Concrete, It Always Shrinks, Doesn’t It?
Overview

- Types of Shrinkage & Mechanisms
- Why the Concern?  Effects of Shrinkage
- Measuring Shrinkage and Evaluating Its Effects
- Ways of Reducing Shrinkage
- “Shrinkage Wizard” Software
Decrease in either Length or Volume
– may be restricted to the effects of moisture content or chemical changes

(as defined in ACI 116, Cement and Concrete Terminology)
Types of Shrinkage

- Plastic Shrinkage
- Autogenous Shrinkage
- Drying Shrinkage
- Thermal Contraction
- Carbonation Shrinkage
Concrete Shrinkage Basics

- Hydraulic cement concrete contains more water than is necessary for the chemical reactions.

- The additional water is held within a network of voids and capillary pores.

- As this additional water evaporates, the volume of concrete reduces.
Plastic Shrinkage

- Shrinkage that occurs **before** concrete sets

- Occurs when rate of evaporation of bleed water **exceeds** bleeding rate.

- Results in Plastic Shrinkage Cracking.
  - Influenced by environmental conditions, low-bleeding mixes & poor construction practices.
Autogenous Shrinkage

- Shrinkage due to **internal depletion** of water during hydration.
- Combination of chemical shrinkage, microstructure refinement & self-dessication within concrete matrix.
- Function of water-cement ratio (w/c).
- More significant in low w/c, high-performance concrete mixtures.

![Graph showing Autogenous Shrinkage at 24 Hours](image)
Drying Shrinkage Mechanism

- Shrinkage that occurs **after** concrete sets

- As moisture is lost from concrete, meniscus forms at air-water interface due to **surface tension forces**.
Surface tension forces exert **inward pulling force** on the walls of the pores.

Capillary tension leads to shrinkage.

Most significant in pore sizes ranging from 2.5-50 nm.
Magnitude of Drying Shrinkage

- **28 Day**
  - Typically 0.040 - 0.055%
  - Range: 0.025 - 0.080%

- **Long Term**
  - Typically 0.08%*
  - Range: **Low:** 0.04%  **High:** 0.12%

(* also expressed as 800 millionths or 800 microstrains)
Magnitude of Drying Shrinkage

Magnitude dependent on:
- Relative Humidity
- Time

Data from 30-year Study

50% of drying shrinkage at 20 years occurred within 2 months of drying; 80% within first year !!!
Why The Concern About Shrinkage?
Effects of Drying Shrinkage

- Cracking *(if shrinkage is restrained)*
- Joint Opening & Curling in Slabs-on-Grade
- Prestress Loss
- **Overall Impact on Aesthetics, Durability & Service Life**

- Transverse cracking in 100,000+ bridges in the U.S.
- 62% of DOTs consider early-age cracking a severe problem *(NCHRP 1995 Report)*
Early-Age Drying Shrinkage Crack
• Effect of Shrinkage Gradient Through the Thickness

Without Reinforcement

With Continuous Reinforcement
Joint Cracking due to Curling
Joint Nightmare!
Measuring Shrinkage & Its Effects
Master Builders Admixtures

Plastic Shrinkage Test & Related Cracking

- Slab panels with stress risers.
Plastic Shrinkage Test & Related Cracking

- Slab panels *(enclosed)* with forced air.
Drying Shrinkage Test

- ASTM C 157 Length Change Prisms
  *(3 x 3 x 11 in.)*
ASTM C 157 procedure does not capture full shrinkage, because initial reading taken at 24 hours does not account for early-age autogenous shrinkage, especially in low w/c concretes.

Aitcin 1998
When Will Shrinkage Cracking Occur?

Material Resistance i.e., ‘Tensile Strength’

Age of Cracking

‘Induced Stress’
Stress That Develops To Maintain Constant Length Under Restraint

Stress Level

Time of Drying
Creep effects cause relaxation and reduce actual tensile stress in concrete

- Increases time to cracking

Graph showing:
- Stress Relaxation
- Stress Based on Hooke’s Law
- Stress in Specimen

Graph axes:
- Calculated Tensile Stress (MPa) on the y-axis
- Age of Specimen (Days) on the x-axis

Age: 0 4 8 12 16 20 24 28
Stress: 0 2 4 6 8 10 12

Graph legend:
- Red line represents stress relaxation
- Blue line represents stress in specimen
For routine evaluations as a basis for material selection, need scientifically sound but “simple” test methods.

