- Materials selection to:
  - Minimize shrinkage, manage temps
- Construction practices:
  - Placement times
  - Environmental conditions
  - Placement, finishing, curing
  - Protections during / after curing

No 2 days of placement are the same!
Thank you