Holcim

Strength. Performance. Passion.

Diagnosing Common Concrete Problems

ACIA / CONCRETE WORKS
A Day of Concrete Knowledge

Tim Cost, P.E., F. ACI

AIA Credits

The Alabama Concrete Industries Association is a Registered Provider with The American Institute of Architects Continuing Education Systems. Credit earned on completion of this program will be reported to CES Records for AIA members who sign in with their AIA member ID. Electronic Certificates of Completion for all attendees will be available 6-7 weeks post show.

This program is registered with the AIA/CES for continuing professional education. As such, it does not include content that may be deemed or construed to be an approval or endorsement by the AIA of any material of construction or any method or manner of handling, using or distributing or dealing in any material or product. Questions related to specific materials, methods and services will be addressed at the conclusion of this presentation

Learning Objectives

Upon completing this program, the participant should be able to:

1. Determine the cause of most drying shrinkage-related cracking of concrete flatwork.
2. Plan effective cracking prevention strategies for future concrete construction projects.
3. Select jointing details and layouts that will help prevent most common jointing-related flatwork issues.
4. Implement strategies for avoiding low strength test results, flatwork surface blemishes, and discoloration issues.

CONTINUING EDUCATION AIA

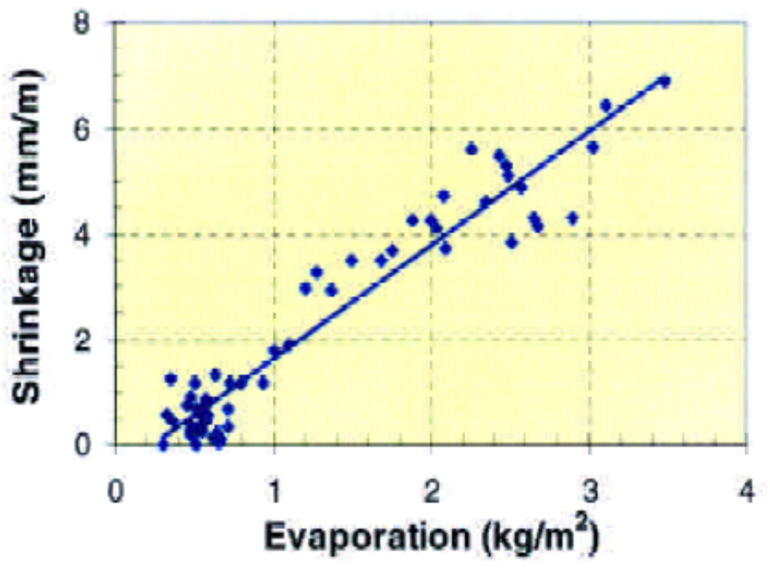
Diagnosing common concrete problems – discussion topics

Cracking	3
Flatwork jointing issues	37
Low strength test results	43
Surface blemishes and discoloration	45
Less common: durability issues, incompatibility	53
Conclusion	63

CRACKING – Why does it happen?

- It's generally about <u>shrinkage vs. restraint</u>
  - 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

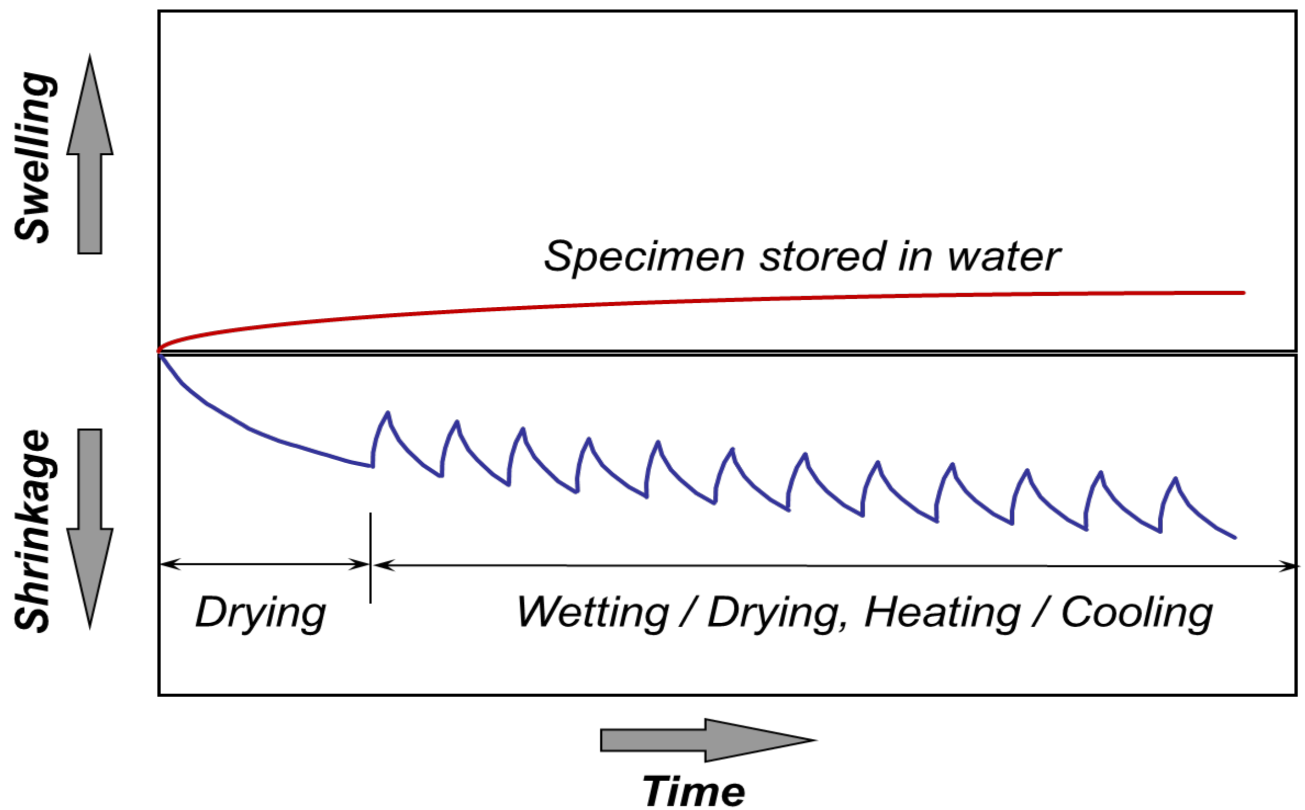
Fundamental concrete volume changes



Erika E. Holt, "Where Did These Cracks Come From?", *Concrete International*, Sept. 2000

- Shrinkage more so than expansion
  - Drying usually most critical
  - Thermal may be an issue as well
  - Other: autogenous, chemical, creep
- Shrinkage occurs as excess mix water evaporates
- Higher water content = greater drying shrinkage
- Both the amount and timing of evaporation influence cracking

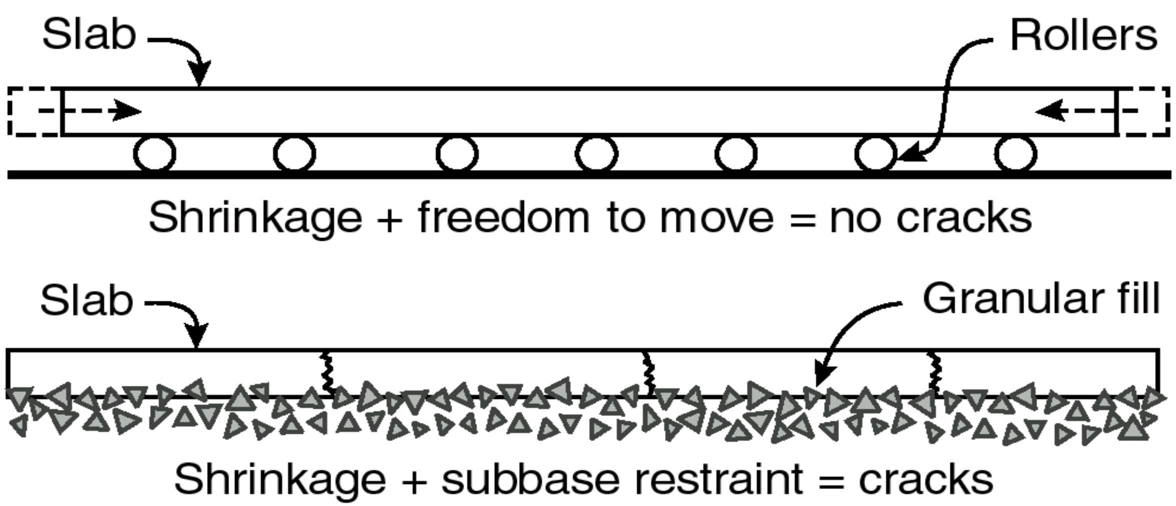
Fundamental concrete volume changes



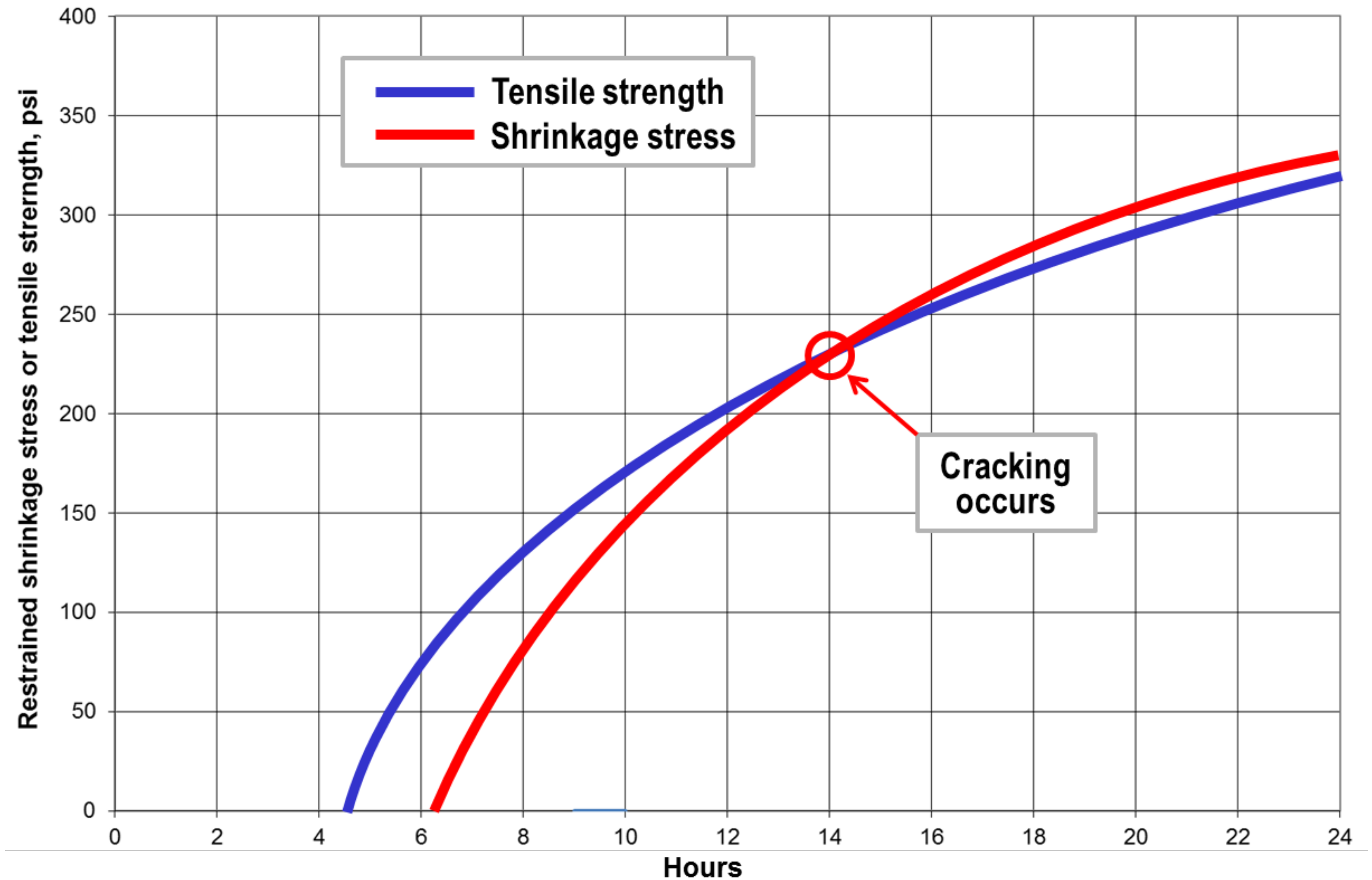
After drying shrinkage, thermal and other volume changes generally cannot restore concrete's original plastic volume

