Control and Prevention of Concrete Cracking

Why does cracking happen?

- It's generally about volume change (shrinkage) vs. restraint
  - Resulting tensile stresses that exceed strength
  - Movements other than shrinkage can also be involved (settlement, load-deflection, expansion, etc.)
- Restraint is usually from mechanical contact
  - Also geometry / mass
- Timing is a key factor
  - Setting time
  - Shrinkage onset and rate
  - Rate of strength development

So, what influences shrinkage and restraint?

<table>
<thead>
<tr>
<th>Causes of shrinkage &amp; influential factors</th>
<th>Sources of cracking-related restraint</th>
</tr>
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<td>Chemical shrinkage</td>
<td>Normal subgrade drag</td>
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<tr>
<td>Autogenous shrinkage</td>
<td>Contact with structures</td>
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<tr>
<td>Subsidence &amp; plastic shrinkage</td>
<td>Subgrade rutting / irregularities</td>
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<td>Drying shrinkage</td>
<td>Steel reinforcement</td>
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<td>Plastic shrinkage</td>
<td>Reinforcement / tiebars across a joint</td>
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<td>Curling – differential shrinkage</td>
<td>Thickness variability</td>
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<td>Panel geometry</td>
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<td>Load-related strain and deflection</td>
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<td>Creep</td>
<td>Differentials in temp across thickness</td>
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<td>Expansion in aggressive environments</td>
<td>Angular granular subbases</td>
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<tr>
<td>Concrete water content</td>
<td>Rigid subbases</td>
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<td>Aggregate grading &amp; size</td>
<td>Bond of overlays to base layers</td>
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<tr>
<td>Fine aggregate FM, impurities, PSD</td>
<td>Ineffective control joints</td>
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<tr>
<td>Cement chemistry &amp; fineness</td>
<td>Late or shallow saw cuts</td>
</tr>
<tr>
<td>SCM chemistry, fineness, PSD</td>
<td>Tooled joints too shallow</td>
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<tr>
<td>Admixtures</td>
<td>Adjacent panels placed previously</td>
</tr>
<tr>
<td>Environmental conditions</td>
<td>Penetrations – manholes, inlets, etc.</td>
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<tr>
<td>Rapid cooling - moisture</td>
<td>Rapid surface moisture loss</td>
</tr>
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Most common & significant influences

- Influences on volume change
  - Plastic shrinkage
  - Drying shrinkage
  - Thermal changes
  - Environmental factors (evaporation rate)
  - Curing effectiveness & timing
  - Warping & curling influences
- Rate of strength gain
- Construction or service issues
  - Restraint variables
  - Jointing & reinforcement issues
  - Excessive loads or fatigue
  - Support settlement or erosion

Fundamental concrete volume changes

- Shrinkage occurs as excess mix water evaporates
- Usually the most significant category of volume change
- Higher water content = greater drying shrinkage
- Both the amount and timing of evaporation influence cracking

After drying shrinkage, thermal and other volume changes generally cannot restore concrete’s original plastic volume
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Stress from restrained shrinkage vs. strength

Cracking occurs when stresses from restrained shrinkage exceed the concrete’s tensile strength at that time.

Shrinkage stress vs. strength, example

Minimizing cracking – reduced or delayed shrinkage

• Various successful strategies for reduced cracking involve moderating or delaying shrinkage
  – Lower paste content mixes
  – Lower hydration heat
  – Lower cementitious content
  – Highly controlled curing
  – Evaporation controls
  – Shrinkage compensating additives or cements
• High potential for benefits at reasonable costs
Concrete water content vs. ultimate shrinkage

Concrete water content is directly related to ultimate drying shrinkage – cement content is indirectly related.

Concrete mix properties and water demand

- Aggregate top size
- Combined aggregate grading
- Fineness of sand and impurities
  - Fineness modulus
  - Clay content
- Cementitious materials
- Temperature

Thermal shrinkage influences

- Concrete sets while hot and is expanded – then it shrinks
- Temperature peaks within the first 12 hours
- Air temperature often drops at the same
- Combined affect can be significant
- All while concrete is very weak
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Airport apron paving with cracking from sudden thermal shock (afternoon rain storm)

Subgrade restraint variables
- Granular materials vs. fine grained soils
- Vapor barriers & slip sheets
- Subgrade surface influences
  - Wheel ruts
  - Grade beams
  - Integral footings, other structural features
- Variable compaction
- Bond to rigid subbases

Evaporation rate influences
- One of the most critical and elusive variables affecting cracking behavior (1)
  - Drives drying shrinkage rate and ultimate shrinkage
  - May cause plastic shrinkage
- Critical factors:
  - Wind
  - Relative humidity
  - Differential temps
- Plastic shrinkage cracking (PSC) danger threshold:
  - ≥ 0.2 lb/sf/hr (most sources)
  - As little as 0.1 lb/sf/hr (recent research)
Plastic shrinkage cracking

- Cracks appear during finishing
- Occurs in plastic concrete when surface evaporation exceeds the concrete’s bleeding rate
- Cracks often parallel, shallow, discontinuous
- Usually occurs only during excessive evaporative influences (wind, low humidity, extreme thermal differentials)
- Occurs most frequently in placements with no protection from surface winds
- Excessive drying shrinkage also more likely

Plastic shrinkage cracking - influences

- Factors that influence surface evaporation:
  - Wind direction & surface exposure to wind
  - Direction and speed of screeding / strikeoff
  - Concrete / air temperature differentials
  - Humidity
- Factors that influence bleeding:
  - Mix water content, paste factor
  - Admixtures & proportions
  - Concrete set time & temperature
  - Fine particle content (microsilica, etc.)
  - Reinforcement (fibers)
  - Dry subgrade?
  - Vapor barrier?