- Shrinkage
- Modulus of elasticity
- Tensile strength
- Tensile creep
Restrained Ring Test: Proposed to ASTM
Cracking Resistance

Steel Ring Strain (µ-strain) vs. Time After Initiation of Drying (days)

-140  -120  -100  -80  -60  -40  -20  0

0 20 40 60 80 100 120 140

HPC-CON` Crack forms in Ring Specimen
Rate of Drying and Time to Cracking

Parameter Related to Rate of Drying (psi/day)

Time-to-Cracking (days)
# Proposed Basis for ASTM Concrete Mixture Classification

<table>
<thead>
<tr>
<th>Accelerated Time-to-Cracking, ( t_{cr} ) (days)</th>
<th>Rate of Drying Parameter (psi/day)</th>
<th>Potential for Cracking</th>
<th>Extent of Shrinkage Cracking Expected in the Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 &lt; ( t_{cr} ) ≤ 7</td>
<td>( S \geq 50 )</td>
<td>High</td>
<td>Extensive cracking</td>
</tr>
<tr>
<td>7 &lt; ( t_{cr} ) ≤ 14</td>
<td>25 ( \leq S &lt; 50 )</td>
<td>Moderate-High</td>
<td>Many visible cracks</td>
</tr>
<tr>
<td>14 &lt; ( t_{cr} ) ≤ 28</td>
<td>15 ( \leq S &lt; 25 )</td>
<td>Moderate-Low</td>
<td>Few visible cracks</td>
</tr>
<tr>
<td>( t_{cr} &gt; 28 )</td>
<td>( S &lt; 15 )</td>
<td>Low</td>
<td>Minimal to no visible cracks</td>
</tr>
</tbody>
</table>

Potential for Cracking based on Ring Test

Accelerated Time-to-Cracking, \( t_{cr} \) (days): The time it takes for the concrete to start cracking under controlled conditions.

Rate of Drying Parameter: The rate at which the concrete loses moisture, measured in psi/day.

Potential for Cracking: The expected extent of shrinkage cracking in the field, ranging from High to Low.

Extent of Shrinkage Cracking Expected in the Field: The expected visual impact of cracking, from Extensive cracking to Minimal to no visible cracks.
Curling & Joint Opening Test for Slabs-on-Grade

- Test slabs for monitoring curling & joint opening

Dipstick Measurement for Curl Height

Joint Opening
Curling of Slabs-on-Grade

Dipstick measurement
Slab 1A (NC)

Vertical displacement (in.)

Distance from reference point (ft)

Joint Curl Height

Day 1
Day 3
Day 7
Day 28
Day 42
Day 56
Day 90
Controlling Shrinkage
Control of Plastic Shrinkage Cracking

- Minimize evaporation rate during finishing
  - *Wind breaks, fogging, sun shade*
  - *Evaporation retarders - (Confilm)*

- Accelerate time of set
  - *Use set accelerating admixture, if necessary*

- Fibrillated synthetic fibers

- Expedite curing for mixes with low bleeding rates.
Reducing Drying Shrinkage

- Lower Cement & Water Contents
- Increase Coarse Aggregate Content & Topsize
- Shrinkage Compensation
- Shrinkage-Reducing Admixtures
Effect of Water Content Content on Drying Shrinkage
Effect of Coarse Aggregate Content on Drying Shrinkage

Increasing aggregate-cement ratio

- $a/c = 3$
- $a/c = 4$
- $a/c = 5$
- $a/c = 6$
- $a/c = 7$
Shrinkage-Reducing Admixture (SRA)

  - 100% active alcohol-based solution

- SRA with similar base composition patented in U.S. in 1996.