Stress from restrained shrinkage vs. strength

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

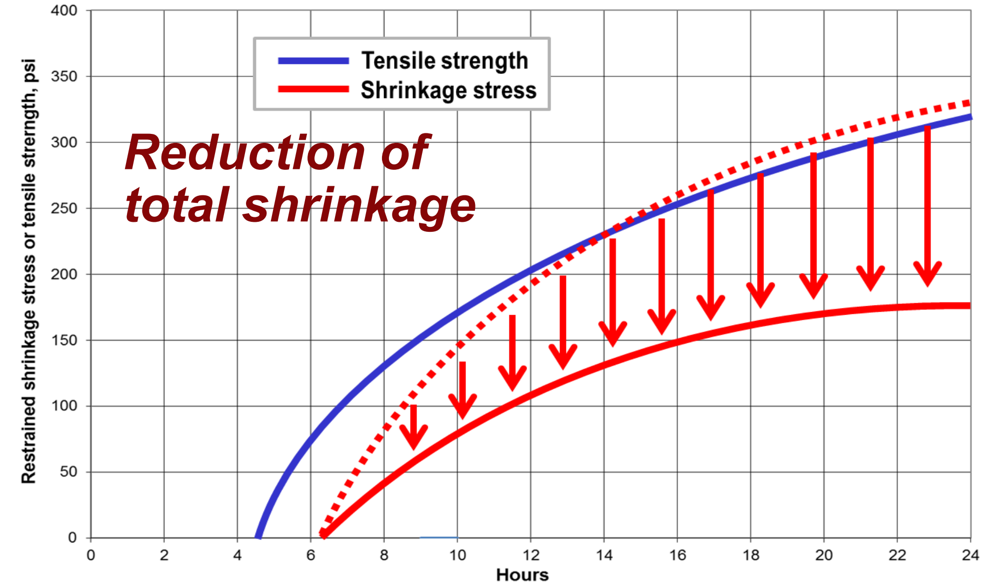


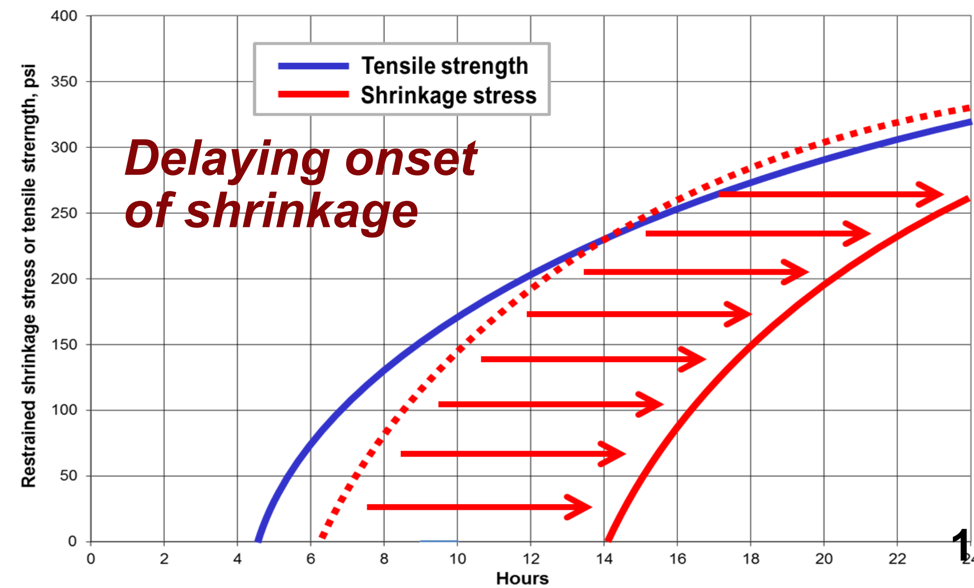
Shrinkage stress vs. strength, example



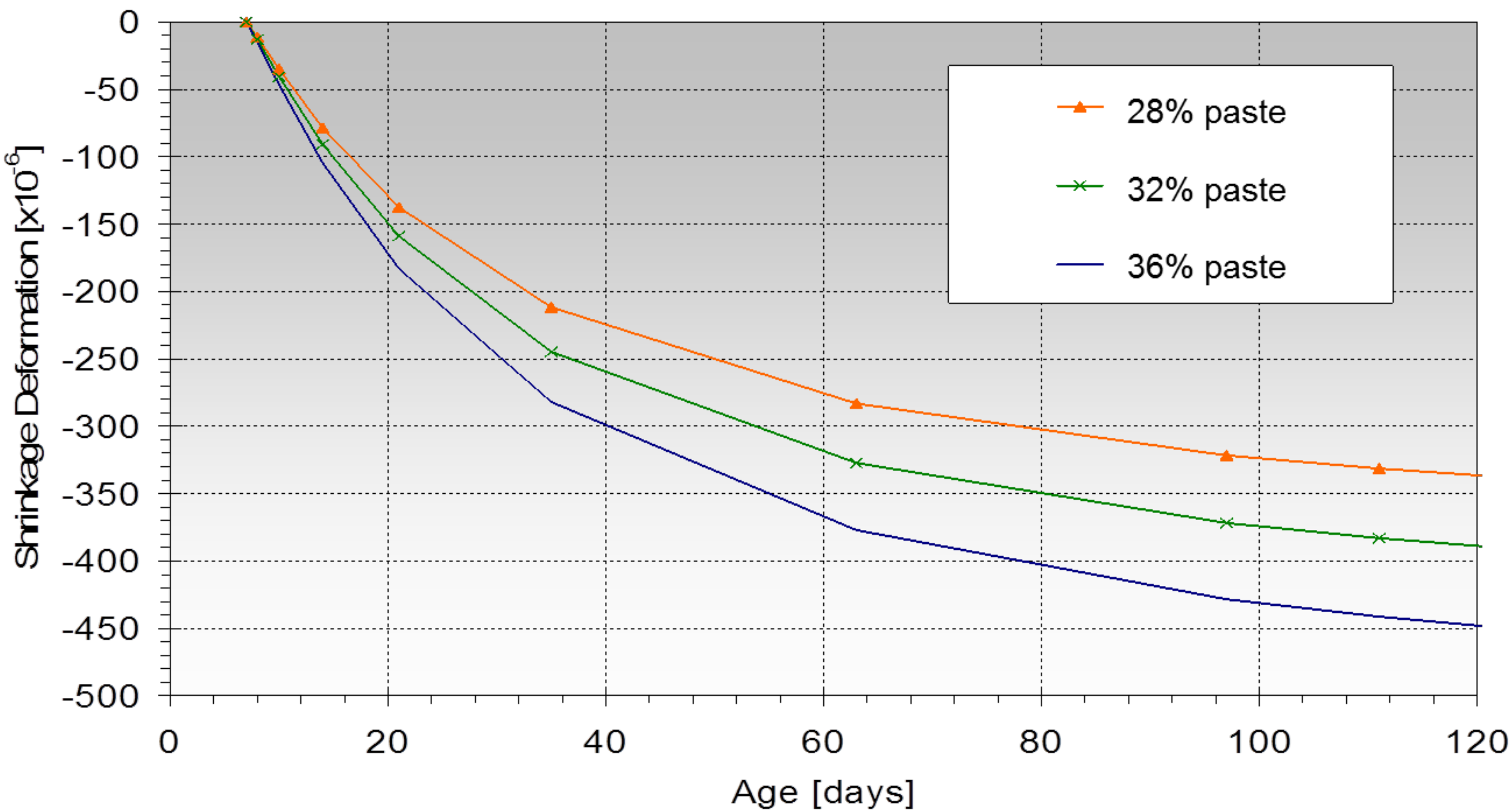
Reduce or delay shrinkage to help prevent cracking

- Reduction of total drying shrinkage
  - Lower paste content (water)
    - Larger top size aggregate
    - Improved aggregate grading
    - Lower cementitious content
    - Lower w/cm
  - Shrinkage compensating additives or cements
- Delay of drying shrinkage
  - Effective, well-timed curing
  - Evaporation controls
- Delay of thermal shrinkage
  - Timing of placement

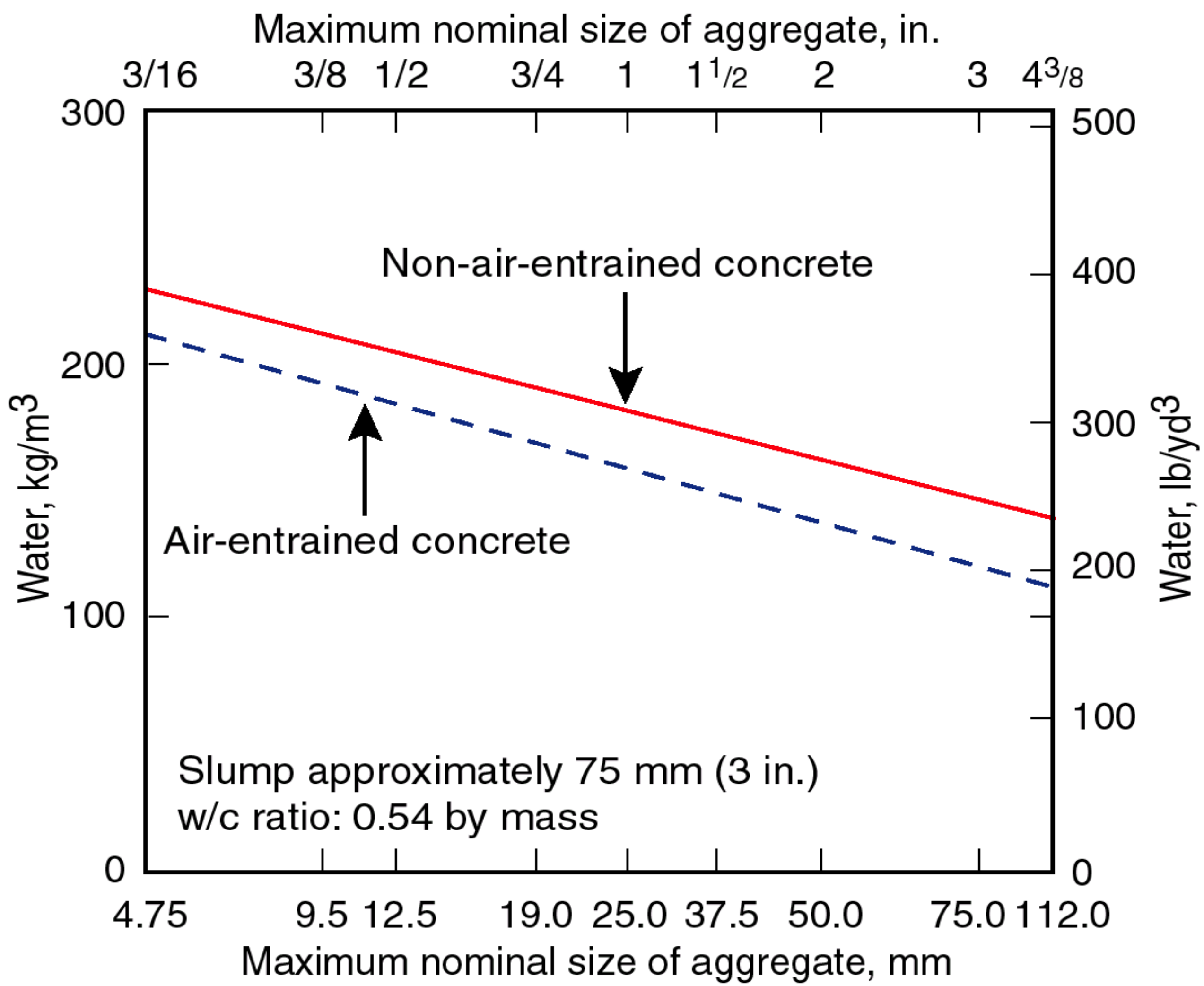




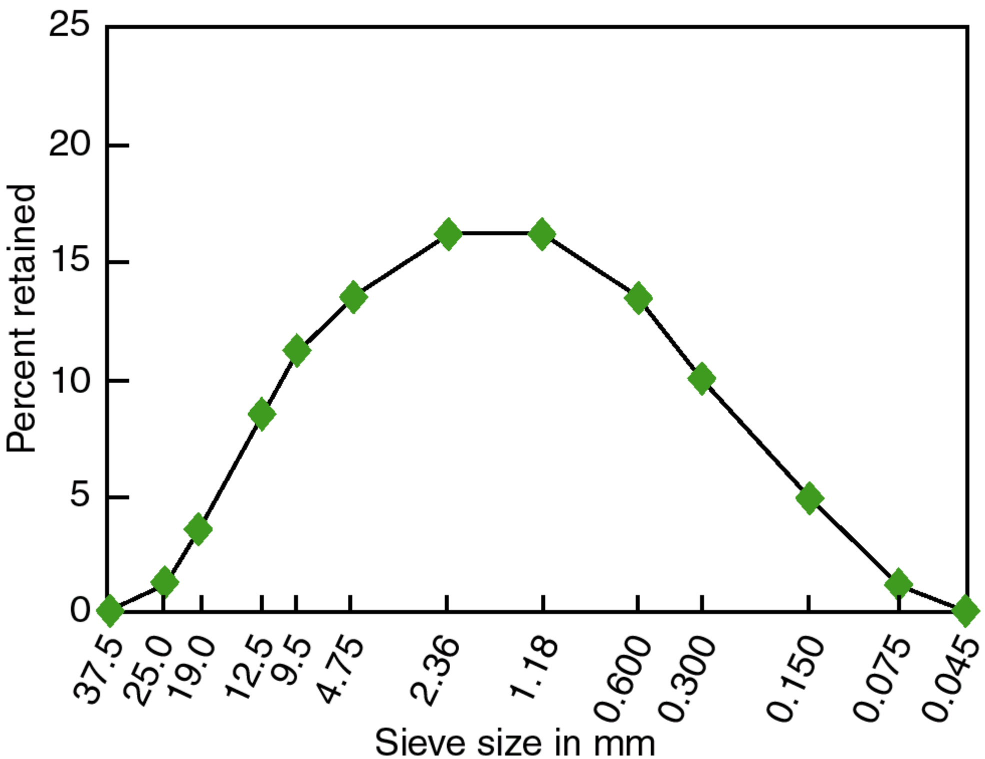
Mix design paste fraction influences drying shrinkage



