Plastic Shrinkage Cracking in Concrete

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Hydration Products

- Calcium silicate hydrate, CSH, 
  - 50-60% volume of HCP (hydrated cement paste)
- Calcium Hydroxide, CH 
  - 20-25% of HCP
- Calcium sulfoaluminates
- Water
- Pores 
  - Capillary pores
  - gel pores
Shrinkage

Decrease in Concrete Volume under constant Temperature (Independent of Loading)

Parameters Affecting Shrinkage:

1. Time
2. Water Content or W/C
3. Aggregate Type
4. Ambient Condition (Humidity, Temp., Wind)
5. Curing Condition
6. Shape Effect (Volume/surface area Ratio)
Origin of ACI nomograph for estimating rate of evaporation of concrete is MENZEL’S FORMULA

Based on lake Hefner near Oklahoma city (1950-2)
Free Shrinkage

**Ultimate Shrinkage**

![Diagram showing shrinkage strain over time with a concrete specimen length l and ultimate shrinkage level.](image-url)
Free shrinkage parameters do not differentiate the contribution of fibers, or cracking.
Capillary and Gel pore System after Hydration of Portland Cement
Shrinkage is due to movement of water from various pore systems.

Schematics of Water removal and Internal Shrinkage

Large pores empty first, followed by smaller pores.
Free Shrinkage

before shrinkage

After Shrinkage
Restrained Shrinkage

shrinkage

No shrinkage
Practical Significance of Shrinkage

- When Movement due to shrinkage can not take place freely, tensile Strain (and Stress) will occur and cause CRACKING of Concrete
- **Cracking** of Roof Slabs, Ground Slabs, Walls, etc

![Diagram of Slab Before Shrinkage with Cracks, Movement, and Restraints](image-url)
Can high performance concrete address the problems?

Shrinkage is a major issue due to the use of Silica fume and high paste content, with low water content.
Bleeding and its control

- problems
  - poor pumpability
  - delays in finishing
  - high w/c at the top
  - poor bond between two layers

- causes
  - lack of fines
  - too much water content

- Remedies
  - more fines
  - adjust grading
  - entrained air
  - reduce water content
Temperature, Humidity, Wind Control

Fresh concrete

Aggregates

Paste
Bleeding
Interaction between bleeding and evaporation

Bleed water = evaporation

Evaporation

Surface water

Bleed water
Too much evaporation

Evaporation

no surface water

drying

Bleed water < Evaporation
Cracks are Dominant form of failure in many engineering, art, natural events
Cracks initiate from points where stresses change rapidly.
Plastic shrinkage cracks

- Commonly occur in the surfaces of floors and slabs when job conditions are so dry that moisture is removed from the concrete surface faster than it is replaced by bleed water.
- Occur before the start of curing, before or after final finishing. As the moisture is removed, the surface concrete contracts, resulting in tensile stresses in the weak material.
Control of shrinkage cracking

- **Reduction of cracking tendency**
  - Lower paste Content
  - less water
  - largest practical maximum-size aggregate
  - well-graded aggregate
  - stiffer consistency
  - lower initial temperature of the concrete
  - Curing

- **Construction**
  - Reinforcement
  - Construction Joints
**Mix design**
- avoiding oversanded mixtures, using the largest maximum aggregate size practical, and using aggregate with the most favorable shape and grading conducive to workability.

**Effect of water content**
- Surface drying will occur except when the surface is submerged or below grade. Drying shrinkage strains of up to $600 \times 10^{-6}$ or more are likely.
- Keep the concrete wet as long as possible so that the concrete will have time to develop more strength to resist cracking forces.
Minimum-Reinforcement
- Between 0.18 and 0.20%, does not normally control cracks to within generally acceptable design limits.
- To control cracks to a more acceptable level, minimum requirement needs to exceed about 0.60%.

Joints
- The use of joints is an effective method of preventing the formation of cracking.
- Contraction joints in walls are made, for example, by fastening wood or rubber strips to the form, which leave narrow vertical grooves in the concrete on both faces of the wall.
Evaporation retarders work well but are frequently misused
Applying curing compound while concrete is still fresh

“It is recommended that a minimum of 7 days continuous moist curing be specified.”
Moist curing after concrete hardens
Sawed Joints for crack control
shrinkage-reducing admixtures (SRAs)

- Marketed by numerous chemical admixture companies for reducing drying shrinkage (and its associated cracking) in concrete.
- Most SRAs function by reducing the surface tension of the pore solution in the concrete.
- In addition to reducing or slowing drying shrinkage, this reduction in surface tension can also potentially reduce autogenous shrinkage in low water-binder ratio mortars and concretes and evaporative water loss during early age curing.
Types of Cracks

- During Hardening
  - Construction movement,
    - forms movement
    - Subgrade movement
  - Plastic
    - Plastic shrinkage
    - Plastic settlement
  - Frost Damage
    - Premature freezing
    - Scaling, crazing