SRA reduces capillary tension by reducing surface tension of water
Effect of SRA Dosage on 28-Day Drying Shrinkage

![Graph showing the effect of SRA dosage on drying shrinkage. The x-axis represents SRA dosage (L/m³) ranging from 0 to 10, and the y-axis represents reduction in drying shrinkage (%) ranging from 0 to 60. Data points are shown for 1 gal/yd³ and 2 gal/yd³, indicating a linear increase in reduction with increasing dosage.]
Ultimate Drying Shrinkage: SRA Effect

Ultimate drying shrinkage & rate of drying shrinkage lower with SRA

**AS-20**
- $\varepsilon_{\text{ult}} = -699 \, \mu\varepsilon$
- $\beta = 24.2$

**Control**
- $\varepsilon_{\text{ult}} = -1253 \, \mu\varepsilon$
- $\beta = 10.3$
Cracking Resistance: Effect of SRA

SRA improves resistance to cracking
Curling of Slab-on-Grade: No SRA

Dipstick measurements
\[ t_{\text{drying}} = 91 \text{ days} \]

Normal concrete and reinforcement

Due to mid-panel cracking

Joint Curl Height
Curling of Slab-on-Grade: SRA Effect

Dipstick measurements
\[ t_{\text{drying}} = 91 \text{ days} \]

SRA concrete and reinforcement

- SRA
- SRA + HR
- SRA + HPP
- SRA + Novomesh

**Vertical displacement (in.)**

**Distance from reference point (ft)**

- Reduced Joint Curl Height
- No mid-panel cracking
Long-Term Curling of Slab-on-Grade: SRA Effect

Control mix
$h_{\text{ult}} = 0.20 \text{ in.}$
$\beta = 8.5$

SRA mix
$h_{\text{ult}} = 0.12 \text{ in.}$
$\beta = 36.5$

Ultimate curl height & rate of curling lower with SRA
Long-Term Joint Opening of Slab-on-Grade: SRA Effect

Ultimate joint opening & rate of joint opening lower with SRA

**Control**
- $h_{ult} = 1.75$ mm

**SRA**
- $h_{ult} = 1.05$ mm
Design Aids & Noteworthy Projects
With reductions in shrinkage, curling and joint opening, a larger joint spacing may be used in slabs-on-grade.

Master Builders has developed “The Shrinkage Wizard” software program to aid design engineers.

Software demonstrates benefit of using shrinkage-reducing admixture in concrete for slabs-on-grade.
Master Builders Shrinkage and Joint Spacing Estimator

What is it?

- Software program
- Illustrates relationship between drying shrinkage of concrete and control joint spacing for interior slab-on-grade applications
- An educational tool for helping to develop shrinkage specifications for quality concrete
- Available upon request at [www.masterbuilders.com/support/Etools](http://www.masterbuilders.com/support/Etools)
Typical joint spacing for 6 in. slab-on-grade for concrete with 28-day shrinkage of 0.050%. 

**Typical range for most concrete floor and slab mixtures.**

NOTE: This joint spacing algorithm assumes normal indoor temperature control. Thermal stresses are not included in the calculation.
Estimated joint spacing for 6 in. slab-on-grade for concrete with 28-day shrinkage reduced to 0.030%.
SRA Applications

- Floors and Walls
- Bridge Structures
- Parking Structures
- Tunneling
- Sewer and Water Treatment Facilities
- Precast and Cast-in-Place
- Restoration and Rehabilitation
- Shotcrete
- Full-Depth Repair
- Residential
  - Basement Walls and Slabs
  - Driveways, Patios, Sidewalks
Burbank Water Treatment Facility

- 4,000 yd³
- Started April ’98
Los Angeles, CA Metro Rail: Red Line

Cast-in-Place Tunnel Lining

- 18,000 yd³
- Started June ’98
Visual observations indicate, to date, it’s Crack Free!!

Shrinkage stresses in deck monitored for 1 year
Mil Davie Dry Dock Rehabilitation Project; Quebec, Canada

80-year old conc. 7 in. thick repairs 20 ft high walls

Photos courtesy of S.E.M. Lab., Quebec City
Thank You!

Questions?