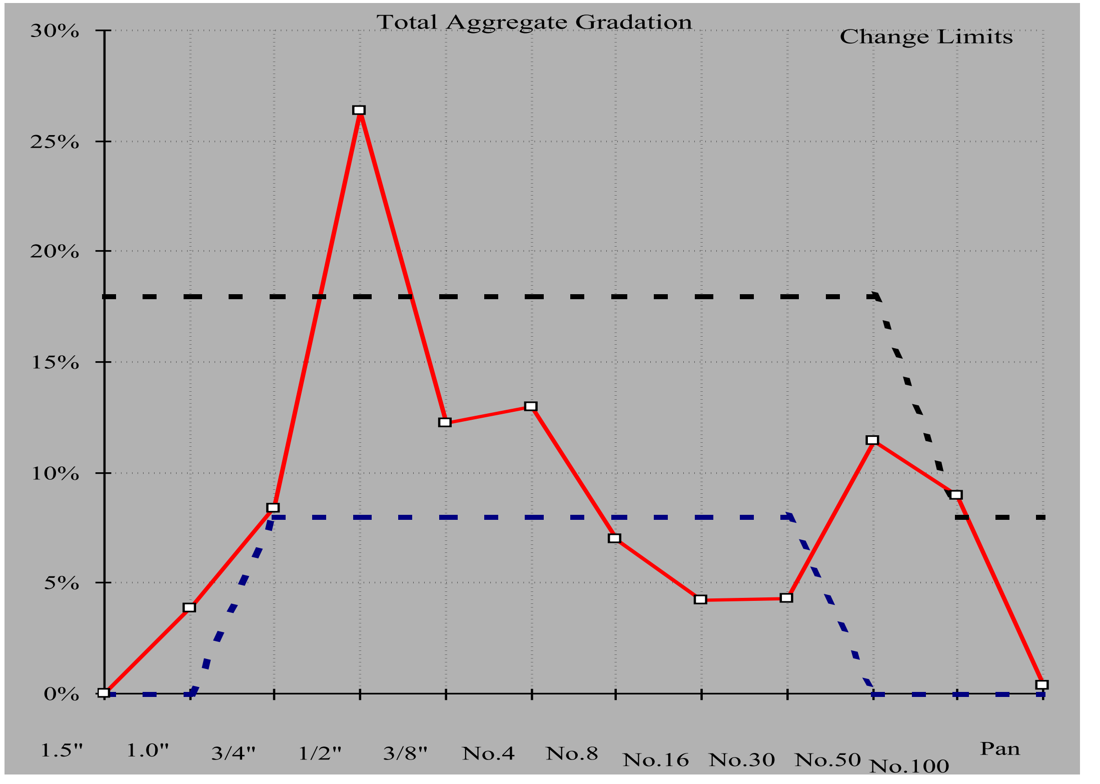
Paste content – inversely related to max aggregate size



Aggregate grading effects on mixture paste content



Ideal combined grading

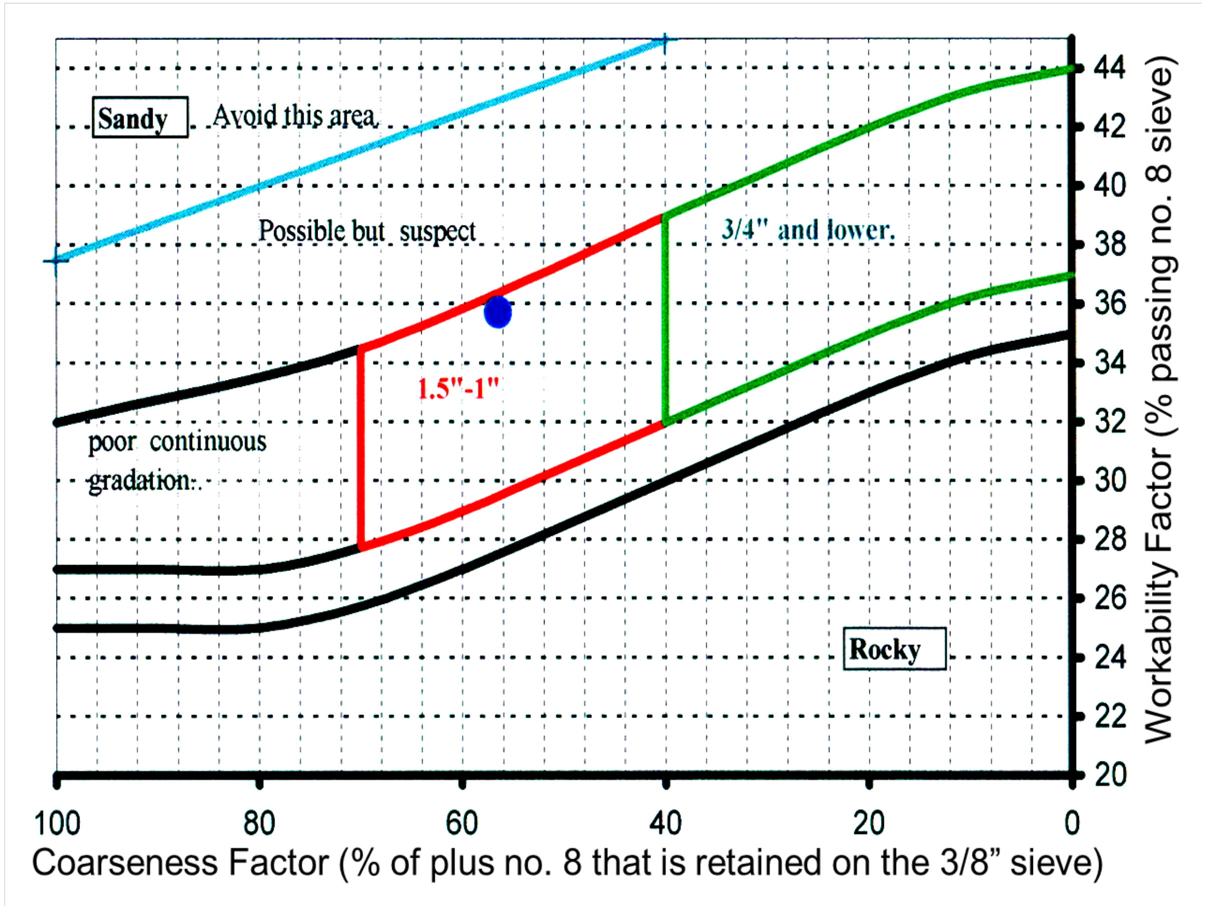


Typical "real world" grading

"Gap graded" aggregates (right) generally increase paste requirements & water demand

Aggregate grading effects on mixture paste content

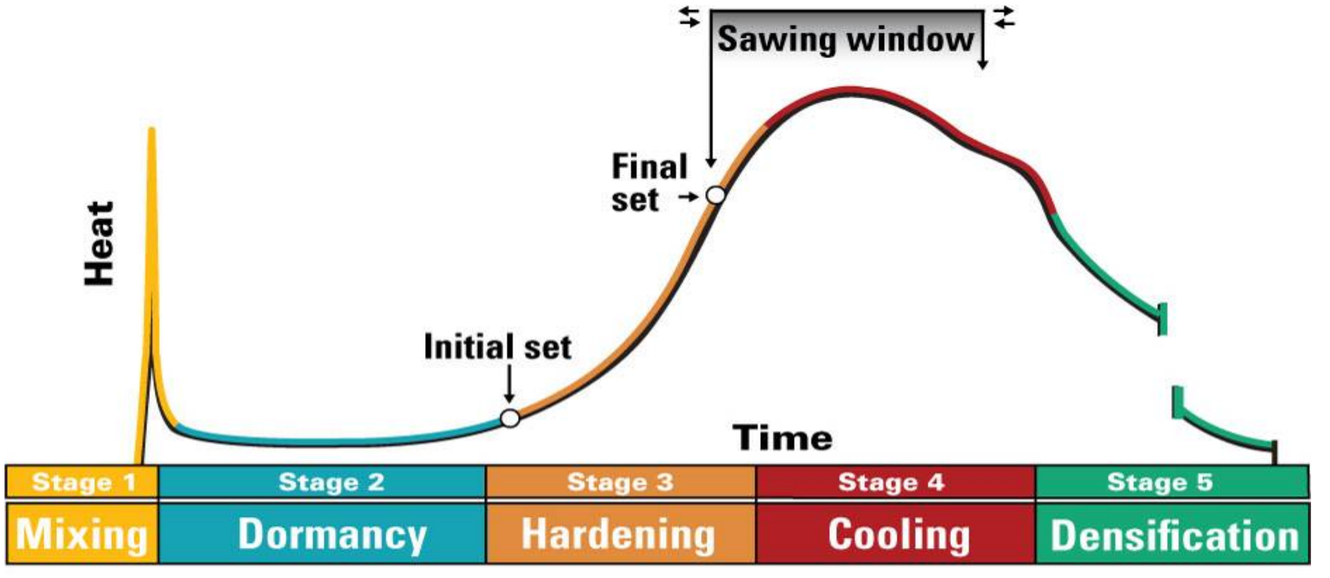
Aggregate grading effects on mixture paste content



- 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.

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



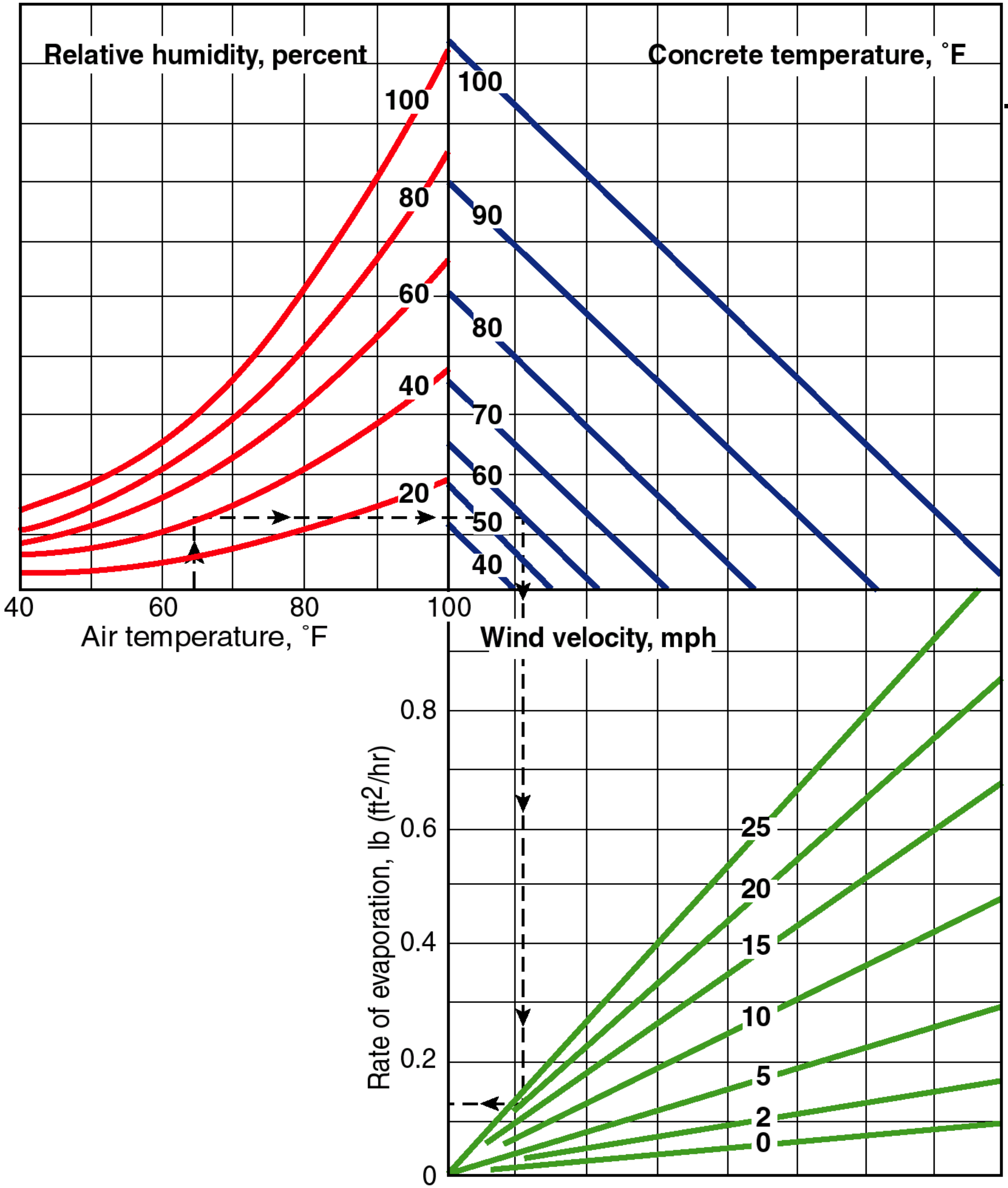
Limiting thermal shrinkage and gradients

- Control initial concrete temperature
- Limit cement content
- Replace cement with pozzolans and/or slag cement
- Protect concrete from thermal shock
  - Time placements to stagger ambient peak temps and hydration peak temps
  - Use insulation and/or active cooling in extreme conditions
- Mass concrete controls properly designed, evaluated, specified

Airport apron paving with uncontrolled 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
- Difficult to diagnose after construction!



