Types of Cracking and Influencing Causes

TRB Cracking Webinar May 25, 2016

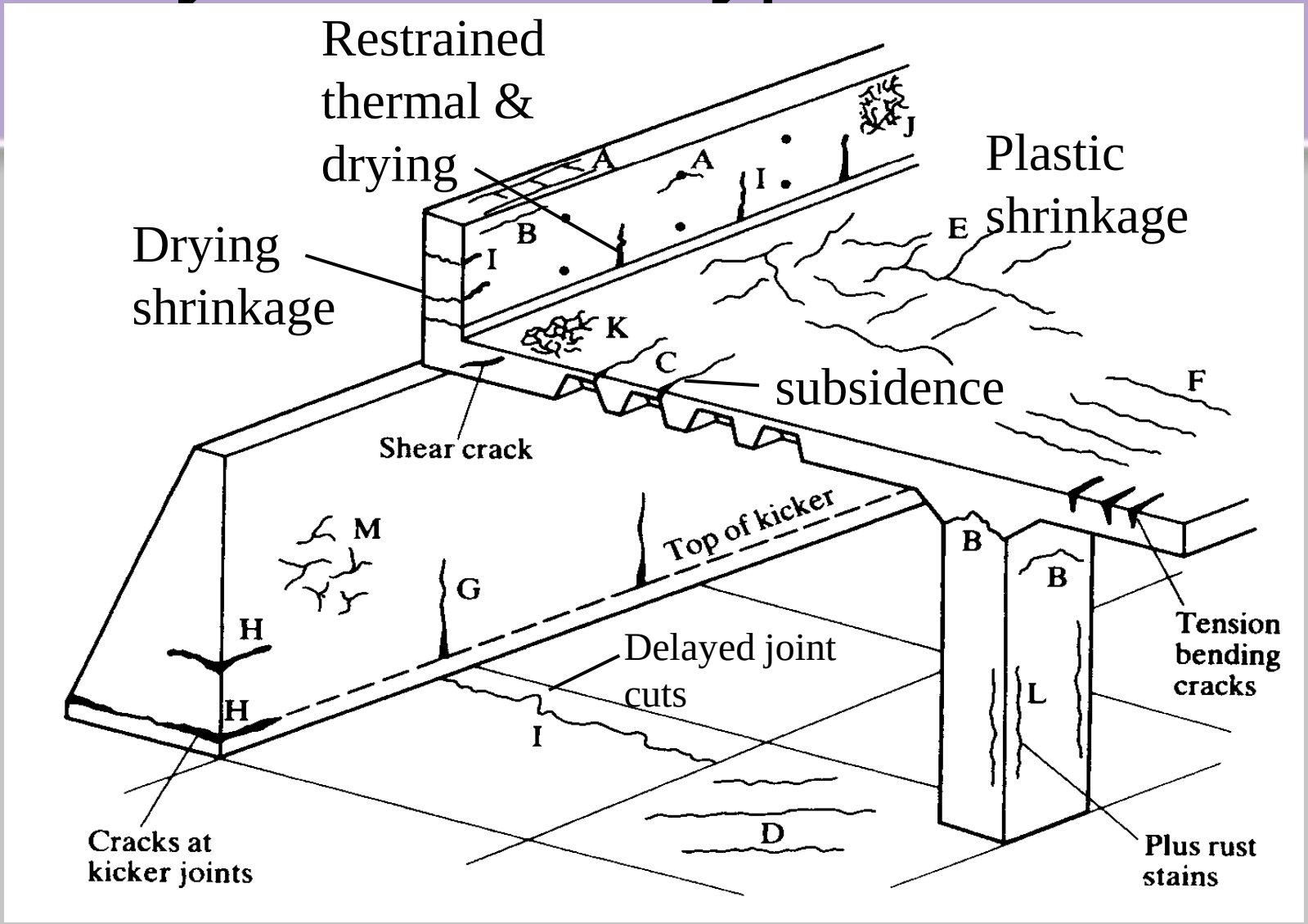
R. Doug Hooton

NSERC/ Cement Association of Canada, Senior Industrial Research Chair in Concrete Durability & Sustainability

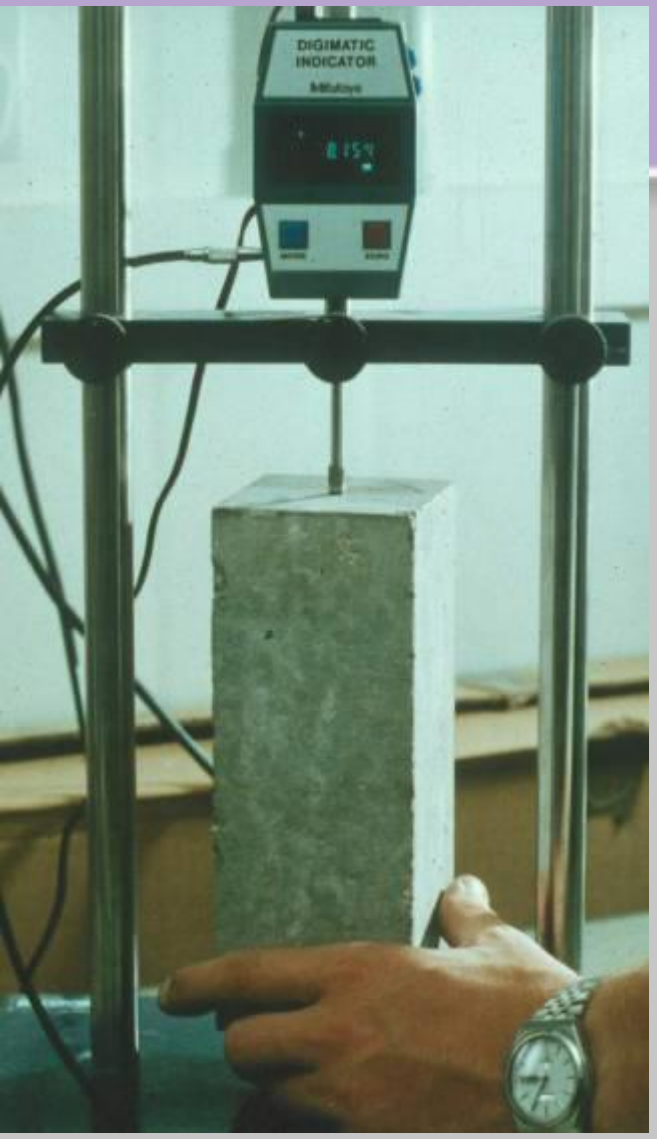
hooton@civ.utoronto.ca

UNIVERSITY OF TORONTO
DEPARTMENT OF CIVIL ENGINEERING

Many Potential Types of Cracks



Volume Changes That Influence Cracking



1. Chemical/ autogenous shrinkage
2. Plastic shrinkage, subsidence
3. Drying shrinkage
4. Thermal exp’n/contraction
5. Creep

Chemical Shrinkage of Hydrating Cement

- Chemical shrinkage occurs due to the reduction in absolute volume of solids and liquids in the hydrating paste.
- Chemical shrinkage continues to occur as long as cement hydrates.
- After initial set, the paste resists deformation, causing the formation of voids in the microstructure.

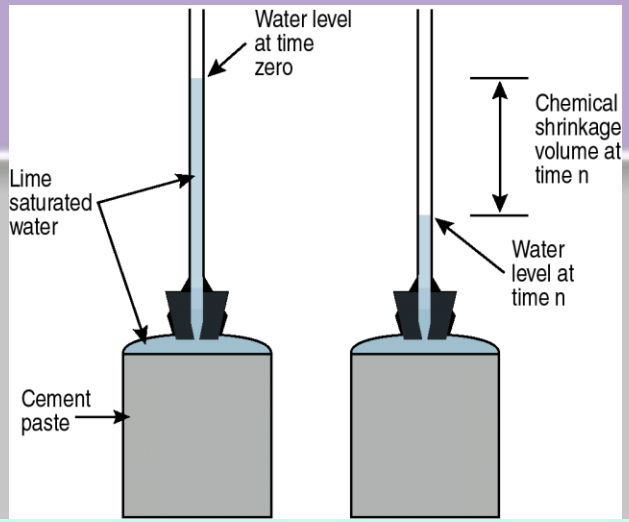
Chemical Shrinkage is not just limited to cement hydration

- Occurs when the volume of the products of chemical reaction is smaller than the sum of the initial reactants.
- Eg. 0.50L of Ethanol mixed with 0.50L of water will only result in 0.96L of fluid (Wikipedia).
- Or 0.5L of cement mixed with 0.5L water, if well hydrated, will result in ~0.94L of hydrated solid material.

