Control and Prevention of Cracking in Concrete Flatwork

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Owner expectations and cracking

- *My concrete should not crack.* (unrealistic)
- Cracks should not be visible.
- Any cracks should not impair performance.
The *realities* of cracking

- *By far the most common project complaint*
- *Frequent source of disputes and litigation*
- *Typical cracking is almost always avoidable!*
Discussion topics

• Review – basic causes of flatwork cracking
• Cracking Influences, their relative significance, and how they can be controlled or minimized
  ▶ Materials & mix designs
  ▶ Construction procedures
  ▶ Site conditions
• Best practices – cracking avoidance or management
• Resources, suggested reading
Why does cracking happen?

- It’s generally about volume change (shrinkage) vs. restraint, and the timing of related events
  - 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 factors:
  - Time of setting
  - Shrinkage onset and rate
  - Rate of strength development
There are many possible influences, but…

**Causes of shrinkage & influential factors**
- Chemical shrinkage
- Autogenous shrinkage
- Subsidence & plastic shrinkage
- Drying shrinkage
- Plastic shrinkage
- Curling – differential shrinkage
- Thermal changes
- Load-related strain and deflection
- Creep
- Expansion in aggressive environments
- Concrete water content
- Aggregate grading & size
- Fine aggregate FM, impurities, PSD
- Cement chemistry & fineness
- SCM chemistry, fineness, PSD
- Admixtures
- Environmental conditions
- Differential temperature / moisture
- Rapid cooling - unexpected rainfall

**Sources of cracking-related restraint**
- Normal subgrade drag
- Contact with structures
- Subgrade rutting / irregularities
- Steel reinforcement
- Reinforcement / tiebars across a joint
- Thickness variability
- Panel geometry
- Dowel / tiebar details & placement
- Differentials in temp across thickness
- Angular granular subbases
- Rigid subbases
- Bond of overlays to base layers
- Ineffective control joints
  - Late or shallow saw cuts
  - Tooled joints too shallow
- Adjacent panels placed previously
- Penetrations – manholes, inlets, etc.
- Rapid surface moisture loss
These are the most common & significant

- 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

...and these influences can usually be managed!
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.
Stress from restrained shrinkage vs. strength

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

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**Diagram:**
- **Slab** connected to **Rollers**
- **Shrinkage + freedom to move = no cracks**
- **Slab** connected to **Granular fill**
- **Shrinkage + subbase restraint = cracks**
Cracks develop when stress from restrained shrinkage exceeds tensile strength (both change over time)
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

Reduction of total shrinkage

Delaying onset of shrinkage
Concrete water content vs. ultimate shrinkage

Directly 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
Mixture paste content and shrinkage

- Shrinkage Deformation [x10^-6]
- Age [days]

- 28% paste
- 32% paste
- 36% paste
Paste content – inversely related to max agg size

Maximum nominal size of aggregate, in.

3/16  3/8  1/2  3/4  1  1 1/2  2  3  4 3/8

300

Non-air-entrained concrete

Air-entrained concrete

Slump approximately 75 mm (3 in.)
w/c ratio: 0.54 by mass
Aggregate grading effects on mixture paste content

Ideal combined grading

Typical “real world” grading

“Gap graded” aggregates (right) generally increase paste requirements and water demand
Aggregate grading effects on mixture paste content
Aggregate grading effects on mixture paste content

• Various graphical and other quick evaluation tools are used to optimize combined grading:
  ▶ 8-18 rule
  ▶ Workability-coarseness
  ▶ 0.45 power chart
  ▶ Mortar fraction
• These have become somewhat controversial – reported impacts on mix shrinkage vary.
• Experience with specific materials is advised.
Mix design shrinkage limits

- Specified shrinkage limits for the submitted concrete mix design(s)
- Testing via ASTM C157 length change test
- Also ASTM C1581 restrained shrinkage ring test
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
Limiting thermal shrinkage and gradients

- Control initial concrete temperature
- Limit cement content
- Use fly ash and/or slag cement
- Protect concrete from thermal shock
  - Time placements to stagger ambient temps and hydration heat peaks
  - Use insulation and/or active cooling in extreme conditions
- Mass concrete protocols & controls
Airport apron paving with cracking from sudden thermal shock (afternoon rain storm)
Colorado highway paving project
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
- Inconsistent compaction
- Bond to rigid subbases
Evaporation rate influences

One of the most critical and elusive variables affecting cracking behavior (!)

- Drives drying shrinkage rate and ultimate shrinkage
- May cause plastic shrinkage

Critical factors:

- Wind
- Relative humidity
- Differential temps

Threshold of plastic shrinkage cracking
Plastic shrinkage cracking

- Cracks appear during finishing
- Surface evaporation exceeds the concrete’s bleeding rate
- Cracks often parallel, shallow, discontinuous
- Causes: excessive evaporative influences (wind, low humidity, extreme thermal differentials)
- More common where there is no protection from surface winds
- Excessive drying shrinkage also more likely
Plastic shrinkage cracking – influences

- Surface evaporation influences:
  - Wind direction & surface exposure to wind
  - Concrete / air temperature differentials
  - Humidity

- Bleeding influences:
  - Mix water content, paste factor
  - Admixtures & proportions
  - Concrete set time & temperature
  - Fine particle content (microsilica, etc.)
  - Reinforcement (fibers)
  - Dry subgrade?
  - Vapor barrier?