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
- 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

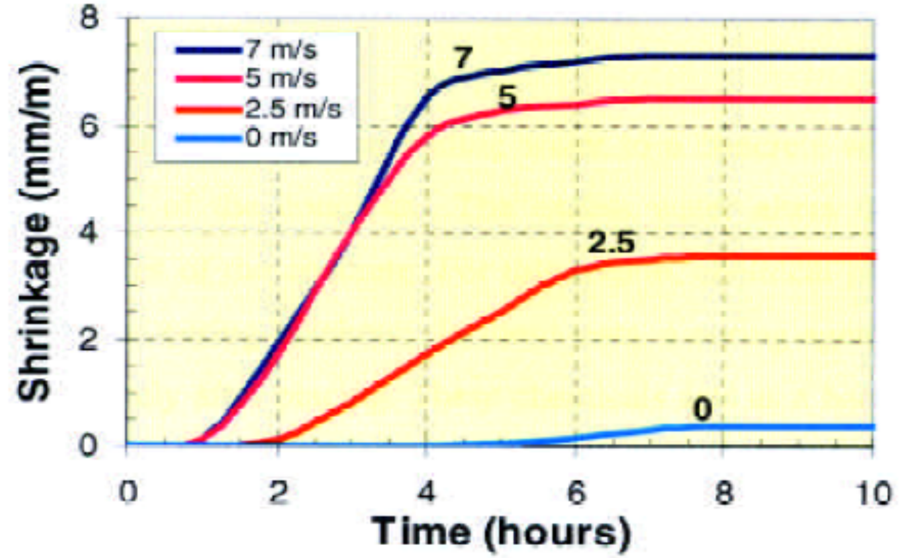
Plastic shrinkage cracking - influences

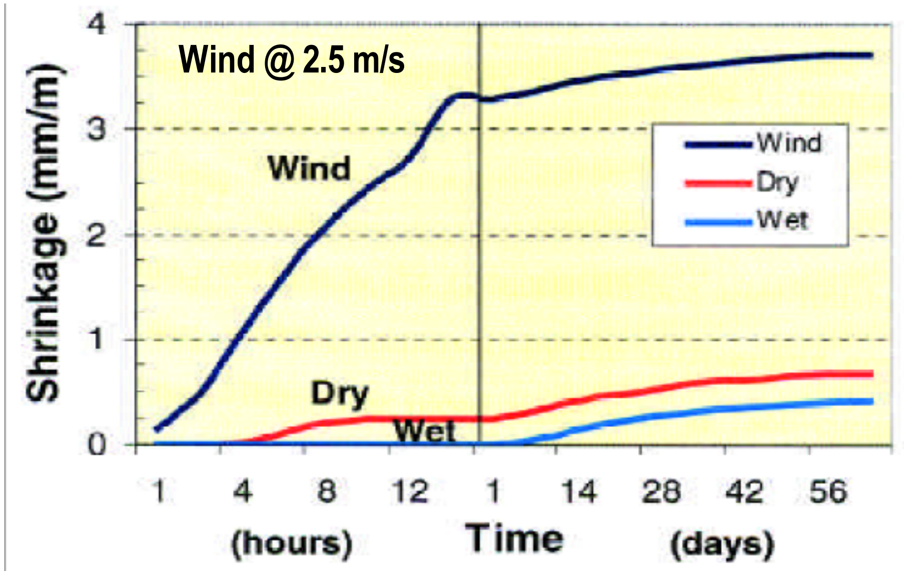
ASTM C 232 bleed test

- Factors that influence surface evaporation:
  - Wind direction & <u>surface exposure to wind</u>
  - 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?

Effects of wind

- Wind results in significantly greater drying shrinkage, both short and long term
- Affects both plastic and drying shrinkage and cracking
- Curing should begin earlier with more aggressive methods

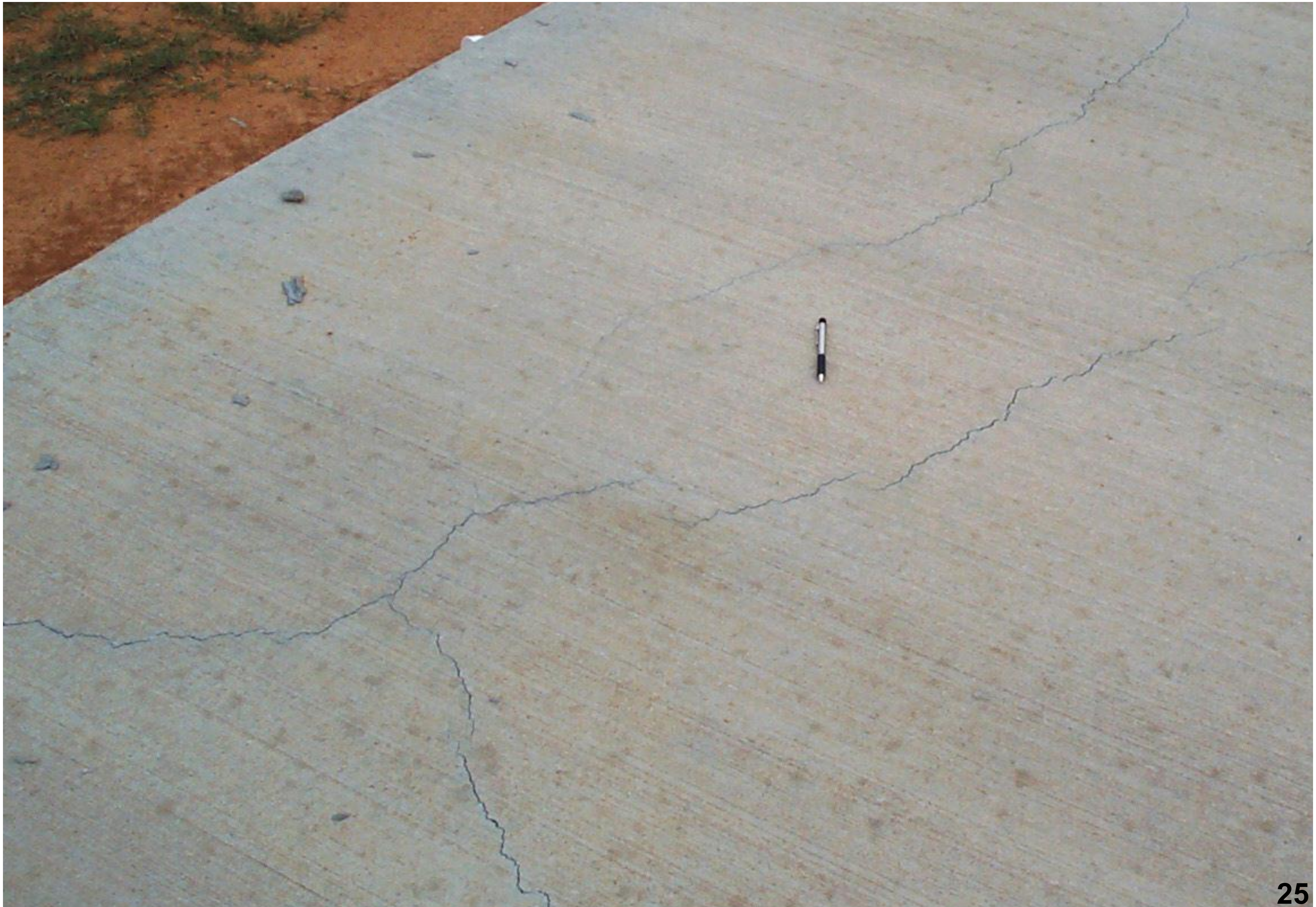




Figures: Erika E. Holt, "Where Did These Cracks Come From?", *Concrete International*, Sept. 2000

Otherwise perfectly good paving torn out because of PSC

- 400+ sy of 7" concrete pavement placed @ 3" slump (vibrating screed)
- Membrane curing compound sprayed shortly after finishing
- Issue occurred on panels placed only on 1 day out of 7 total paving days
- No strength issues or other spec non-compliance



Plastic shrinkage cracking is predictable!

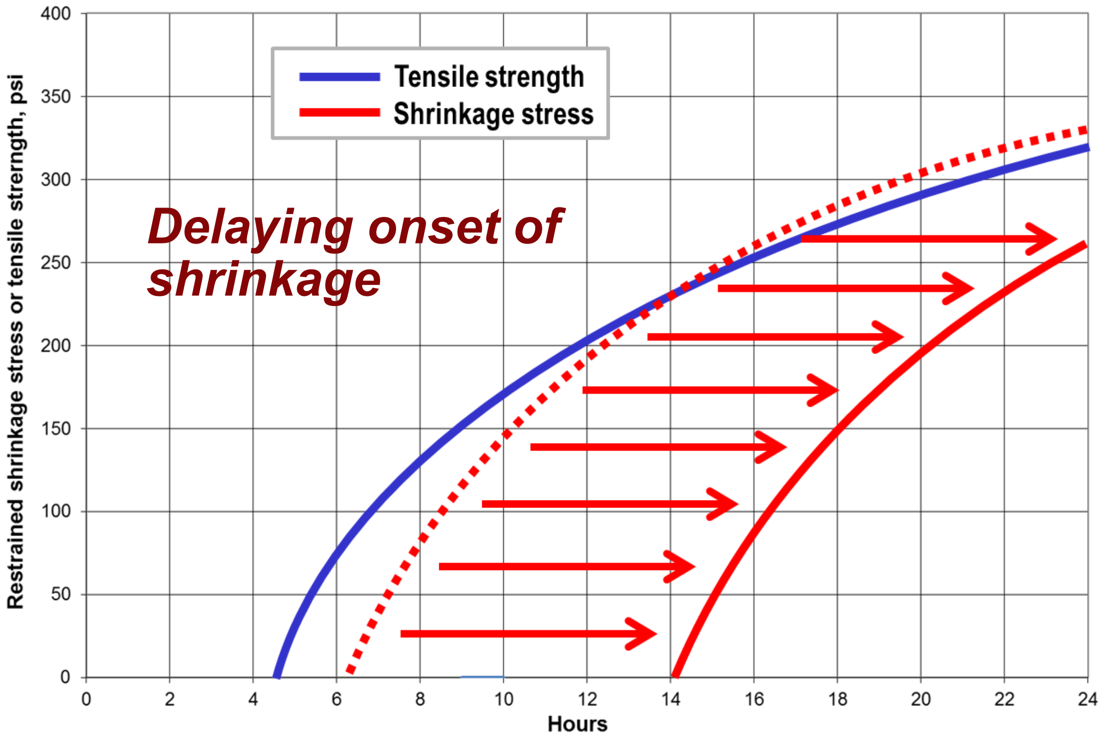
Concrete placement for a convenience store parking lot on a windy day

Plastic shrinkage cracking is predictable!

Plastic shrinkage cracking is predictable!