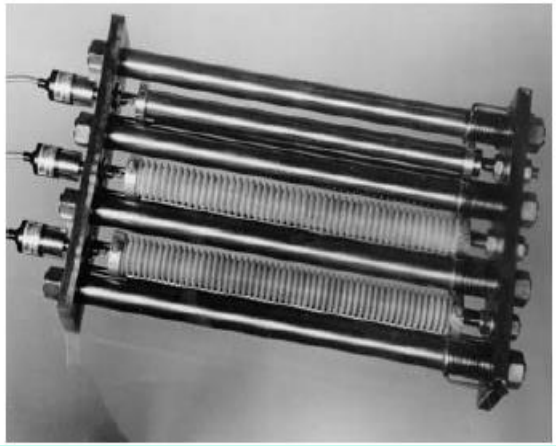
Autogenous Shrinkage

- Autogenous shrinkage is the dimensional change of concrete caused by chemical shrinkage.
- When internal relative humidity is reduced below a given threshold (i.e., extra water is not available), self-desiccation of the paste occurs, resulting in a uniform reduction of volume.
- **Becomes significant at low water/cement ratios, less than about 0.42**

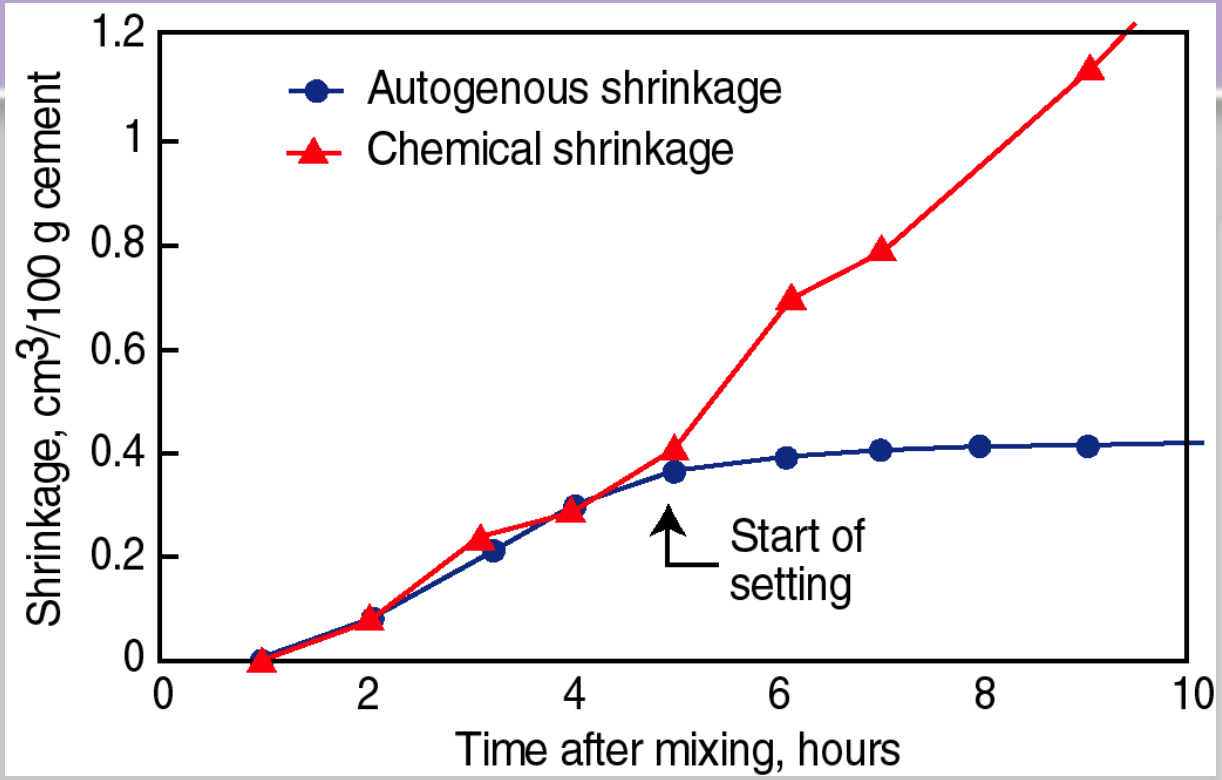
Chemical and Autogenous Shrinkage of Cement Paste



ASTM C1608



ASTM C1698

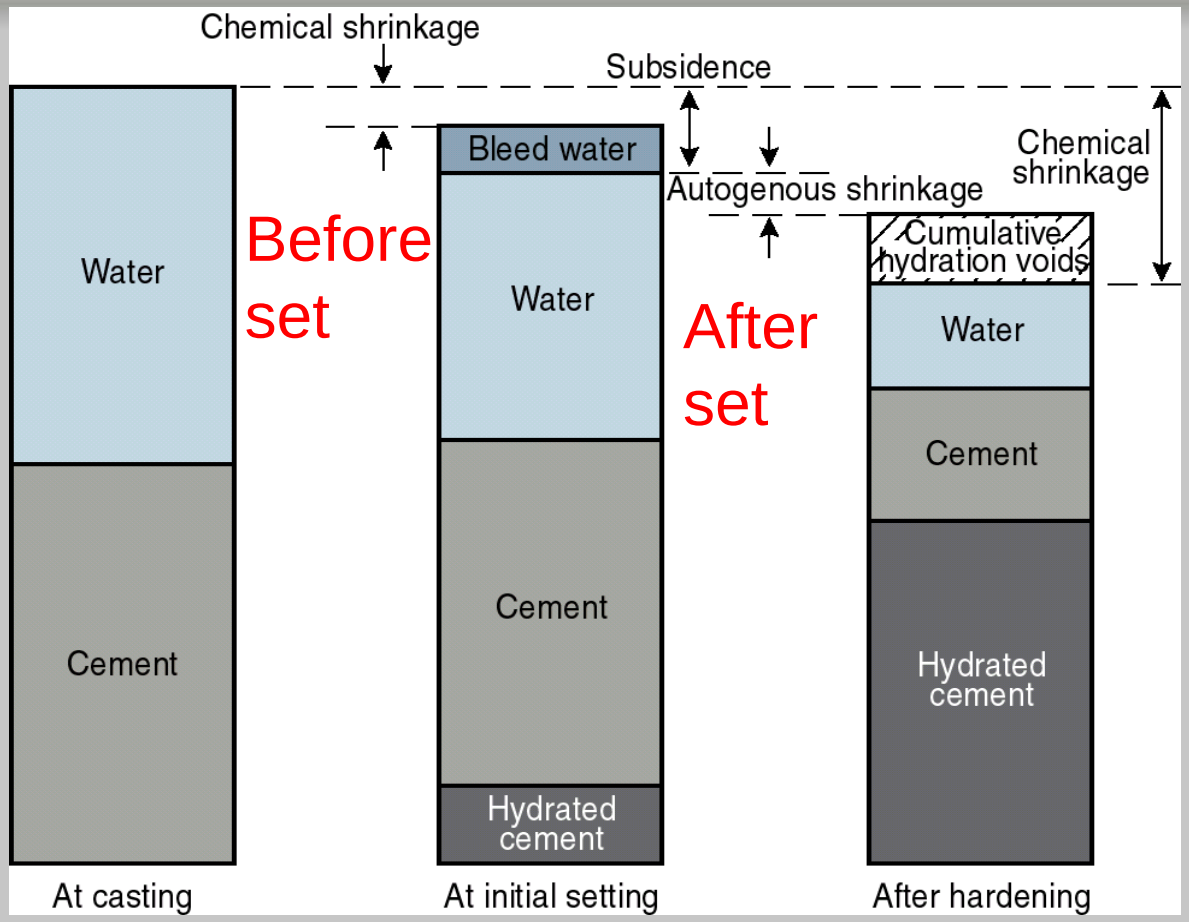


Becomes significant at low w/cm typical of HPC mixtures

Figure from PCA Design & Control of Concrete Mixtures

R D Hooton U. of Toronto, TRB Webinar May 25, 2016

Volumetric Relationship Between — Subsidence, Bleed Water, Chemical and Autogenous Shrinkage