- After Hardening
  - Volume instability
    - Drying shrinkage
    - Thermal change
    - creep
  - Structural design
    - Design load/overload
    - Design subgrade
    - Fatigue
  - Physio-Chemical
    - AAR/ASR/DEF
    - Steel Corrosion
    - Freeze thaw Cycling
Cracks in Concrete Can transfer forces if they are maintained at a very small opening.
### Reasonable Crack Widths in RC Under Service Loads

<table>
<thead>
<tr>
<th>Exposure Condition</th>
<th>Crack Width</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>in</td>
</tr>
<tr>
<td>Dry Air or Protective Membranes</td>
<td>0.016</td>
</tr>
<tr>
<td>Humidity Moist Air, Soil</td>
<td>0.012</td>
</tr>
<tr>
<td>Deicing Chemicals</td>
<td>0.007</td>
</tr>
<tr>
<td>Seawater and Seawater Spray, Wetting, Drying</td>
<td>0.006</td>
</tr>
<tr>
<td>Water Retaining Structures</td>
<td>0.004</td>
</tr>
</tbody>
</table>
The Importance of Crack Width

- No Leakage
- Crack Healing
- Controllable Leakage
- Visible Leakage
- Leakage
- Corrosion

ACI limitation: 0.0022”-0.005”
Crack Width (in): 0.013-0.016”
Crack Width (in): 0.03”-0.125” Visible
Use of Alkali Resistant Glass Fiber Reinforcement

St. Gobain Alkali resistant Glass Fibers
Role of Fibers in Toughening

\[ V_f = 20 \text{ Kg/m}^3 \]
\[ V_f = 10 \text{ Kg/m}^3 \]
\[ V_f = 5 \text{ Kg/m}^3 \]

Control

0 0.2 0.4 0.6 0.8 1
Crack Mouth opening Displacement, mm

Load, KN

W/C = 0.4
Age = 28 Days
HP12
Restrained Shrinkage Testing

Experimental Program

restrained shrinkage specimens

Constant humidity chamber subjected to constant flow of air around the specimens.
Crack width Measurements using a microscope with a 10x objective

A- HD24
B- HP12
C- Control
Evaporation is simulated under low pressure condition.
- The mold consists of interlocking pieces made of Polycarbonate
- Anchor hooks are used to fully connect the paste with the mold, providing restraints in two directions.

Load cell serves as a scale after calibration to weigh the sample continuously.
Effect of Initial Curing Duration

- **Cumulative moisture loss:**
  - Decreased from 65 to 49 and 26 g
  - Translates to 24% and 60% reduction

- **Evaporation rate:**
  - Initial Evaporation rate:
    - decreased from 0.42 to 0.39 and 0.34
  - Evaporation rate at 12 h:
    - decreased from 0.3 to 0.2 and 0.07 kg/(m²h)

- **Transition time:**
  - Changed from 9.7 h to 7.3 h and 3 h

- **Moisture diffusivity:**
  - Decreased by as much as 62% and 93%
Stages of Drying Cement Paste in Vacuum Vessel

Pouring cement paste

- Casting
- Restrained Molds (4\texttimes{}4\texttimes{}0.5”)

- Pouring cement paste
- A film of water on surface
- t = 30 min

- Formation of voids on paste surface
- t = 1 hr

- Cracking on paste surface
- t = 4 hr

- No layer of water on surface
- t = 2 hr
Time-Lapse Photography (Effect of w/c ratio)

w/c = 0.45

w/c = 0.65

w/c = 0.55

Drying Time: 07:00
Results of Time-Lapse Photography

Paste

Fabric Reinforced Paste

Drying Time:
07:00
Crack Pattern Evolution

after 3.5 h

after 3.75 h

after 4 h

after 4.25 h

after 4.5 h

after 4.75 h

after 5 h

after 4.25 h
Image Analysis Process

1. **Split Image**
2. **Filter Image**
3. **Binary Image**
4. **Construct Image**
5. **Crack area and max crack width measurement**
## Results of image analysis on 2D cracks

### Plain Concrete
- Max. Crack Width (mm): 1.28
- Reduction in Max. Crack Width by Adding Fiber (%): -
- Areal Fraction of Cracks (mm²/mm²): 0.018
- Reduction of Crack Area by Adding Fiber (%): -

### Fiber content = 3 kg/m³
- Max. Crack Width (mm): 0.68
- Reduction in Max. Crack Width by Adding Fiber (%): 47%
- Areal Fraction of Cracks (mm²/mm²): 0.014
- Reduction of Crack Area by Adding Fiber (%): 25%

### Fiber content = 6 kg/m³
- Max. Crack Width (mm): 0.37
- Reduction in Max. Crack Width by Adding Fiber (%): 134%
- Areal Fraction of Cracks (mm²/mm²): 0.007
- Reduction of Crack Area by Adding Fiber (%): 84%
Conclusions

- Shrinkage in concrete materials is a major durability concern.
- Adequate Curing, minimizing paste content, using largest aggregate size, reducing water remand, and novel admixtures are some the methods of mitigation of shrinkage cracking.
- Fibers provide internal bridging mechanisms for the closure of the cracks.
- Test methods and modeling techniques can be used to better address the performance of concrete materials.
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