Beware of Wind

- Wind results in significantly greater drying shrinkage, both short and long term
- Affects both plastic and drying shrinkage and cracking
- Necessitates extreme and immediate curing measures!
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Rampant PSC devastated this otherwise successful paving project.

Holcim weather APP (weatherapp.us)
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Holcim weather APP (weatherapp.us)

Hand-held evaporation rate meter

EvapoRATE by Eric Anderson, PE, KDOT Bridge Section
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Fogging a bridge deck placement during finishing

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The most overlooked tool for control of cracking!

CURING

CURING

Curing cannot be over-emphasized...

• Curing is anything done to maintain saturation
• Curing delays shrinkage
• Must begin immediately after finishing
• During PSC conditions something must also be done during finishing

Delaying onset of shrinkage
What application rate of curing compound is needed to prevent shrinkage? (sprayed on immediately, wind = 2.5 m/s or 5.6 mph)

- Basic
- 150 g/m²
- 225 g/m²
- 975 g/m²

(0.1 psf = 0.02 in)


Curling / warping of slabs

- Can result from differential moisture created by surface drying while the slab bottom remains wet
- Can also result from differential temperature

Measures for reducing curling / warping

- Place concrete on “normally dry” subgrades
- Thicker slabs
- Shorter joint spacings
- Internal curing, enhanced long-duration curing
When curling/warping must be minimized, ACI 302 and 360 documents now recommend the use of a granular fill placed over the vapor retarder, serving as a “blotter” to equalize moisture loss from slab top and bottom. This must be carefully monitored!

Vapor retarders can worsen the problem

Effects of steel reinforcement on cracking
- Distributed steel reinforcement is not needed or recommended in most types of flatwork, and can actually cause more cracking
- The more steel and the longer the panel, the more cracks
- In typical use, steel should be cut at all joints
- Example – consider continuously reinforced pavement:

Rate of strength gain influences on cracking
- Slow strength gain can be a cracking problem without effective curing
  - Low temperatures
  - Low cementitious content
  - High SCM content
  - Retarding admixtures
- Immediate, extended curing becomes critical to delay shrinkage
Poor subgrade support

Unusually one of the most common causes of cracked flatwork

Jointing of flatwork for control of cracking

Uncontrolled cracking of flatwork is too often caused by poor jointing!

Objectives of jointing:
- Control the location of expected (normal) cracks
- Provide constructability
- Provide necessary load transfer at all joints and cracks
- Assure that random (unexpected) cracks pose no performance problems

Recommended joint spacing for floors, feet

<table>
<thead>
<tr>
<th>Slab thickness, in.</th>
<th>Maximum-size aggregate less than 1/2 in.</th>
<th>Maximum-size aggregate 3/8 in. and larger</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>7</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>9</td>
<td>18</td>
<td>23</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>25</td>
</tr>
</tbody>
</table>

From PCA EB075.02D
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Recommended joint spacing for pavements

<table>
<thead>
<tr>
<th>Slab thickness, in.</th>
<th>Maximum spacing, ft.</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 – 4.5</td>
<td>10</td>
</tr>
<tr>
<td>5 – 5.5</td>
<td>12.5</td>
</tr>
<tr>
<td>≥ 6</td>
<td>15</td>
</tr>
</tbody>
</table>

Exception: load transfer design may call for closer spacings.

Timing of joint sawing

Sawed joints must be made within 4-12 hours after final finishing

This joint was sawed soon enough

This one was sawed too late

Joint type selection and proper detailing

- Cracking can be caused by using the wrong joint type or detail
- Most common mistakes:
  - Keyways (not recommended)
  - Isolation joints as regularly spaced joints
  - Staggered joints
  - Isolation joints in high load areas, no load transfer
  - Reinforcement through joints
  - Joints not intersecting reentrant / structure corners
Examples – poor joint details & related cracking

Keyways are not recommended as a joint detail for slab thickness < 11”!

Fibers as secondary reinforcement

- Monofilament or fibrillated polypropylene, polymers, steel, other synthetics, blends
- Various engineering properties achievable
- Reduced cracking possible (especially PSC but also drying)

Special admixtures and cement types

- Shrinkage reducing admixtures
  - Reduce rate and ultimate drying shrinkage by lowering water surface tension & capillary tension
- Expansive cements and additives
  - Type K cements
  - Other ettringite-forming components
  - Lime-based additives
  - Calcium aluminate systems
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Internal curing using LWA fines

- Internal curing – replacing a portion of the mixture fine aggregate with lightweight aggregate (LWA) fines
  - Usually around 15% of the FA depending on absorption, etc.
- LWA is porous, providing internal curing water storage
  - Absorbed moisture within LWA is released over time for enhanced curing
  - Especially helpful for high performance concrete that is nearly impermeable to externally applied curing moisture
- Shown to reduce or eliminate autogenous shrinkage, reduce drying shrinkage, increase strength development

Internal curing implementation guidelines (NIST)


Summary – management of cracking

- Consider likely influences
- Minimize mix shrinkage potential
  - Cement content & properties
  - Water content
  - Aggregates size, grading, fines content
- Minimize subgrade restraint, curling influences
- Evaluate evaporation rate & mitigate if extreme
- Immediate and effective curing
- Cure longer for slow strength gain mixtures, cool weather or high evaporative conditions
- Proper jointing
- Consider available special tools & techniques
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Questions?

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