PCA Design & Control of Concrete Mixtures

R D Hooton U. of Toronto, TRB Webinar May 25, 2016

Window of Finishability or Window of Plastic Shrinkage Cracking

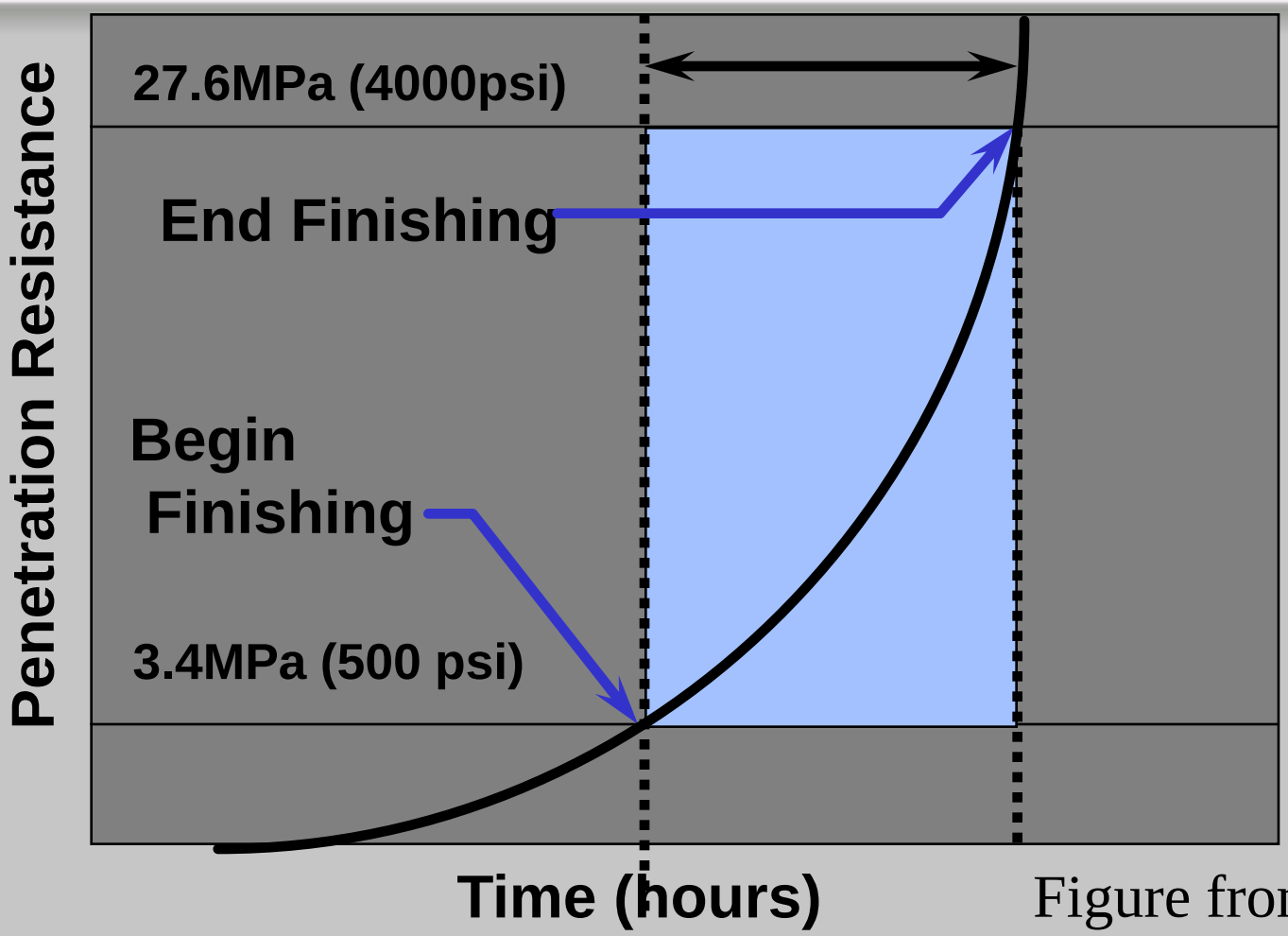
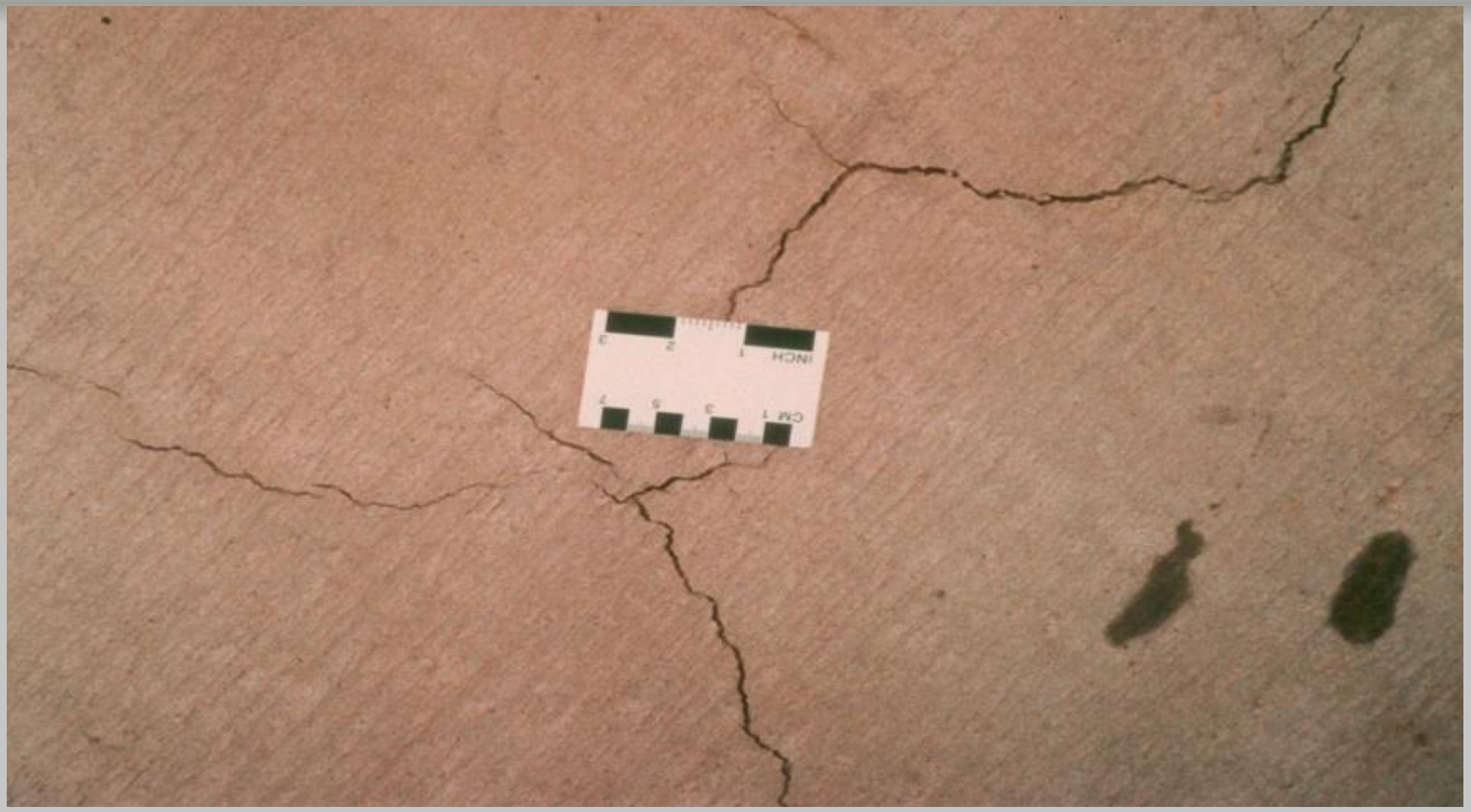


Figure from K. Hover

From initial float until time of set and application of curing

Plastic Shrinkage Cracks on HPC Bridge Deck
(delayed set & lack of evaporation control)



Sprayed on Evaporation Retarder

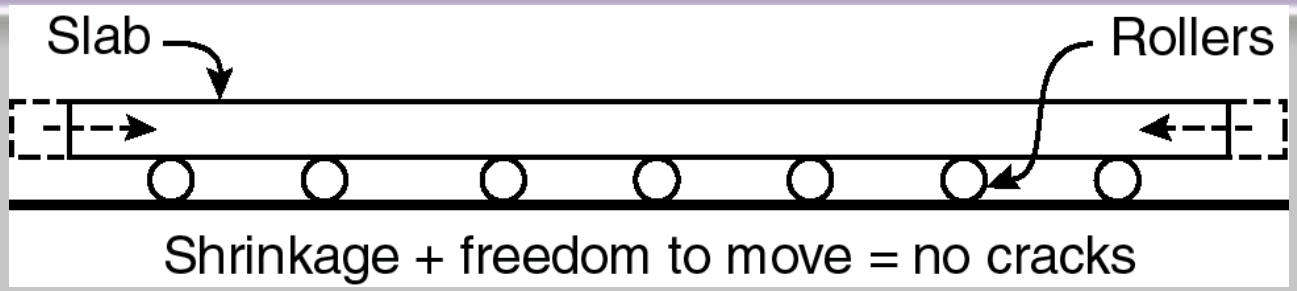
Fog Misting from Upwind Edge

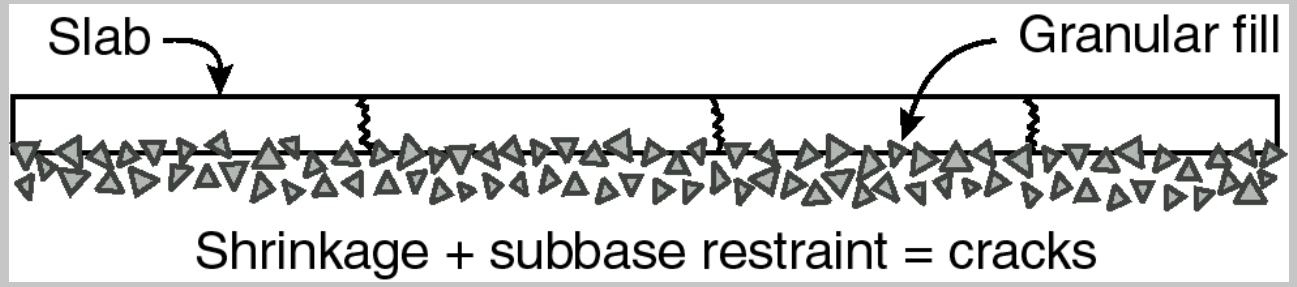
One short plastic crack near edge of deck