Effective and timely curing is critical in cracking prevention

Effective and timely curing is critical in cracking prevention

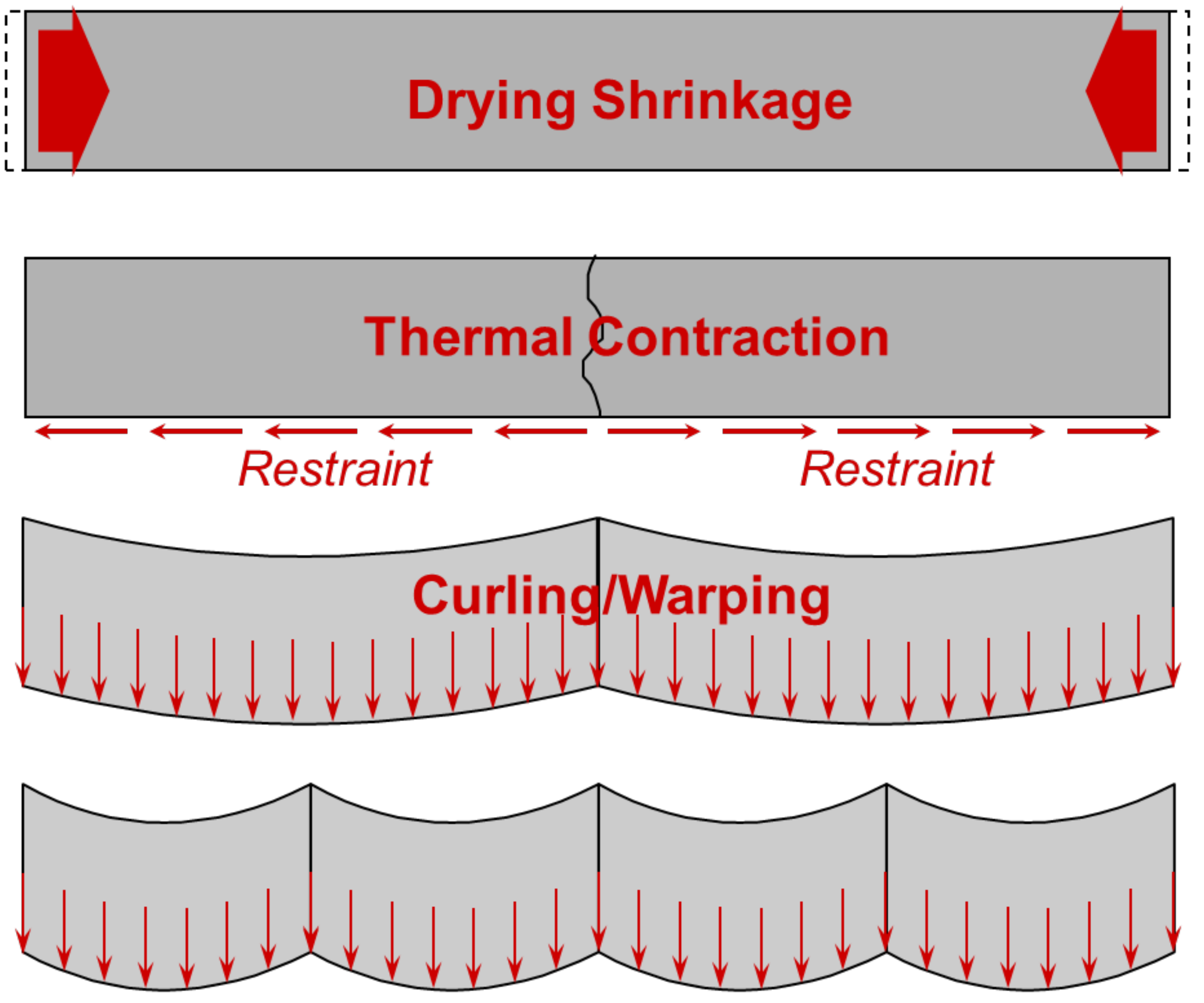


- Curing is anything done to maintain saturation
- Curing delays shrinkage
- Must begin immediately after finishing
- During PSC conditions something must also be done during finishing

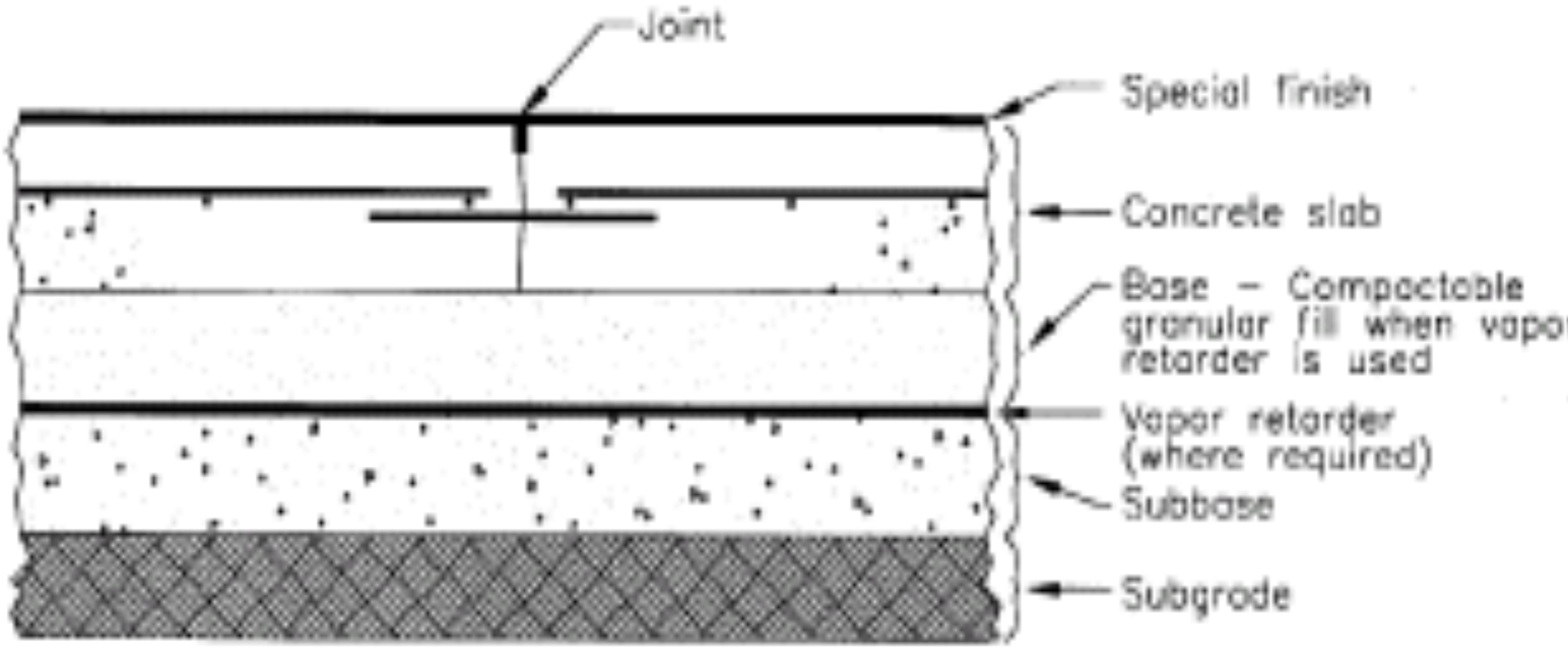
Curling / warping of slabs & related cracking

- Can result from differential moisture created by surface drying while the slab bottom remains wet
- Can also result from differential temperature
- Effects become more severe with thinner slabs and/or longer joint spacings

Typical crack formation sequence



Vapor retarders aggravate curling / warping

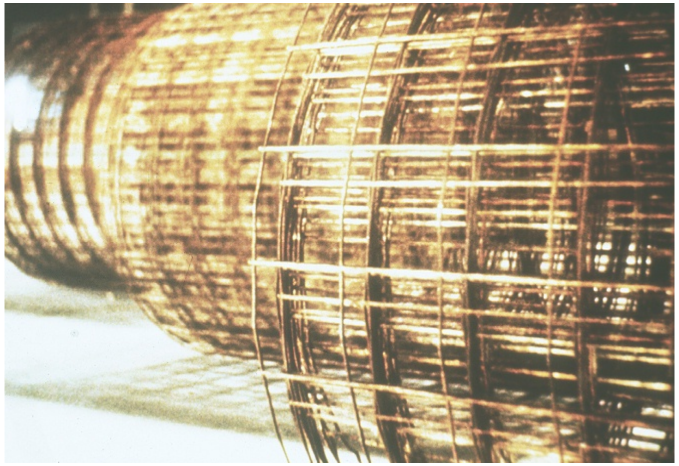


When curling / warping must be minimized, ACI 302 and 360 documents recognize the potential benefit of a granular fill placed over the vapor retarder, serving as a "blotter" to help equalize moisture loss from slab top and bottom.

Dampening the subgrade – similar effects

Even when no vapor retarder is used, a damp or wet subgrade can accentuate curling. Dampening the subgrade is generally <u>no longer recommended</u>.

Effects of distributed steel reinforcement on cracking

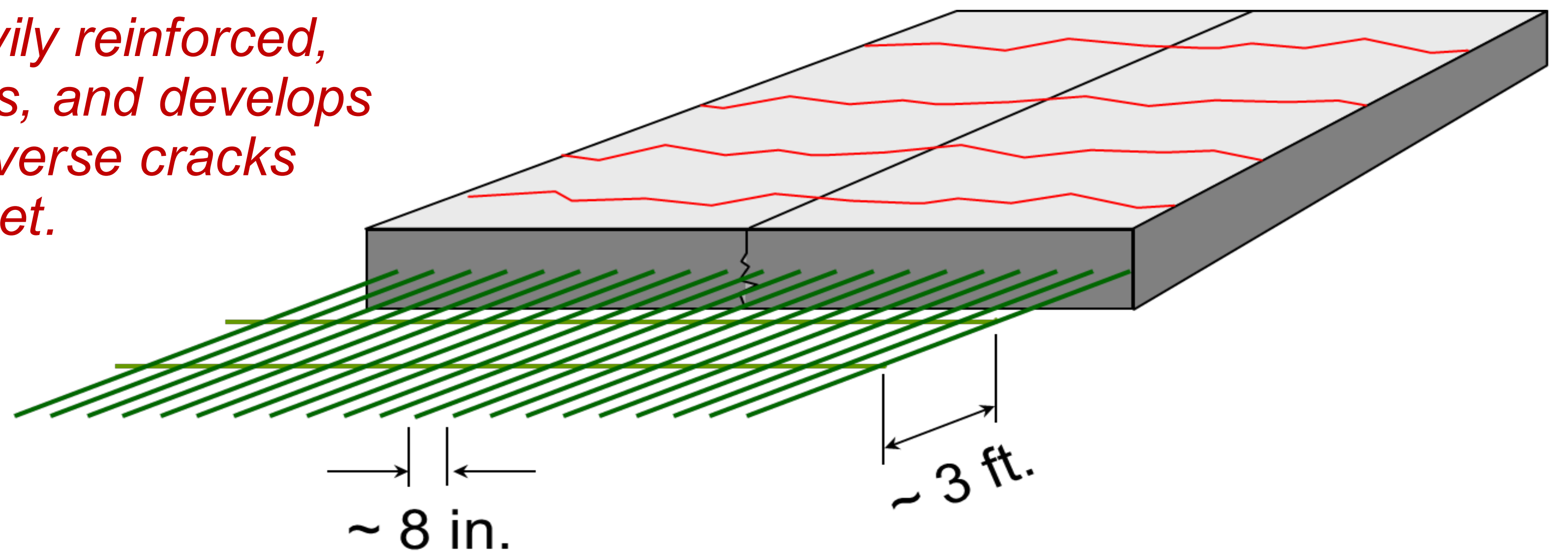


- Steel is <u>not recommended</u> for most flatwork apps
- Purpose is to control movement across cracks
- It never gets placed where it can function

