Shrinkage and Cracking: Test Methods, Materials Innovations and Improved Specifications

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The 1980-90’s usher in Higher Strength

• “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
Benefits of High Strength Concrete

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**Disadvantages**
- Costs

It’ll knock your socks off..
And it’ll get’em whiter.
Asking for Higher Strength with the Best of Intentions....

True or False:
Increasing Strength Improves Performance
Asking for Higher Strength with the Best of Intentions….

True or False: Increasing Strength Improves Performance

……….Misconceptions of Using Lower W/C, Higher Strength Concrete
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
Let's Look at the Fundamentals

• What causes cracking?

Initial Specimen

Initial Pavement
Bridge Deck or Industrial Floor
Conceptual View of Stress Development

Initial Specimen

Shrinkage Effect

Restraint Effect

Initial Pavement
Bridge Deck or Industrial Floor

Disconnect it From The Subgrade

Apply Force to ‘Simulate’ Subgrade

Maintain “Zero” Displacement

(In real-life actually not complete but…)
Condition for Cracking

Stress That Develops To Maintain Constant Length

Material Resistance i.e., ‘Strength’

Age of Cracking

Time of Drying

Stress Level
Reality is a Bit More Complex

Initial Specimen

Shrinkage Effect

Restraint Effect

Creep/Cracking Effect

Stress Relaxation

Stress Relaxation

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

Calculated Tensile Stress (MPa)

Age of Specimen (Days)

Weiss et al. 1998, JEM
Let's Look at the Fundamentals

• What causes cracking? - Concrete Shrinks, Stress Develops if Restrained

• Why does concrete shrink?
Shrinkage of Different Cement Based Materials

- Shrinkage - Volumetric Change Associated With A Loss Of Water

![Graph showing measured shrinkage over drying time for concrete.](chart.png)
Shrinkage of Different Cement Based Materials

- Shrinkage - Volumetric Change Associated With A Loss Of Water
- Aggregate Generally Does Not Shrink (In the US)
Shrinkage of Different Cement Based Materials

- 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

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

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

- w/c = 0.42; No Air; 564 lb/yc³ Cement
- 5 to 6% Shrinkage Per 1% Paste Change
- Assuming 2.3% Entrapped Air
Let's Look at the Fundamentals

• What causes cracking? - Concrete Shrinks

• Why does concrete shrink? Loss of water from the paste (we will come back to this)

• More Importantly, Controlling Aggregate Volume is the First Key Step not w/c

• Loss of water from the paste you say…. Let's talk theory
Kelvin-Laplace-Young-Gauss

- Some insights on the factors influencing shrinkage

\[
p_{cap} = -\frac{2\gamma \cdot \cos \theta}{r}
\]

\[
\ln\left(\frac{p}{p_0}\right) = \ln(RH) = -\frac{2\gamma \cdot \cos \theta \cdot V_w}{r \cdot RT} = p_{cap} \frac{V_w}{RT}
\]

Thomas Young (1773 – 1829)
Carl F. Gauss (1777 - 1855)
Marquis de Laplace (1749 - 1827)
Lord Kelvin (1824 - 1907)
Lets Make This Useful

• Concrete is Made of Little Tiny Holes, Called Pores
• Size of the Pore Matters
• Pressure ($p_{cap}$) is related to surface tension ($\gamma$) and inversely related to radius of the meniscus that forms ($r$)

$$p_{cap} = -\frac{2\gamma \cdot \cos \theta}{r}$$

• Big Pores – Low Pressure, Low Shrinkage
• Water is a clingly material – High Shrinkage
Lets Look at the Fundamentals

• What causes cracking? - Concrete Shrinks

• Why does concrete shrink? Loss of water from the paste, but the size of the pores matters

• Can I Reduce Shrinkage by knowing KLYG
Using the KLPG Theory For Good

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

• 1983 – Japan
• 1997/99 – Weiss
• US Commercial Product in 1999 from Grace

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

![Graph showing the effect of water-cement ratio (w/c) and shrinkage reducing admixtures (SRA) on the age at first crack. The graph compares 0.50 w/c and 0.30 w/c with and without SRA, indicating a delay in the age at first crack in the presence of SRA.](image-url)
Some SRA Observations

- $w/c = 0.30$
- $w/c = 0.30 + 5\%$ SRA
Using the KLPG Theory For Good

• To reduce shrinkage we reduce pressure, this means we either... reduce surface tension and/or we increase the size of the pore.

• Not really impacted by w/c .. Long story

• We want to keep pores filled up

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

Castro et al. 2009
Dry LWA Absorbs Water

Wet LWA Gives off Water

Things Professors Think About

Trtik et al. 2010
What is Internal Curing?