Epoxy Repair of plastic shrinkage cracks on new bridge deck (~1991)

good concrete between the cracks

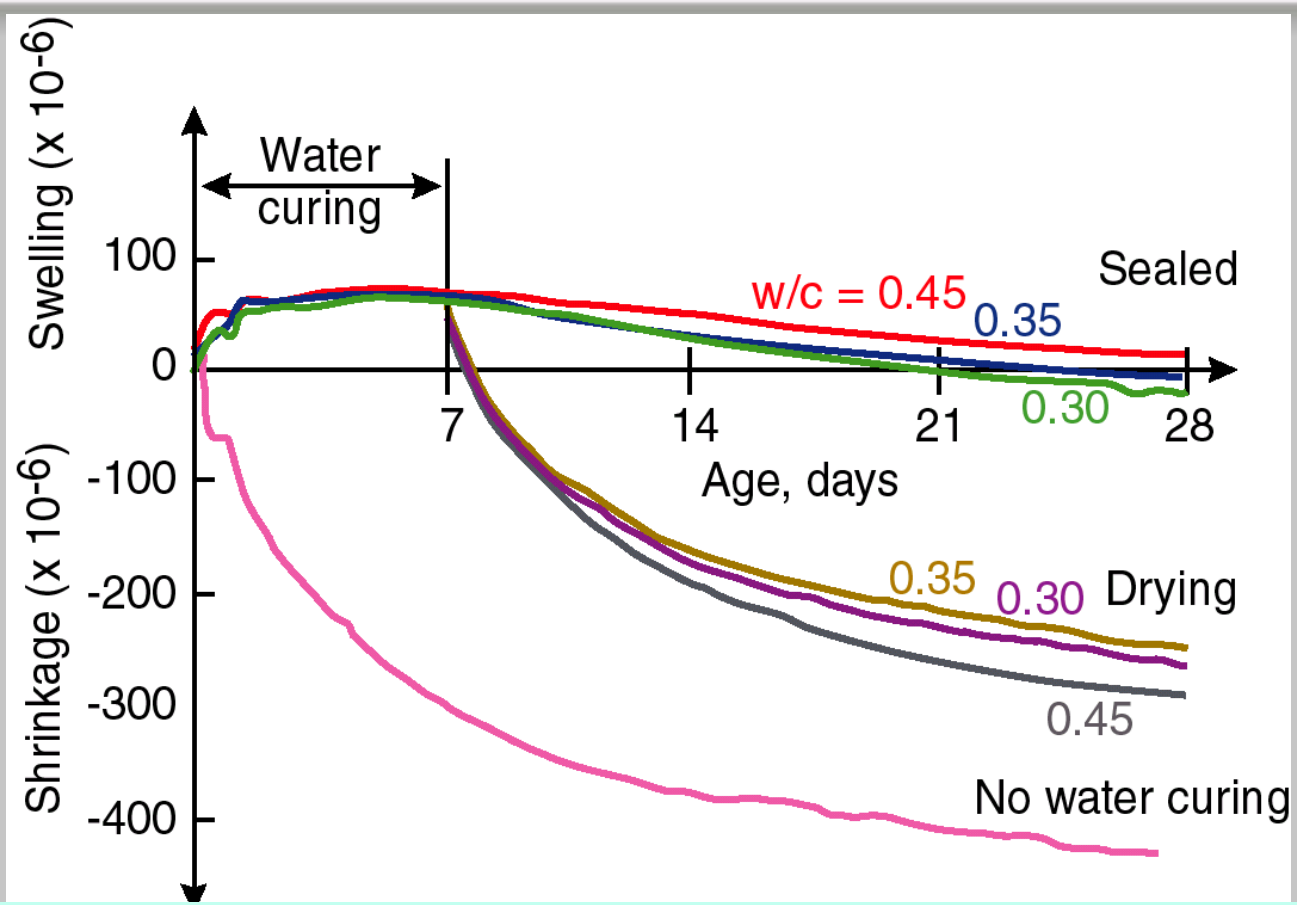
Drying Shrinkage and Cracking





Cracking results from restraint.

Influence of Wet Curing on Shrinkage



More curing reduces on-set and rate of drying shrinkage

Drying Shrinkage and Water Content

Specifying min. cement contents prevents producer from reducing unit water content of mixture

Use of water reducers will reduce shrinkage

Less shrinkage with more aggregate (better packing & larger max. size agg.)

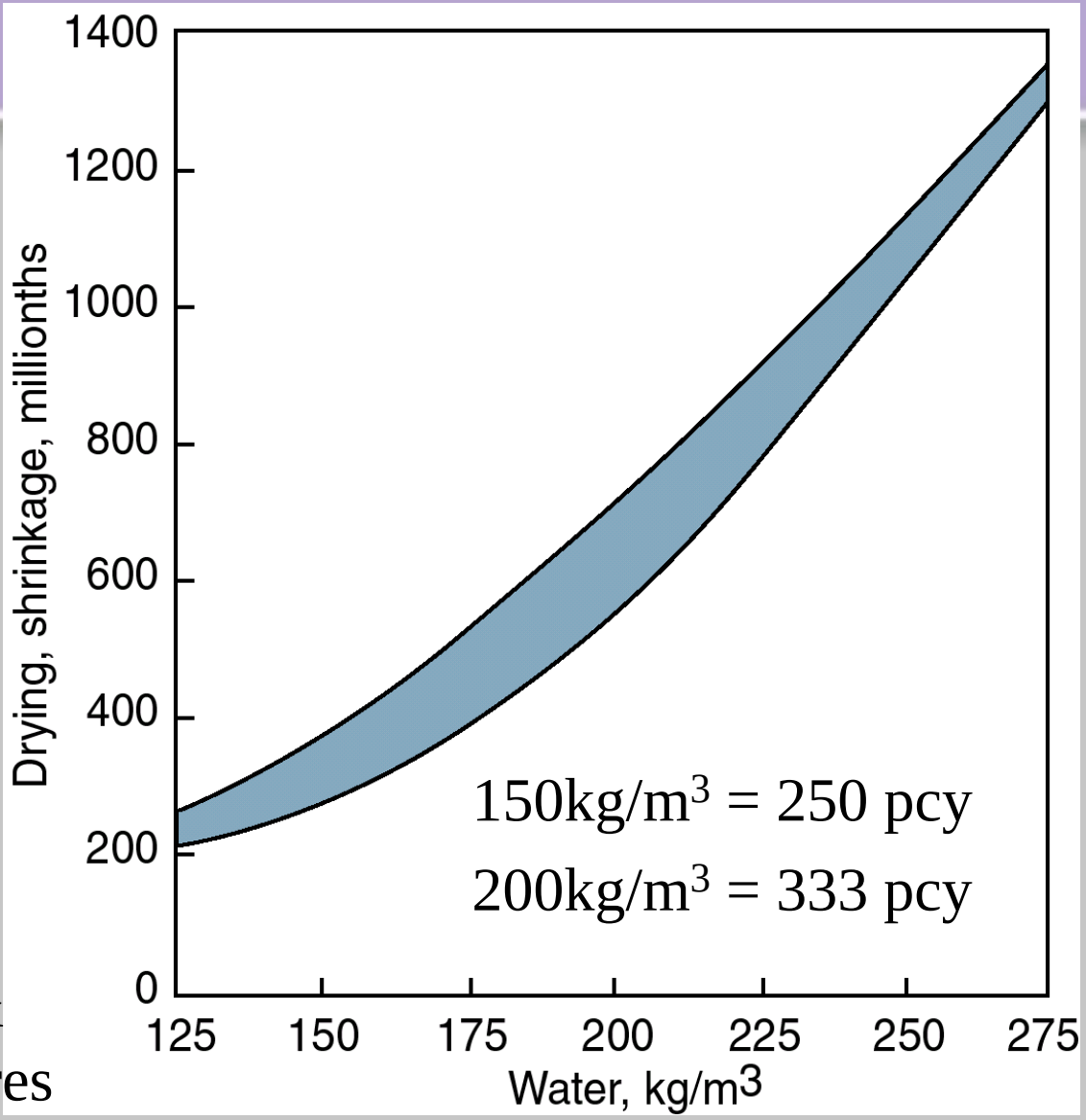
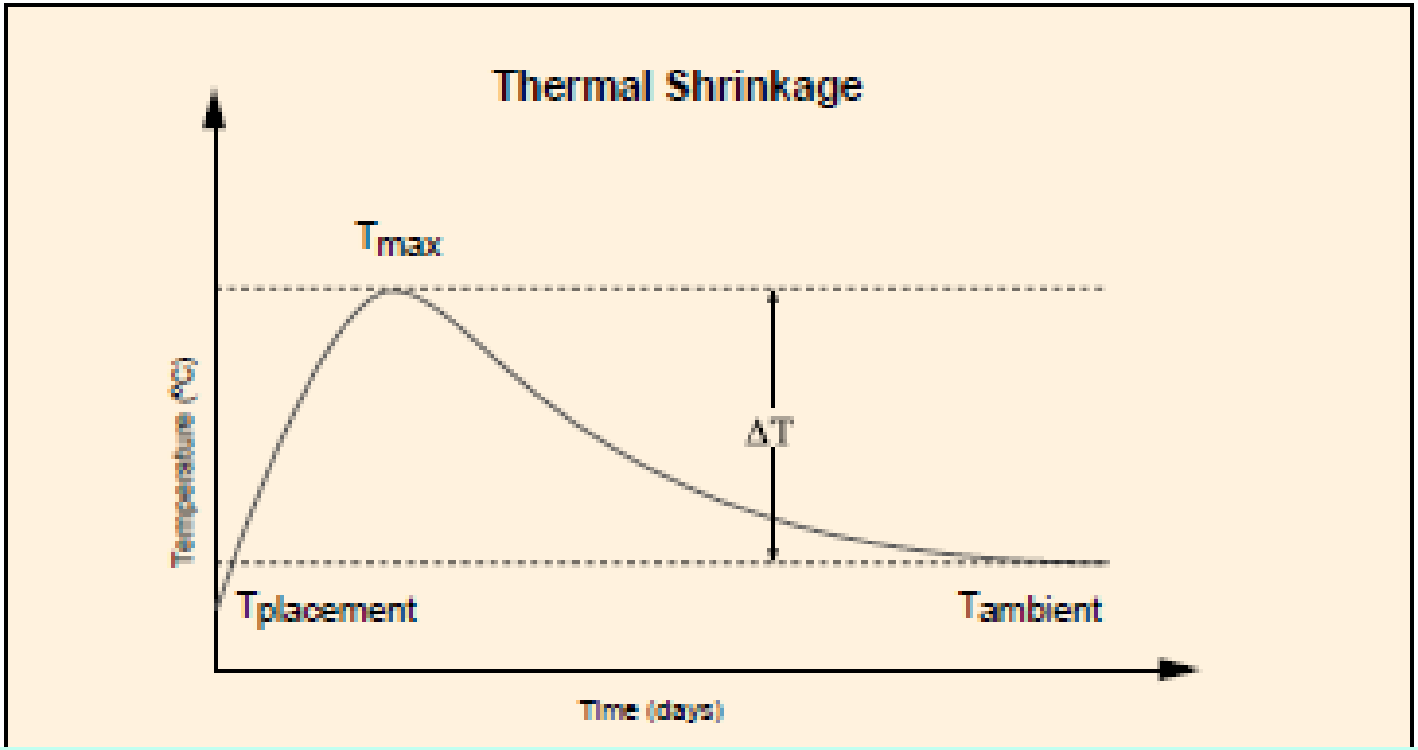


Figure from PCA Design & Control of Concrete Mixtures

Thermal Cracking

- Can result from **excessive temperature gradients** resulting from heat of hydration of cement.
- Can also result from **restraint from adjacent cool temperature components** preventing contraction on cooling (often seen on barrier walls dowelled into previously placed base slabs, with cracks starting from the bottom).