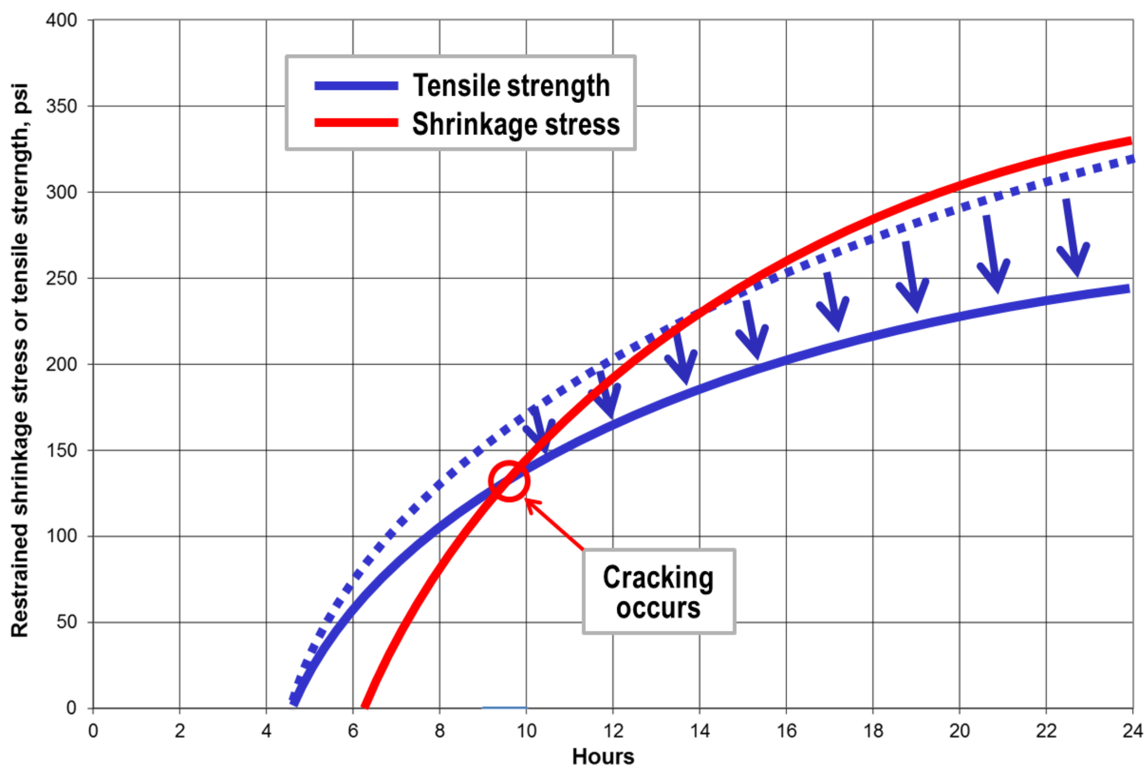
Effects of distributed steel reinforcement on cracking

- It's not just a bad idea, steel can cause <u>more</u> cracking
- The more steel and the longer the panel, the more cracks
- In typical use, steel **<u>should be cut at all joints</u>**
- For 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 on cracking



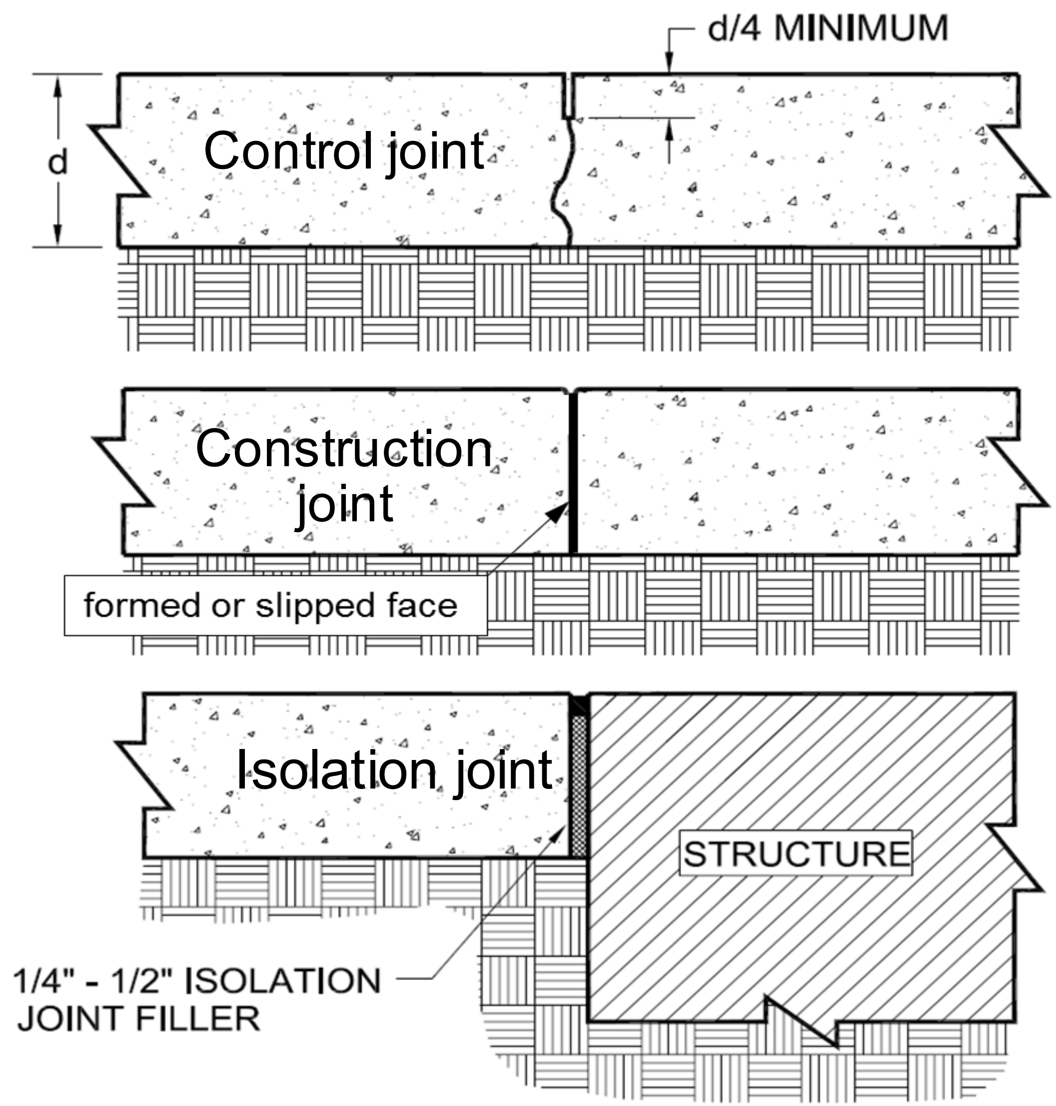
- Slow strength gain can be a cracking problem unless effective curing is used
  - Low temperatures
  - Low cementitious content
  - High SCM content
  - Retarding admixtures
- Immediate, extended curing becomes critical to delay shrinkage

Poor subgrade support

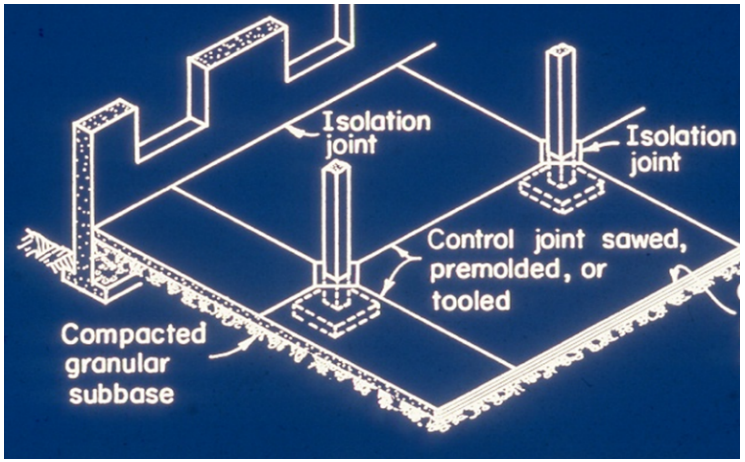
Unfortunately one of the most common causes of cracked flatwork

Flatwork jointing issues

- Cracking can be caused by using the wrong joint type or detail, or excessive joint spacings
- Most common mistakes:
  - 4 Too few joints
  - 4 Keyways (not recommended)
  - 4 Isolation joints as regularly spaced joints
  - 4 Staggered joints
  - 4 Isolation joints in high load areas, no load transfer
  - 4 Reinforcement through joints
  - 4 Joints not intersecting reentrant / structure corners



Recommended joint spacing for floors, feet



Slab thickness, in.	Maximum-size aggregate less than ¾ in.	Maximum-size aggregate ¾ in. and larger
5	10	13
6	12	15
7	14	18
8	16	20
9	18	23
10	20	25

from PCA EB075.02D

Recommended joint spacing for pavements

Slab thickness, in.	Maximum spacing, ft.
4 – 4.5	10
5 – 5.5	12.5
≥ 6	15

from ACI 330R-08

Exception: load transfer design may call for closer spacings.

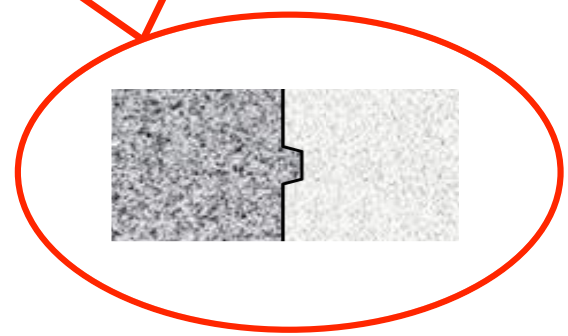
Sawed joints – effects of timing and depth of cut

Sawed joints must be made within 4-12 hours after final finishing, at least t/4 deep

 This joint was sawed soon enough

This one was sawed too late

Examples - poor joint details & related cracking



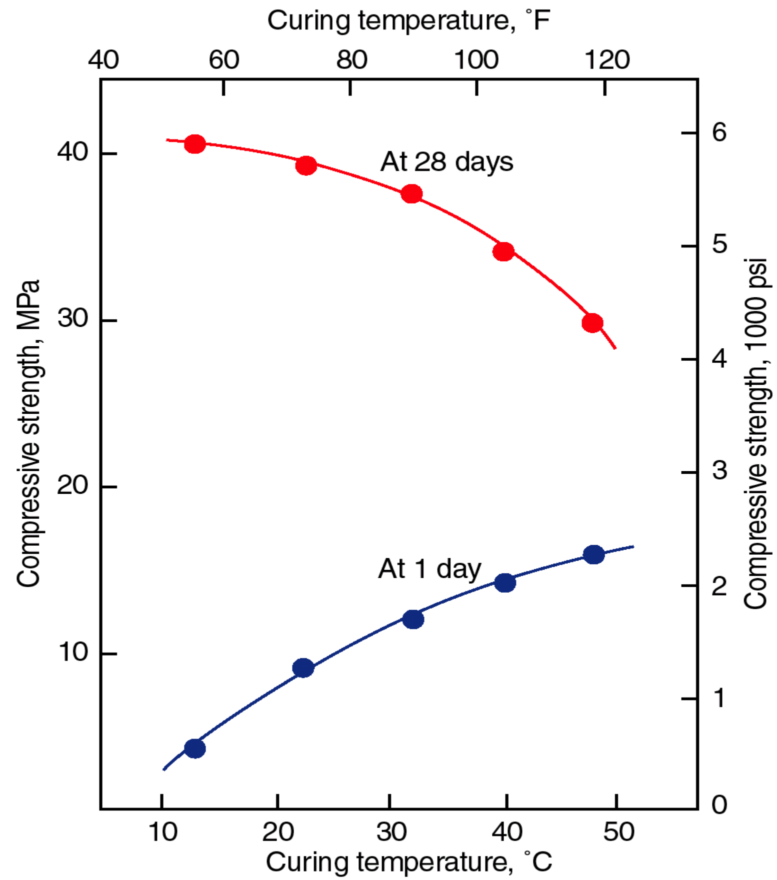
Joint spalling and frequent causes

- Incompressibles in joint
- Keyways
- Insert or isolation joint material not installed plumb
- Rocking action – curled slabs & rolling loads

Low strength test results – frequent causes

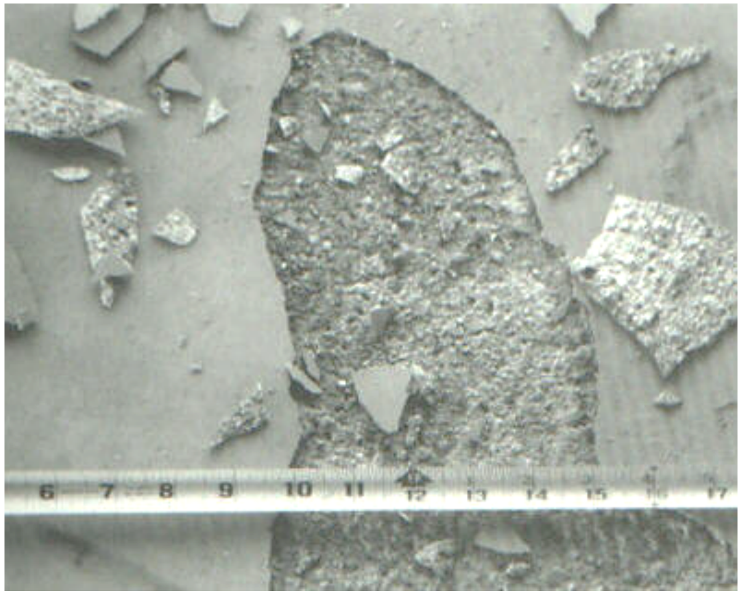
- Handling and curing of cylinders
- Air content issues
- Other jobsite sampling & testing issues
- Excessive on-site water addition
- Less frequent but possible:
  - Batching or mixing issues
  - Mix design adequacy & f'cr
  - Non-conforming materials
- NOTE: Required tests when strength results are to be used for acceptance:
  - Sampling (C172)
  - Strength specimens (C31)
  - Slump (C143)
  - Air content (C231 or C173)
  - Unit weight & yield (C138)
  - Temperature (C1064)