• Its Concrete 101 with a twist
• Add water to cure concrete properly
• The twist... the water comes from inside the concrete
• Water held in LWA or SAP
• Magically released
Lots of Confusion Around Proportioning – It's Really This Simple

- Based on theory
- Need a current set of mixture proportions you really like
- Enter them in orange
- Enter an aggregate’s properties you really like, in green
- Wait 1 second..... voila
Volumetric Proportions
How Do I know If It Works

• Compressive Strength – Generally no change, especially if water cured
• Slump – Generally no change (depends on aggregate FM and angularity)
• Air Content – Generally no change
• Transport Properties – Generally no change or a slight reduction
• Shrinkage Cracking Reduced
Euclid discovers his proofs in the pudding.
Bloomington Indiana Decks - 2010

• At 18 months Plain (3 cracks) IC (none)
• At Year three very small crack in the IC
Internal Curing in Indiana 2013-15

- 10+ ICHPC Bridge Decks (All specs achieved)
- Very limited cracking (at most negative moment region due to settlement – construction Issue)
- Typical INDOT design 18 years
- ICHPC 60-90 yrs

![Graph showing total chloride percentage over duration of years for different materials, with IC-HPC highlighted.](image)
Internal Curing in New York

- 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

Streeter et al. 2012
Internal Curing in Colorado

• 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

Bates et al. 2012
Internal Curing in Texas

- RR intermodal facility
  - 250,000 yd$^3$ of low slump IC material
- CRC Paving for TxDOT
  - 6 months 1 crack, 5.5 years minor drying or plastic shrinkage cracking

Friggle et al. 2008
Internal Curing in Illinois

- Tollway has used a SRA or IC Option
- Very happy with current experience and reduced cracking
- A neighboring states photo to fill the page ...
- No change in construction
Cost Implications

- 1 bridge not three, 5% materials, 1% project
- Sustainable, Safety, Public Benefits
Let's Look at the Fundamentals

• What causes cracking? - Concrete Shrinks

• Why does concrete shrink? Loss of water from the paste, but the size of the pores matters – Kelvin Equation

• Shrinkage Reducing Admixtures – \( (\gamma) \)
• Internal Curing – Supplies Water to increase \( r \)

• What Tests Should I Do?
Laboratory Tests to Measure Shrinkage

- ASTM C-157
- ASTM C-341

$$\varepsilon = \frac{\Delta l}{l_0}$$

<table>
<thead>
<tr>
<th>Time after Drying (Days)</th>
<th>Measured Shrinkage</th>
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$\Delta l$ is the measured shrinkage, and $l_0$ is the original length.
Measuring Shrinkage
Starting Time is Critical

![Graph showing the relationship between water to cement ratio and shrinkage strain.]

- **Shrinkage Strain** (mm/mm x 10^-6)
- **Constant Aggregate Volume (70%)**
- **Water to Cement Ratio**
- **Time (Days)**

Actual Shrinkage
Measuring Shrinkage
Starting Time is Critical

- 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

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

Hossain and Weiss, 2003
The Dual Ring Test
What Does Concrete Data Look Like
Let's Look at the Fundamentals

• What causes cracking? - Concrete Shrinks

• Why does concrete shrink? Loss of water from the paste, but the size of the pores matters – Kelvin Equation
  – Shrinkage Reducing Admixtures
  – Internal Curing

• What Tests Should I Do? Ring, 1698, Dual Ring

• Thoughts on Prediction/Specification
A Simple Model

- Prediction of Stress Development

\[ \varepsilon_{\text{Permit}}(t) = \int_0^t \left[ \left( \frac{1}{E_\sigma(\xi)} + \frac{1}{E_c} \phi(t, \xi) \right) \frac{d\sigma(\xi)}{d\xi} + \frac{d\varepsilon_{\text{Shr}}(\xi)}{d\xi} \right] \cdot d\xi \]

(Weiss, 1997)

- Age/Time Dependent Material Properties

\[ E_c(t) = E_\infty \frac{C_1(t-t_s)}{1 + C_1(t-t_s)} \]

\[ f_{\text{ten}}(t) = f_{\text{ten-}\infty} \frac{C_2(t-t_s)}{1 + C_2(t-t_s)} \]

(McIntosh, 1956)
Including ‘Random Variation’

Predicted Age of Cracking

Stress or Strength (MPa)

Specimen Age (Days)

Stress
Strength
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 percentage of specimens cracked over time with deterministic age of cracking and 5% probability threshold.](image-url)
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
Eager Beavers

- OSU - strong materials group wanting to help improve concrete performance
- Early age/shrinkage mitigation expertise (SRA, IC)
- SCM/Limestone/
- Durability Testing and Prediction
- Sustainability Related Research
- Non Destructive Testing
- Mechanical Properties and Reinforced Concrete
- Service Life Modeling – Corrosion, Freeze-Thaw
- Fluid Movement
Thank you
Are There Any Questions

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