Heat Rise in Concrete Due to Hydration of Cement



As concrete heats up it swells, then it contracts on cooling back to ambient temperature----inducing tensile stresses

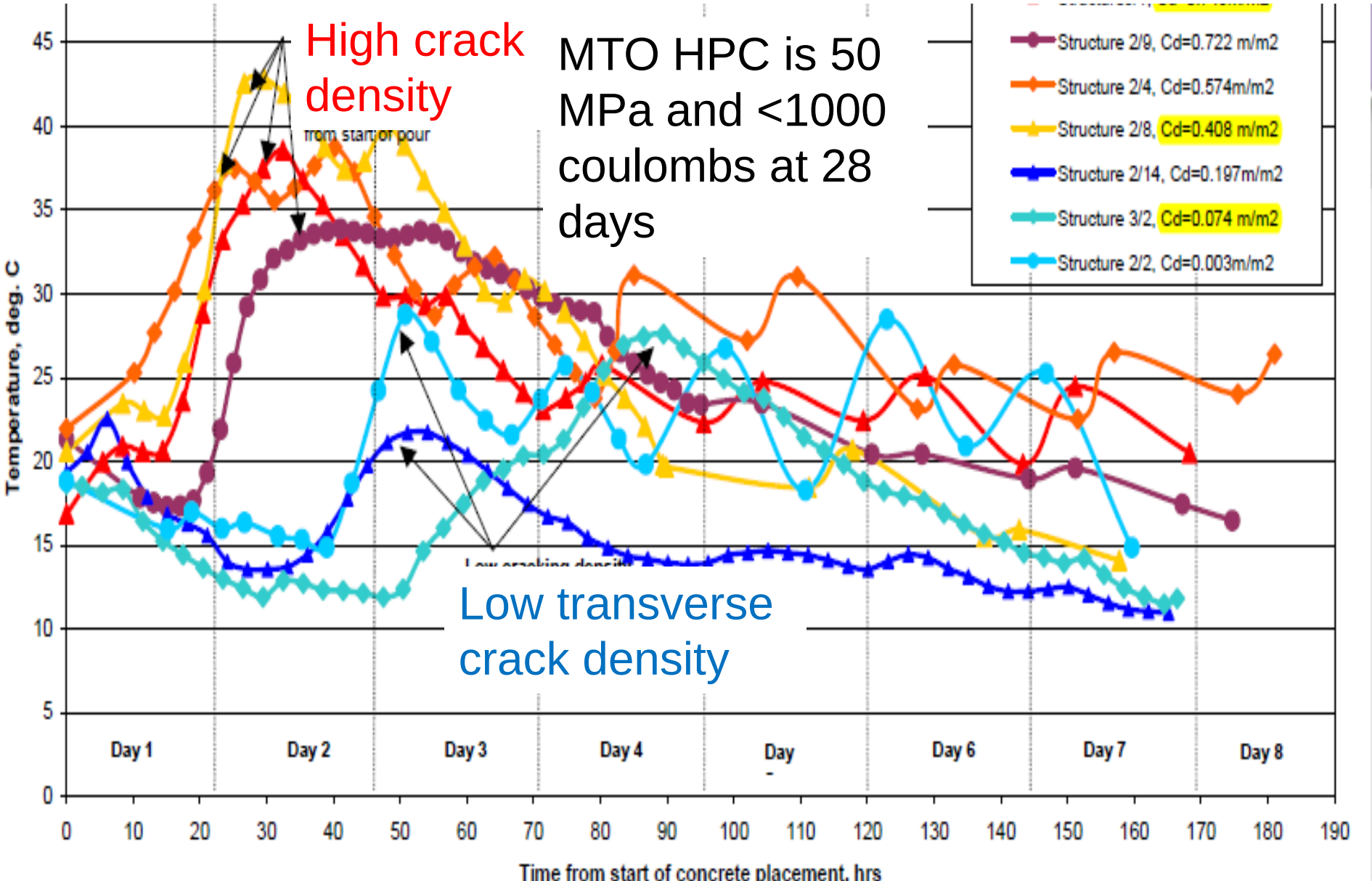
Thermal Length Change

- Concrete contracts about 6×10^{-6}/ ^{o}F
- (10×10^{-6}/ ^{o}C) on cooling.

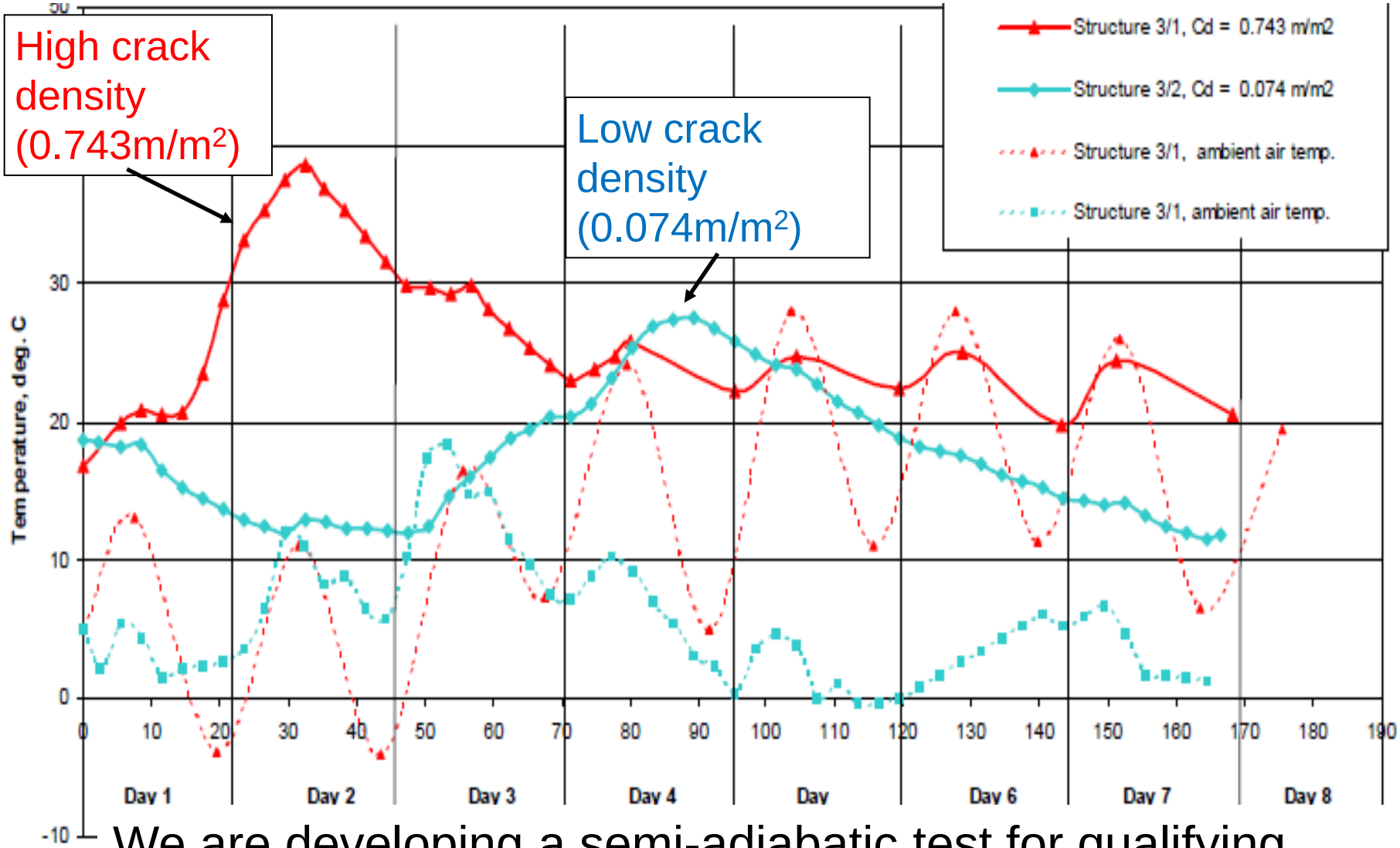
  (varies with volume and type of coarse aggregate)
- The outside cools faster than the core so tensile stresses can cause cracks if the thermal gradient > 35°F (20°C)
- With bridge decks, the substructure is cool and similar gradients will induce transverse cracking

Water Leaking Through New Bridge Deck Due to Transverse Cracks (thermal + shrinkage)