Concrete curing temperature and strength effects



- Standard curing requirements:
  - Initial curing (up to 48 hours), 60° to 60°F (68° to 78°F for f'c ≥ 6000 psi), in a moist environment (capped / sealed), documented temps via max/min recording thermometer
  - Final curing (immediately after initial curing, until test day), 73° ± 3° F, free water on exp. surfaces, storage tanks or rooms meeting Specification C511

Surface blemishes – delamination and blistering



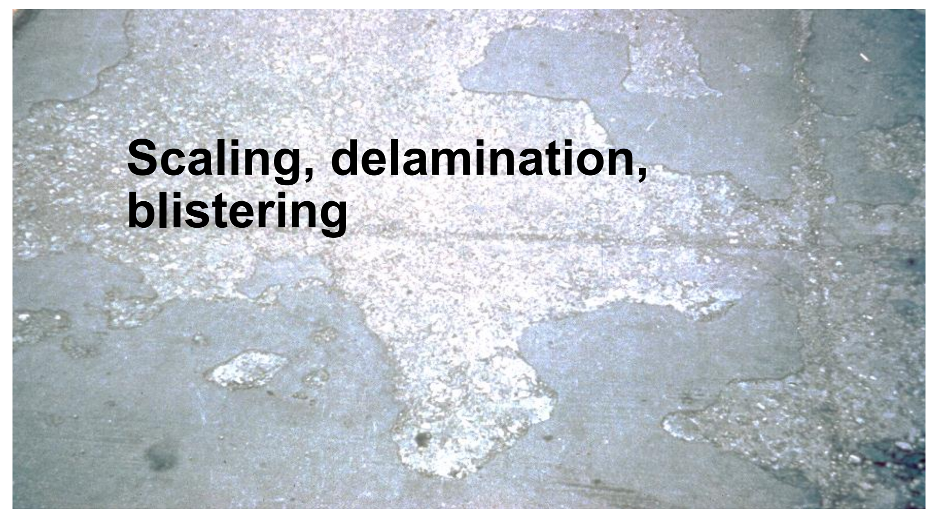
- Usually due to finishing while bleed water is still rising
- Can result from trowel finishing air entrained concrete

Detection: hollow sound w/ chain drag or hammer strike

Surface blemishes – scaling

- Insufficient air content or strength upon freezing
- Excessive slump, bleed water
- Premature finishing (delamination)
- Insufficient air drying period before exposure to deicing salts

Surface blemishes caused by finishing procedures



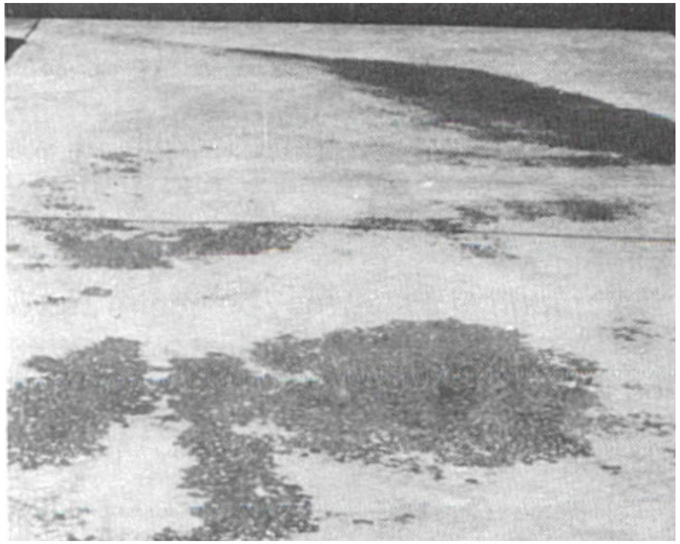
Practices that result in surface blemishes, poor durability

- Excessive water addition
- Overuse of bullfloat
- Premature finishing
- Sprinkling the surface during finishing
- Use of inappropriate tools
- Poor jointing or curing

Surface blemishes – popouts

- Usually caused by porous rock, moisture, & freezing
- Deleterious / organic materials in aggregates
- Can be caused by ASR

Surface discoloration, most prevalent causes



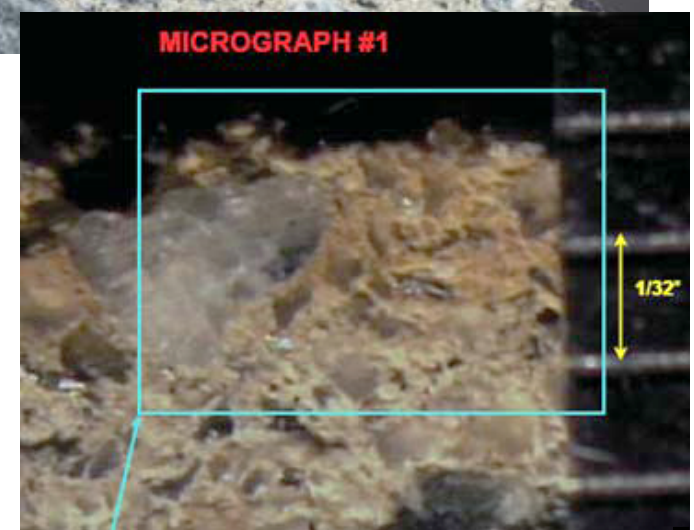
Inconsistencies in:
- Curing adequacy
- Bleed water
- Finishing procedures or timing

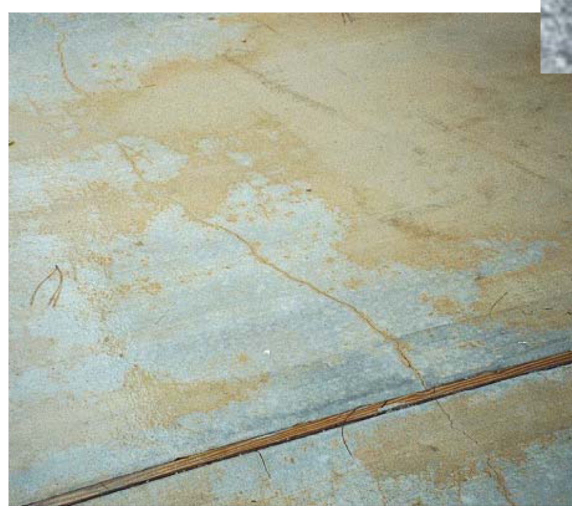
Use of calcium chloride

Dusting surface w/ cement

Fly ash – related (usually Class C)
- Mild blotches of buff hues to extreme (redish-brown) surface stains
- Usually happens with excess water and bleeding, may be exaggerated by curing with plastic sheeting

Surface discoloration, Class C fly ash staining examples





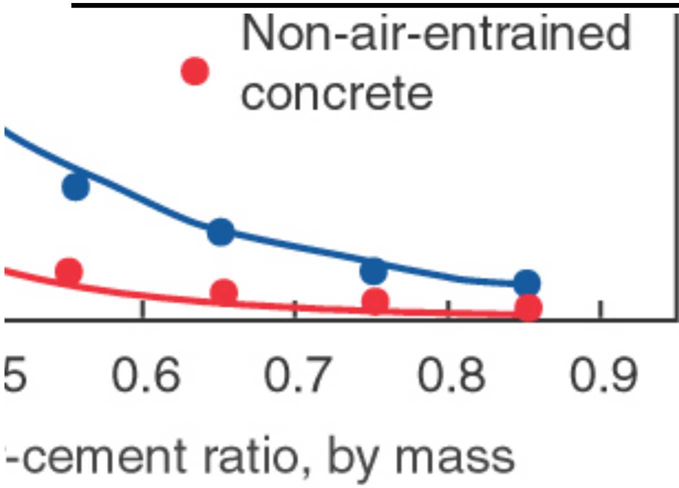
Surface discoloration / staining from efflorescence

- White deposit on surface of concrete
- Generally harmless
- Formed when soluble salts are carried to the surface by moisture
- Often most evident along cracks or joints

Concrete durability issues (less common)

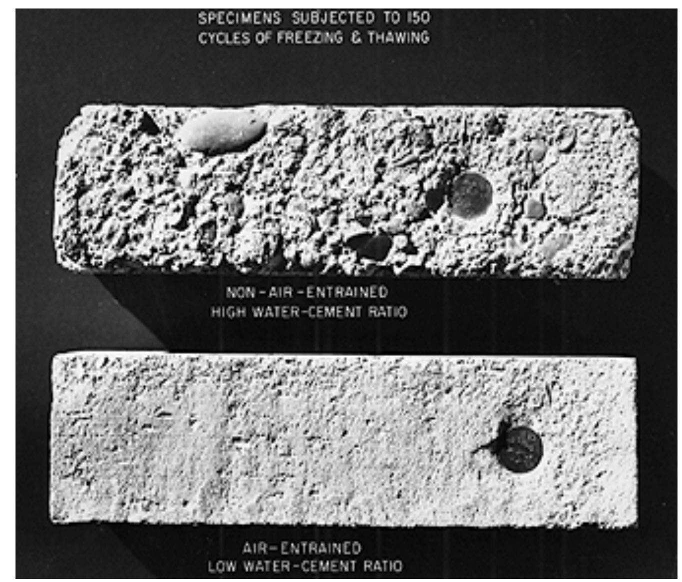
- Freeze / thaw
- Cracking
- Corrosion of steel
- Sulfate attack
- Alkali-aggregate reactivity
  - ASR
  - ACR

Control of concrete durability – freeze / thaw



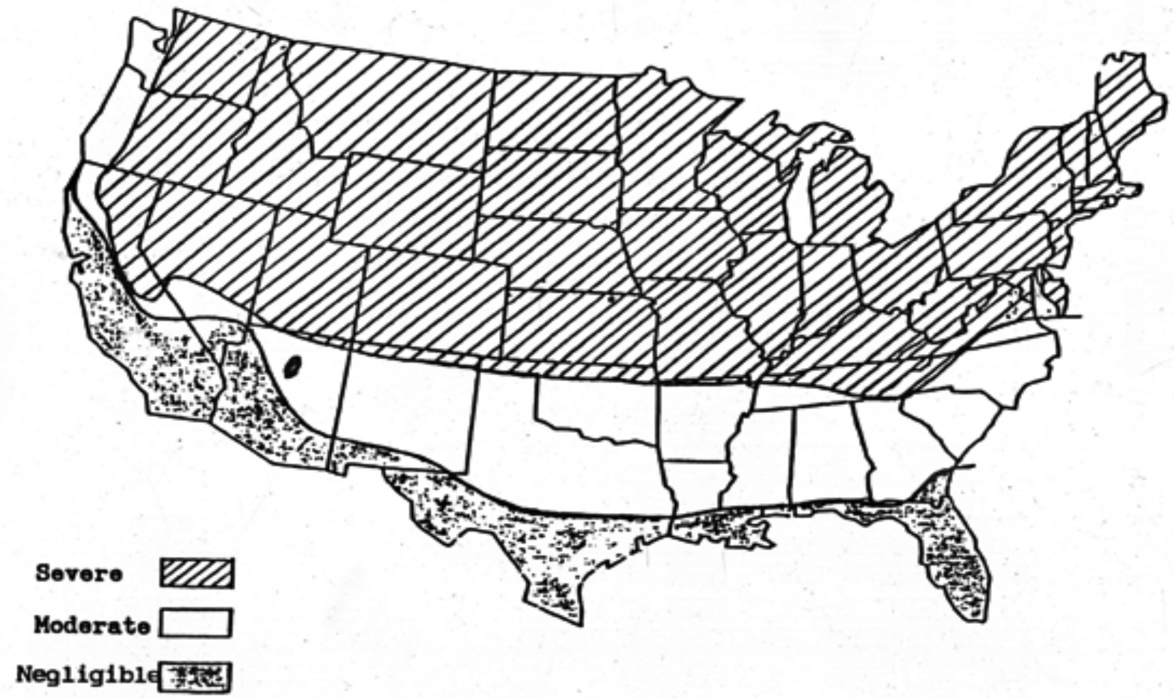
Both air entrainment and w/c are factors

Type I cement



Control of concrete durability – freeze / thaw

Exposure severity and recommended air content

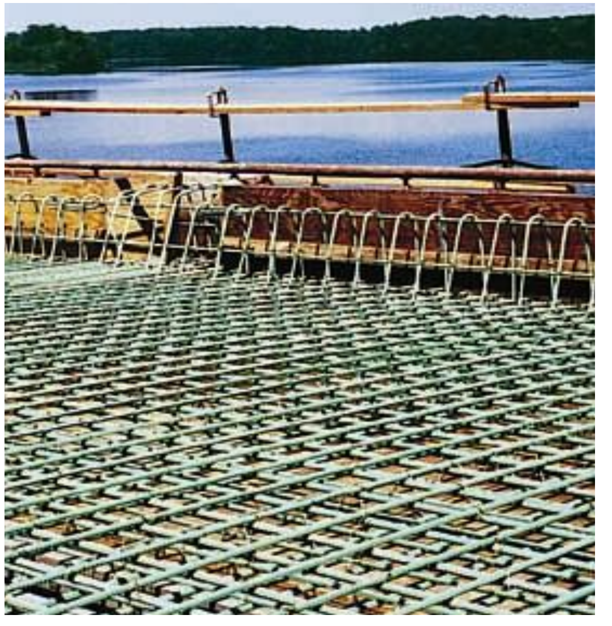


From ACI 211:

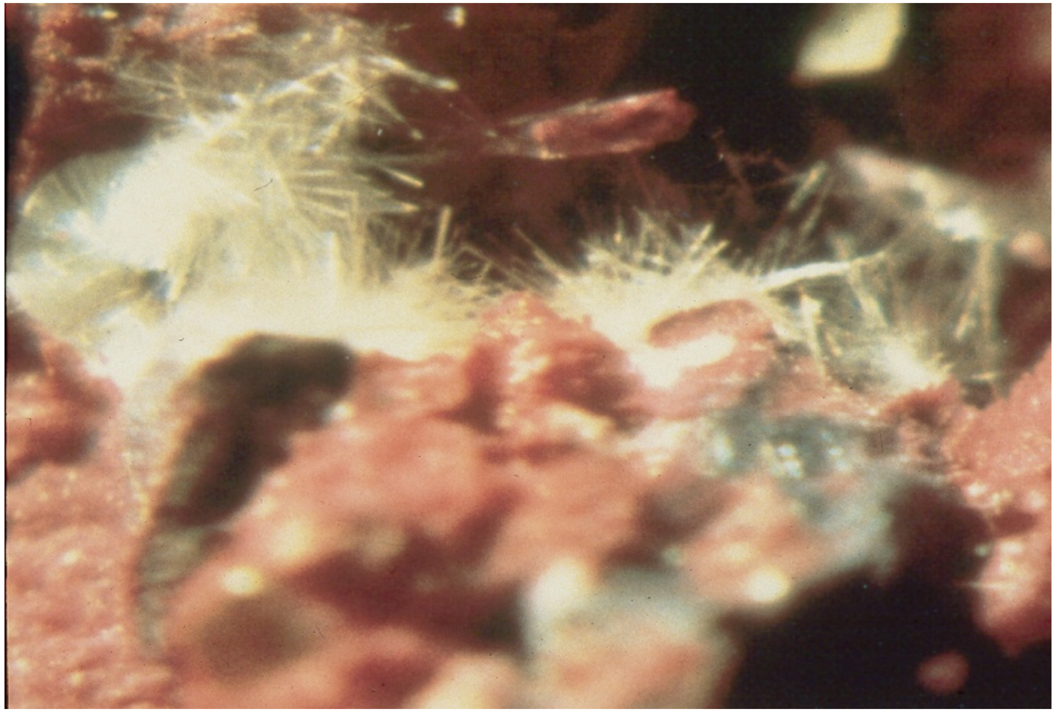
Recommended average total air content, percent, for level of exposure								
Max. aggregate size:	3/8 in.	½ in.	¾ in.	1 in.	1½ in.	2 in.	3 in.	6 in.
Mild exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
Moderate exposure	6.0	5.5	5.0	4.5	4.5	4.0	3.5	3.0
Severe exposure	7.5	7.0	6.0	6.0	5.5	5.0	4.5	4.0

Control of concrete durability – rebar corrosion

- Low w/cm ratio
- Moist cure
- Reduced permeability with SCM's
- Increased concrete cover
- Corrosion inhibitors
- Epoxy-coated reinforcing steel
- Concrete overlays
- Surface treatments
- Cathodic protection



Control of concrete durability – sulfate attack



Magnified ettringite in dyed concrete paste

Appearance of concrete affected by sulfate attack

- Expansion of paste due to growth of ettringite crystals, requiring:
  - Source of external sulfates in solution
  - Moderate or greater permeability
  - Wetting and drying (transport)
  - Available reactive aluminates

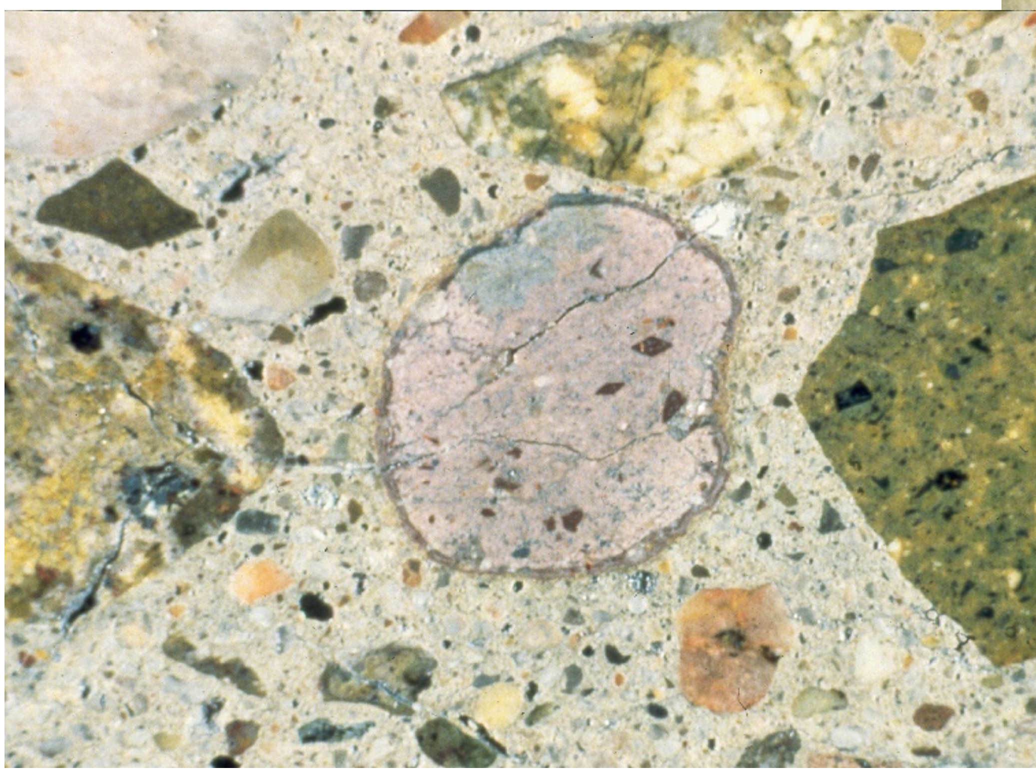
Control of concrete durability – sulfate attack mitigation

- Moderate exposure
  - type II cement
  - type I cement + fly ash or GGBFS
  - blended cement
- Severe exposure
  - type V cement
  - type II cement + fly ash or GGBFS
  - blended cement or ternary mix
- Very severe exposure
  - type V cement + fly ash or GGBFS
  - special blends with extreme resistance

Control of concrete durability – alkali-silica reactivity (ASR)

ASR deterioration of concrete

Polished section view of
ASR effects



- Expansion due to growth of byproduct rings around aggregate particles, from chemical interaction between reactive silica-containing aggregates and available alkalis in cement paste

Cementitious materials and w/cm for durability

- Corrosive environments
  - Mineral admixtures & GGBFS for reduced permeability
- Sulfate exposure
  - Cement type
  - Fly ash, GGBFS
- ASR potential
  - Low alkali cement
  - Fly ash, GGBFS
- All influenced directly by permeability, thus indirectly by w/cm

Abnormal behavior due to incompatibility of materials

"Incompatibility" of concrete materials

- Occurs when there are higher demands for sulfates (gypsum) in fresh concrete than the cement can supply, complicated by admixtures, some SCM's (esp. Class C fly ash), hot weather
- Early C3A hydration becomes excessive, resulting in unpredictable set effects and/or slump loss, interrupted strength gain

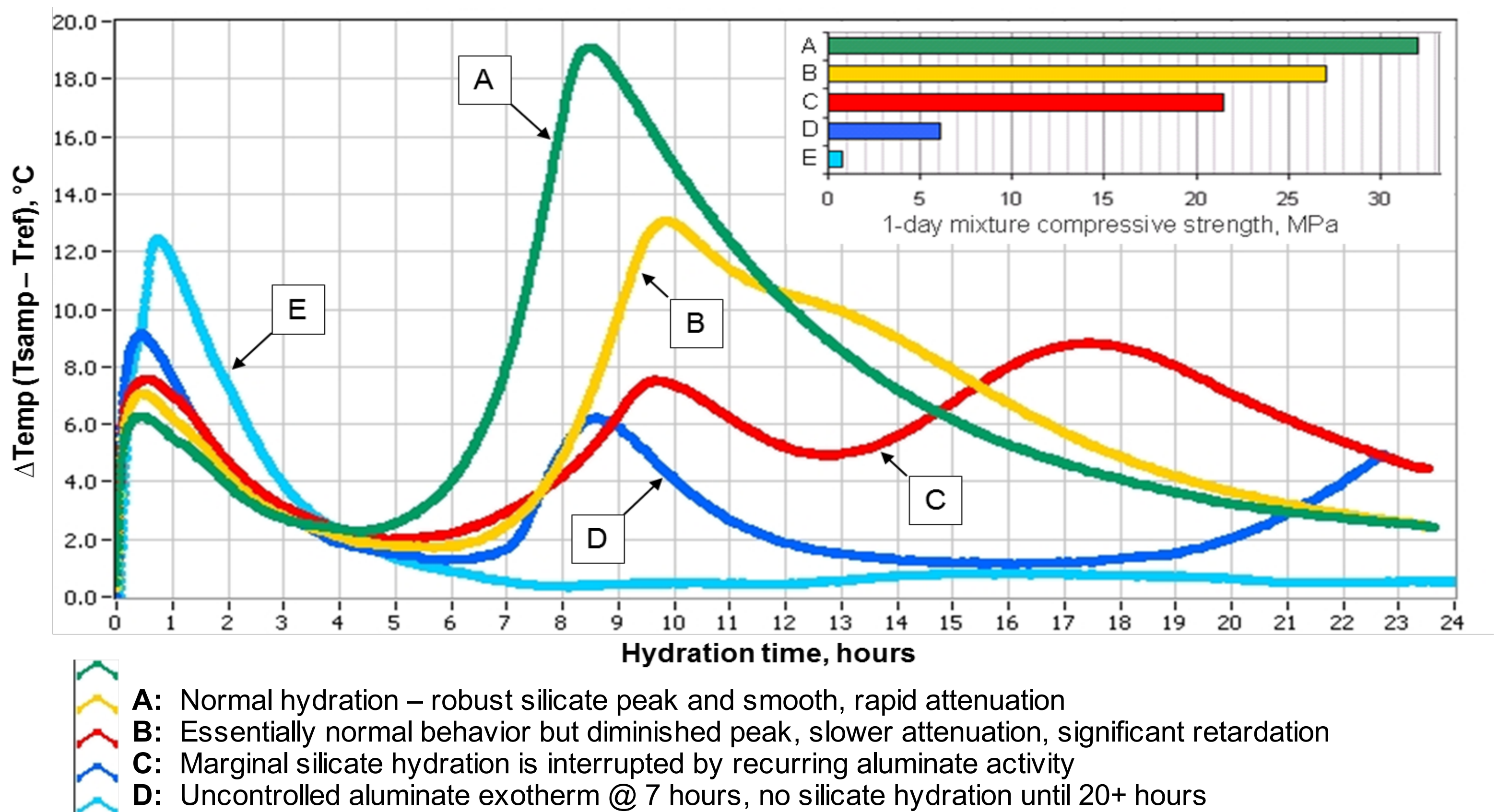
Related concrete behavior:

- Mild cases:
  - Increased rate of slump loss
  - Ssomewhat extended set time
  - Sluggish early-age strength gain
- Severe cases:
  - No normal set for 1-2 days, or…
  - Flash set (extreme cases)
  - No strength gain for several days

Diagnosing incompatibility using simple "calorimetry"

Sulfates-related abnormalities are clearly evident in thermal profiles:

- Normal behavior = traditional thermal profiles with normally timed peaks
- Abnormal behavior = misshapen profiles or non-traditional behavior, indicating a mixture sulfate imbalance (incompatibility)



A: Normal hydration – robust silicate peak and smooth, rapid attenuation
B: Essentially normal behavior but diminished peak, slower attenuation, significant retardation
C: Marginal silicate hydration is interrupted by recurring aluminate activity
D: Uncontrolled aluminate exotherm @ 7 hours, no silicate hydration until 20+ hours
E: Flash set from immediate, uncontrolled aluminate activity, no silicate hydration thru test period

Questions?

Holcim

Tim Cost, P.E., F. ACI
tim.cost@holcim.com