ASTM C 232 bleed test
Beware of Wind

- Wind results in significantly greater drying shrinkage, both short and long term
- Affects both plastic and drying shrinkage and cracking
- Calls for extreme and immediate curing measures!

Severe PSC devastated this otherwise successful paving project.
Plastic shrinkage cracking is predictable!

Concrete placement for a convenience store parking lot on a windy day

4/10/2009 - 12:30 pm
Plastic shrinkage cracking is predictable!
Plastic shrinkage cracking is predictable!
Weather APP for smart phones (weatherapp.us)

Our new free weatherAPP can help ready mix customers and concrete contractors plan according to a four-day forecast of a building site’s weather conditions. Developed using methods outlined in ACI 305, our weather APP not only displays expected weather conditions but also calculates the evaporation rate based on wind speed, relative humidity, air temperature, and concrete temperature. With this information weatherAPP displays whether plastic shrinkage cracking is not likely, probable, or most probable to occur for the conditions.

Simply access the weatherAPP from your Apple iPhone® or iPad®, Android™, Blackberry® Smartphone, Tablet or your desktop PC.

To pour or not to pour? Now we have a free app for that.

Weather conditions may impact how you handle a concrete placement. Now you can access the latest weather information from your Smartphone, Tablet or your desktop for any zip code or city and state in the US.

To access and save to your device, go to: weatherapp.us
Hand-held evaporation rate meter
EvapoRATE by Eric Anderson, PE, KDOT Bridge Section

Threshold Evaporation Rate for Required Precautions
If the rate of evaporation approaches the default value of 0.2 lb/ft²/hr (1 kg/m²/hr), precautions against plastic-shrinkage cracking are necessary (Leich 1957).

The default value may be revised by the architect/engineer. Concrete mixtures with lower water cement ratios or containing conventional or ultra-fine pozzolan or cementitious materials may require lower allowable evaporation rates.

- Use default rate of 0.2 lb/ft²/hr
- Use alternate rate of 0.05 lb/ft²/hr

Wind speed is the average horizontal air or wind speed in mph (km/h) and should be measured at a level approximately 20 in. (510 mm) higher than the evaporating surface. Air temperature and relative humidity should be measured at a level approximately 4 to 6 ft (1.2 to 1.8 m) higher than the evaporating surface on its windward side shielded from the sun's rays (PCA Journal 1997).

Variation Legend
- Successful Variation
- Fixed Input Value
- Illegal Math or Outside Valid Limits

Variation Scenarios to Get Evaporation Rate of 0.1 lb/ft²/hr

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<tr>
<th>T_a (°F)</th>
<th>RH (%)</th>
<th>T_c (°F)</th>
<th>V (mph)</th>
<th>Evap (lb/ft²/hr)</th>
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Variation Scenarios to Get Evaporation Rate of 0.2 lb/ft²/hr

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<th>RH (%)</th>
<th>T_c (°F)</th>
<th>V (mph)</th>
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Redraw Nomograph Solution
Only necessary if erased by other forms or after resizing window.

RateACI = \left\{\frac{\text{ConcreteTemp} - 2.5 \cdot \text{RelativeHumidity}}{100 \cdot \text{AirTemp} - 2.5} \right\} \cdot \left[1 + 0.4 \cdot \text{WindVelocity}\right] \cdot 10^{-6}
Fogging a bridge deck placement during finishing
The most overlooked tool for control of cracking!

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
- **Rate of application of curing compound must be ≥ that called for by manufacturer!!**
Curling / warping of slabs

- Can result from moisture gradients 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
Some specifications call for 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!
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:

CRC is heavily reinforced, without joints, and develops stable transverse cracks every 3-6 feet.
Influence of rate of strength gain

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

Unfortunately 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
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 connected to structure or blockout corners
  ▶ Acute angles at slab edges
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 expansive mix additives
  - Calcium aluminate systems
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
Starting with the cement content in the graph on the upper right, find the chemical shrinkage of the mixture (a good default value is 0.07). Proceed to the value on the y-axis and starting with this same value in the graph on the upper left, find the line for the mixture's w/c ratio. (Note that there is a single (thick) line for all w/c ratios greater than or equal to 0.36 as for these w/c ratio values, it is assumed that complete hydration of the cement powder can be achieved.) Proceed to the value on the x-axis and starting with this same value in the graph on the lower left, find the line for the absorption (dry mass of aggregate basis) of the lightweight aggregate. Finally, proceed to the value on the y-axis to obtain the recommended level of lightweight aggregate (dry mass basis) to be added to the concrete mixture. This replacement should then be conducted on a volumetric basis, replacing an equal volume of normal weight aggregates with pre-wetted (SSD) lightweight aggregates.

Hiperpav – cracking prediction software

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The State DOT and Industry Reps from the Field Verification including:
- Minnesota
- Nebraska
- Arizona
- Texas
- North Carolina
- California
- Illinois
- South Dakota
- Wisconsin
- Iowa
- Michigan
- Morelos (Mexico)
Pre-construction conference

- Cracking avoidance is only one of many project elements that can benefit
- Helps to define and communicate all project responsibilities
- Improves project quality
- Saves time and money
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
Suggested Reading

Short Articles


Industry Technical References


Questions?

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