Concrete Temperature development for different HPC Bridge Decks (MTO 2012)

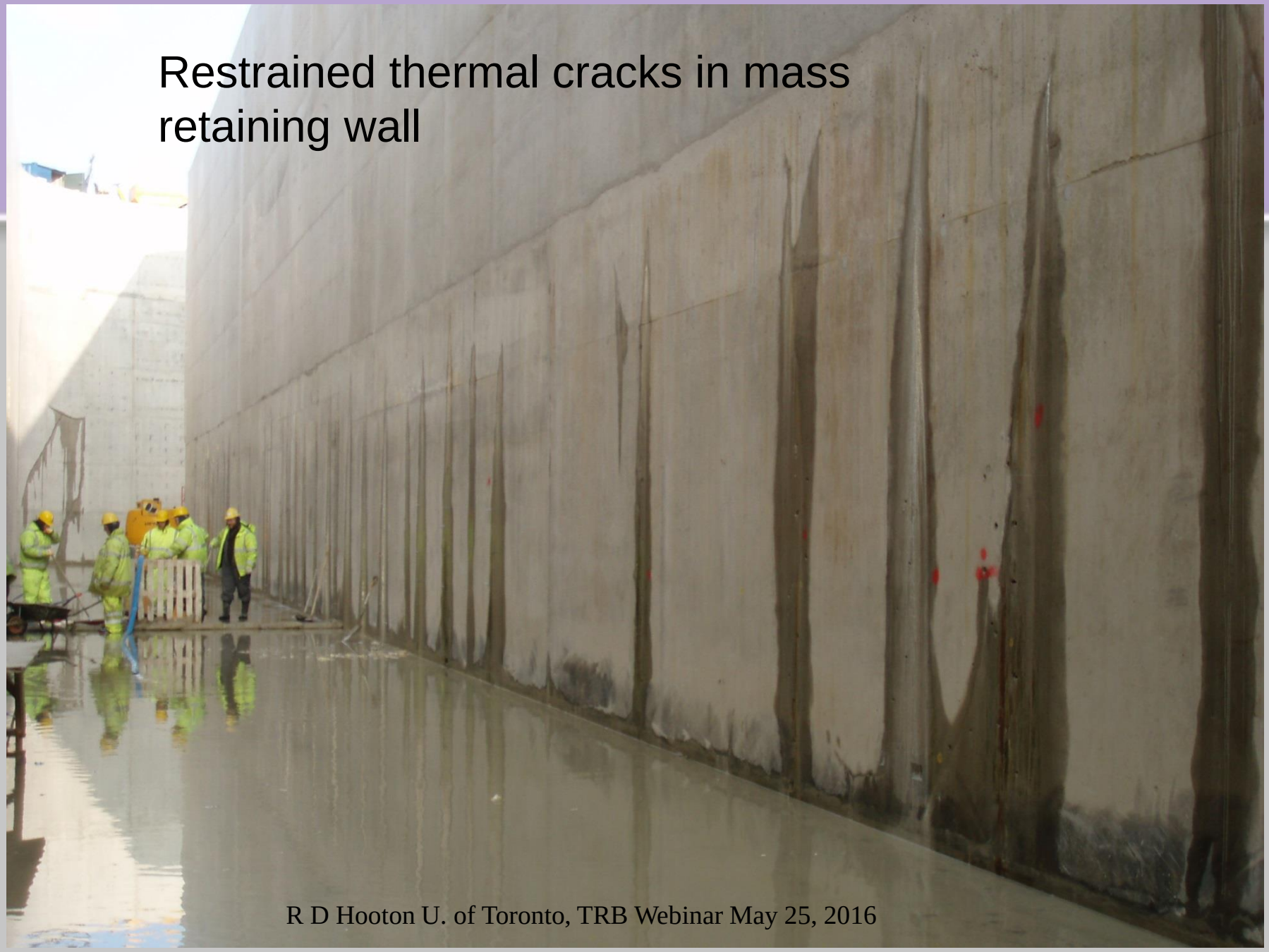


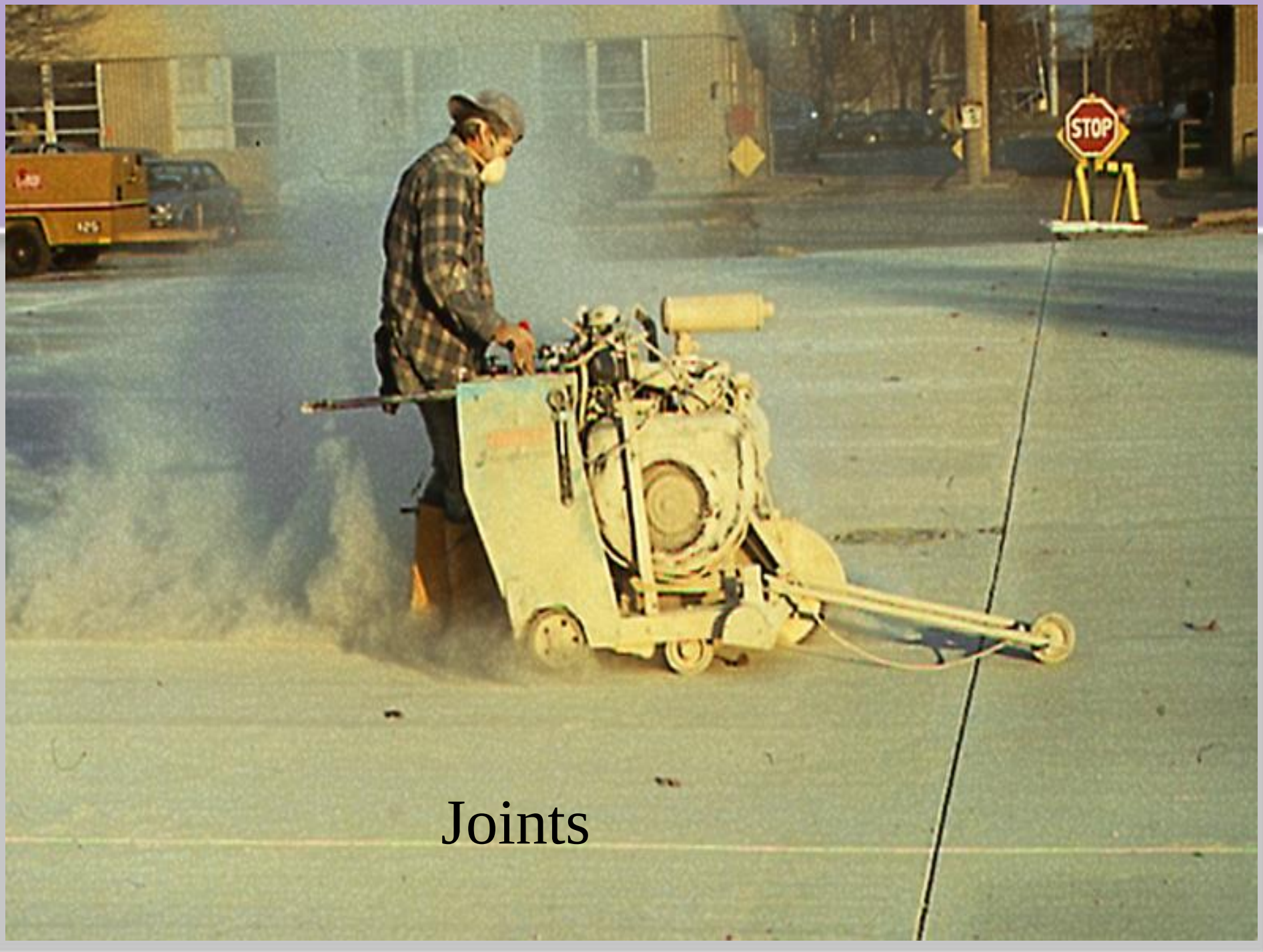
Two HPC Bridge Decks with high and low crack density (MTO 2012)



We are developing a semi-adiabatic test for qualifying mixes that measures thermal and autogenous shrinkage

Restrained thermal cracks in mass retaining wall

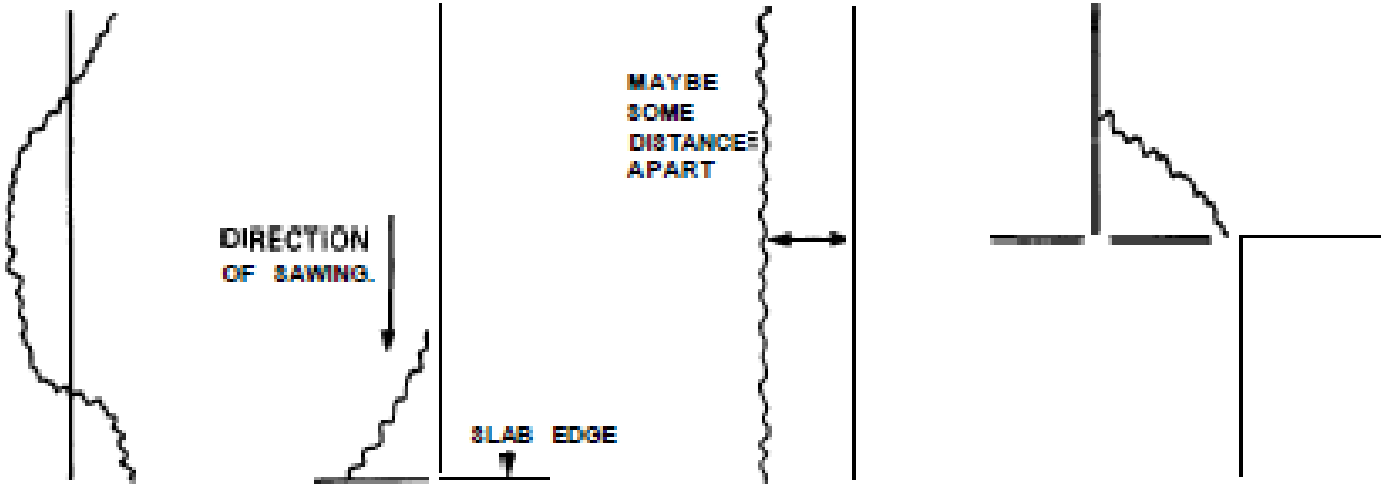




Joints

Saw Cuts 1/3 depth of 400 mm (16 inch) thick airport pavement

Causes of Random Cracks near saw-cut joints



(D) Crack follows and/or crosses joint. May be due to (A)(B) (C) or sawing joint late after crack had already formed

(E) (i) Crack ran ahead of sawing to slab edge due to late cutting
(ii) Infiltration of incompressible material from shoulder

(F) Sealant reservoir (groove) or crack inducer not deep enough to form plane of weakness at desired joint location

(G) Joints at intersection were not lined up. Crack occurs to complete omitted continuity

ACI C504

Minimizing Cracks

a) Protect the fresh concrete from **plastic shrinkage** cracking

b) Do not specify minimum cement contents that increase unit water content of mixtures. Keep the concrete sufficiently moist after set to lower early **drying shrinkage**

c) Minimize **thermal cracking** due to temperature gradients (i.e. control heat evolution from concrete mixture & protect from cold temperatures or from the hot sun)

d) Proper timing and depth of joints

Reducing Shrinkage Cracking: Materials, Testing, and Specification

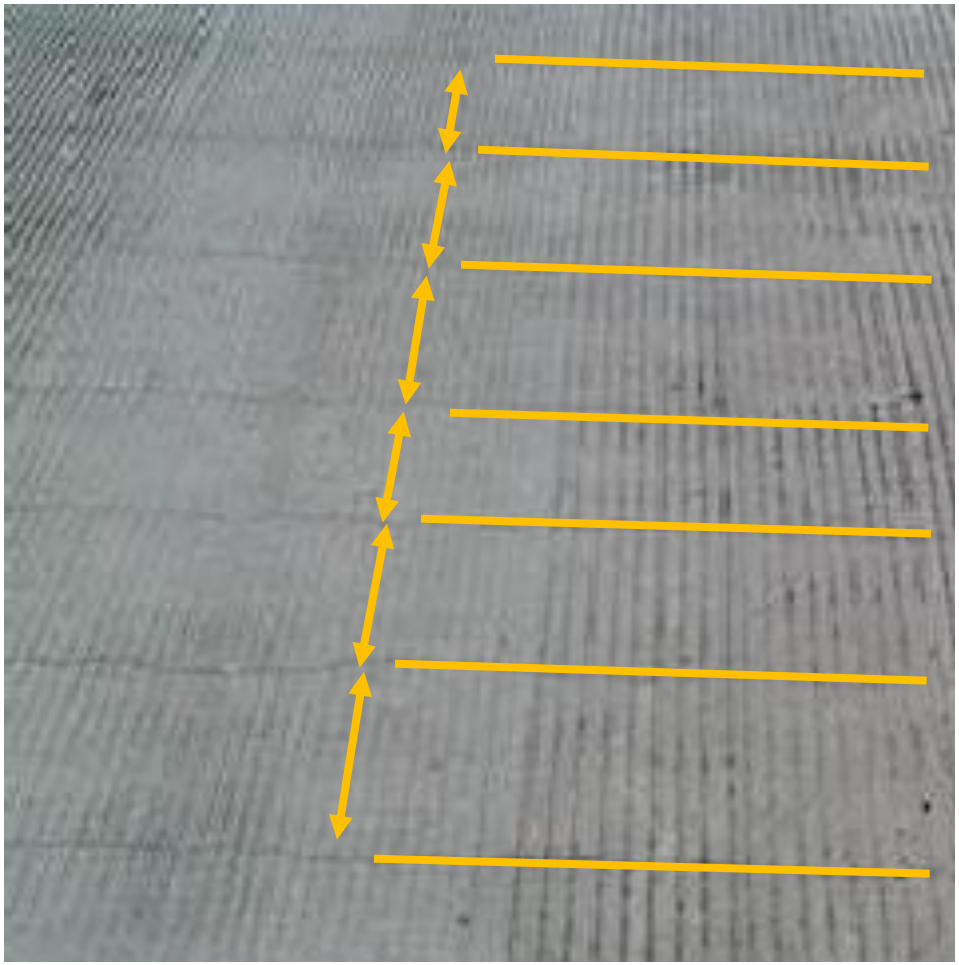
Jason Weiss, Oregon State University

jason.weiss@oregonstate.edu

765-412-8358

Motivation

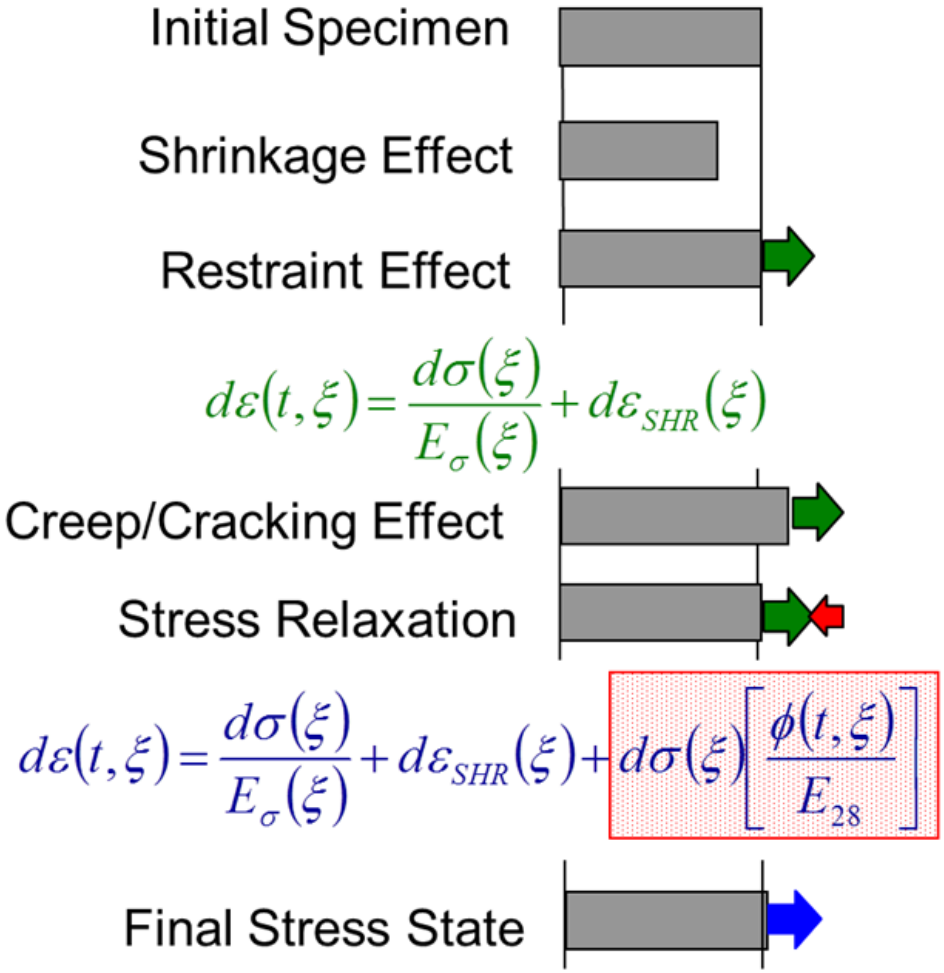
- Transverse cracking in 100,000+ bridges
- 62% of DOT's consider cracking as a problem
- Cracks shorten service life, increase maintenance cost, and accelerate corrosion

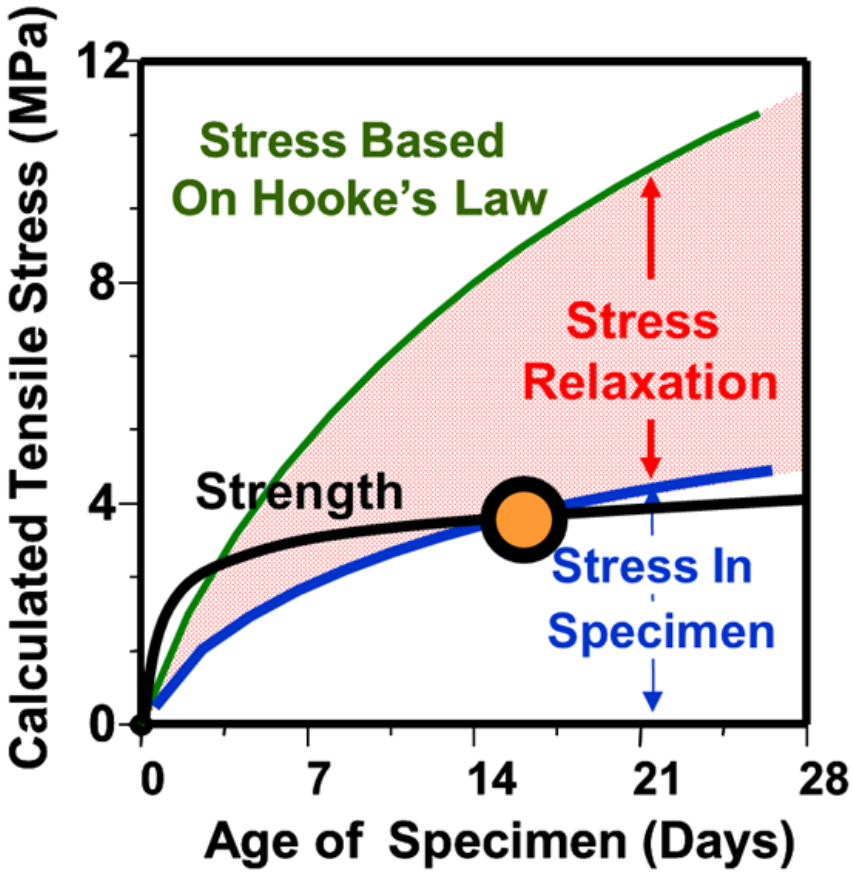


http://www.aggregateresearch.com/caf/file/newdeckcracking.pdf

Here we see cracks spaced at 0.8 m
On the approaches to a bridge

Reality is a Bit More Complex





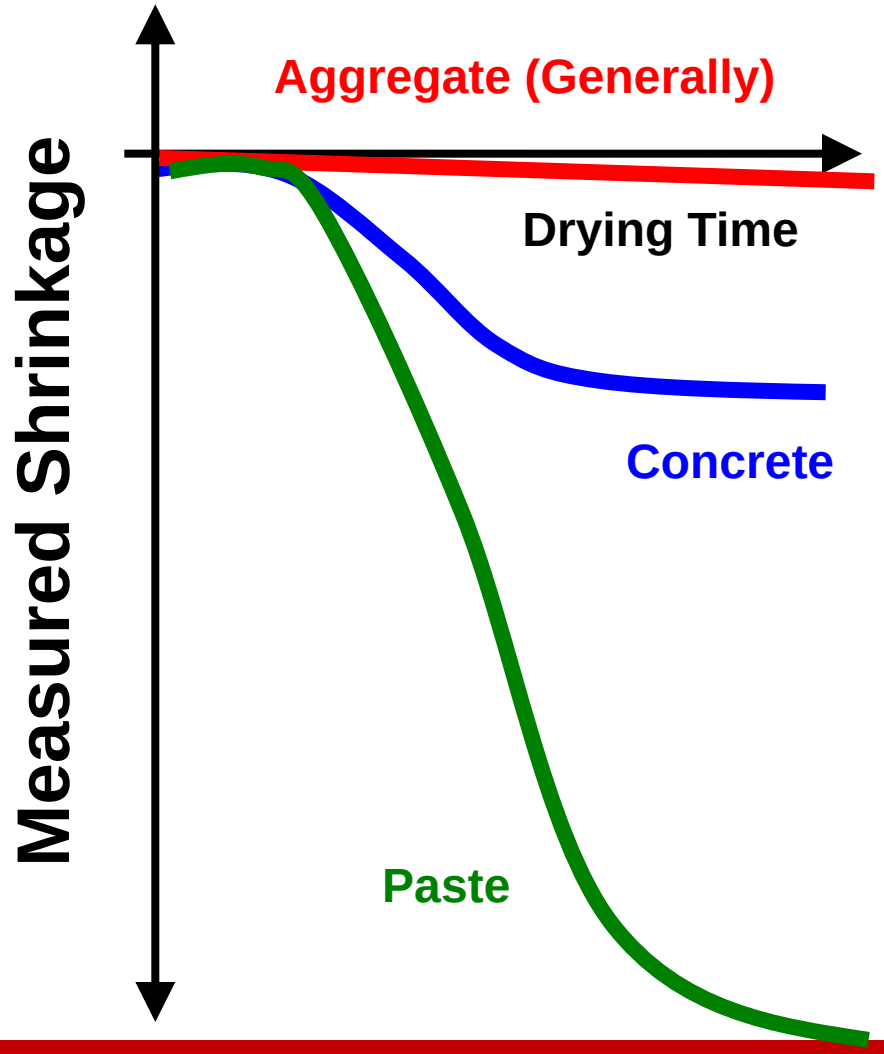
Weiss et al. 1998, JEM

Outline

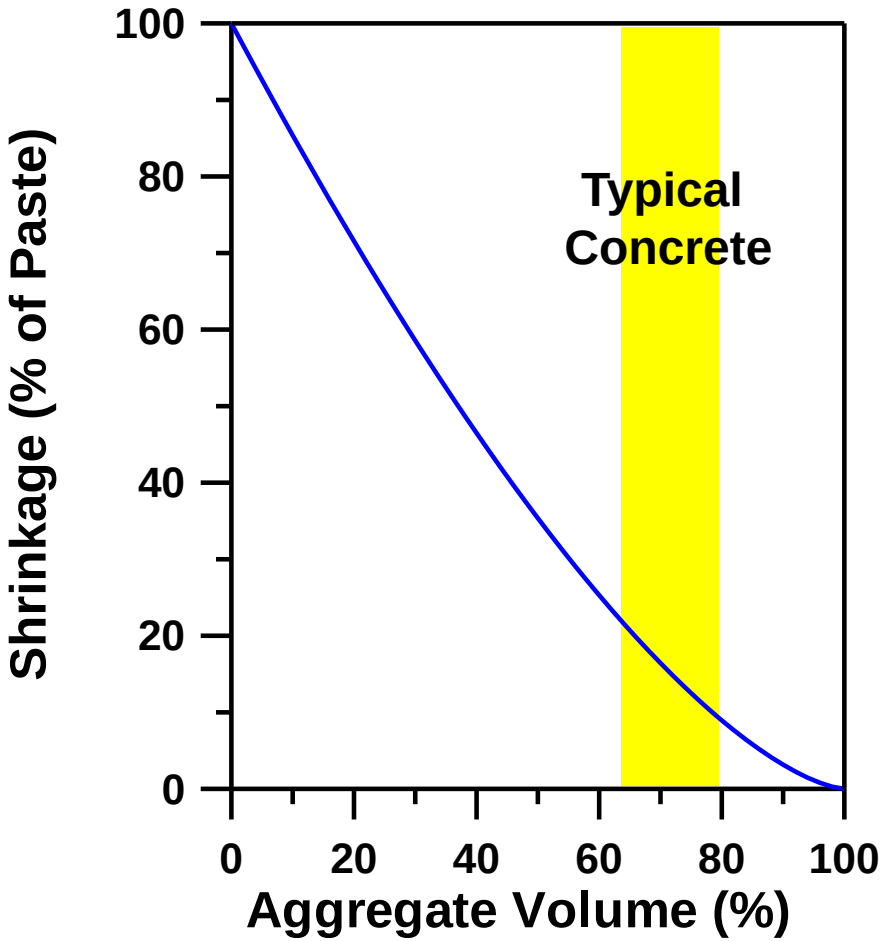
- Materials Approaches to Reduce Cracking
  - Aggregate Volume
  - Shrinkage Reducing Admixtures
  - Internal Curing
- Tests to Evaluate Shrinkage and Cracking
  - New Shrinkage Tests
  - Dual Ring Test Has Merit and is Fast
- Performance Based Specifications
  - Model Based on Risk of Cracking

Shrinkage of Concrete Constituents

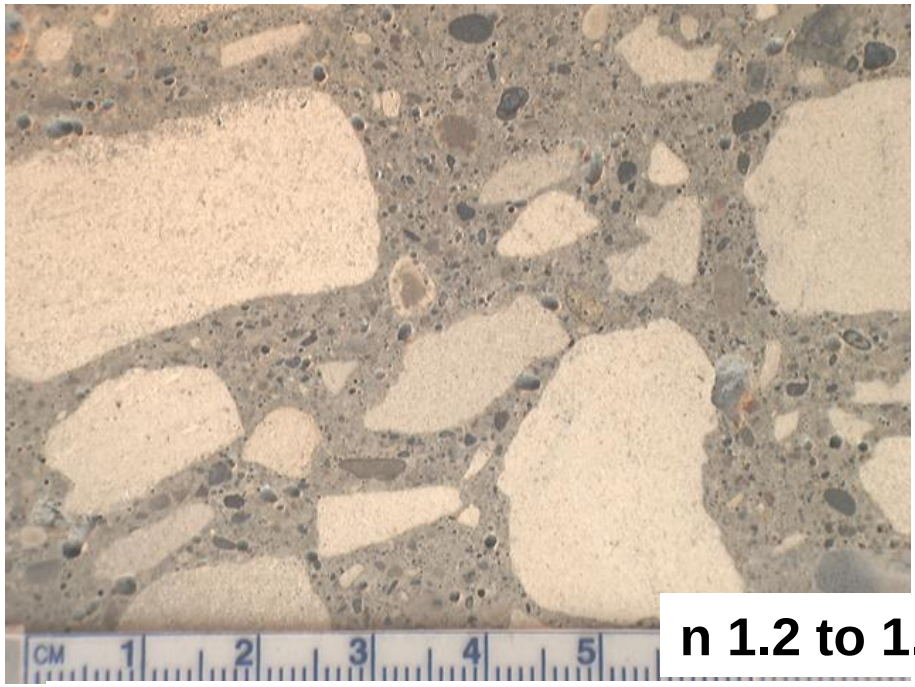
- Shrinkage - Volumetric Change Associated With A Loss Of Water
- Aggregate Generally Does Not Shrink (In the US)
- It's the Paste That Shrinks



Shrinkage is a Paste Property



Stiffer Aggregate More Effective In Restraining Paste Shrinkage

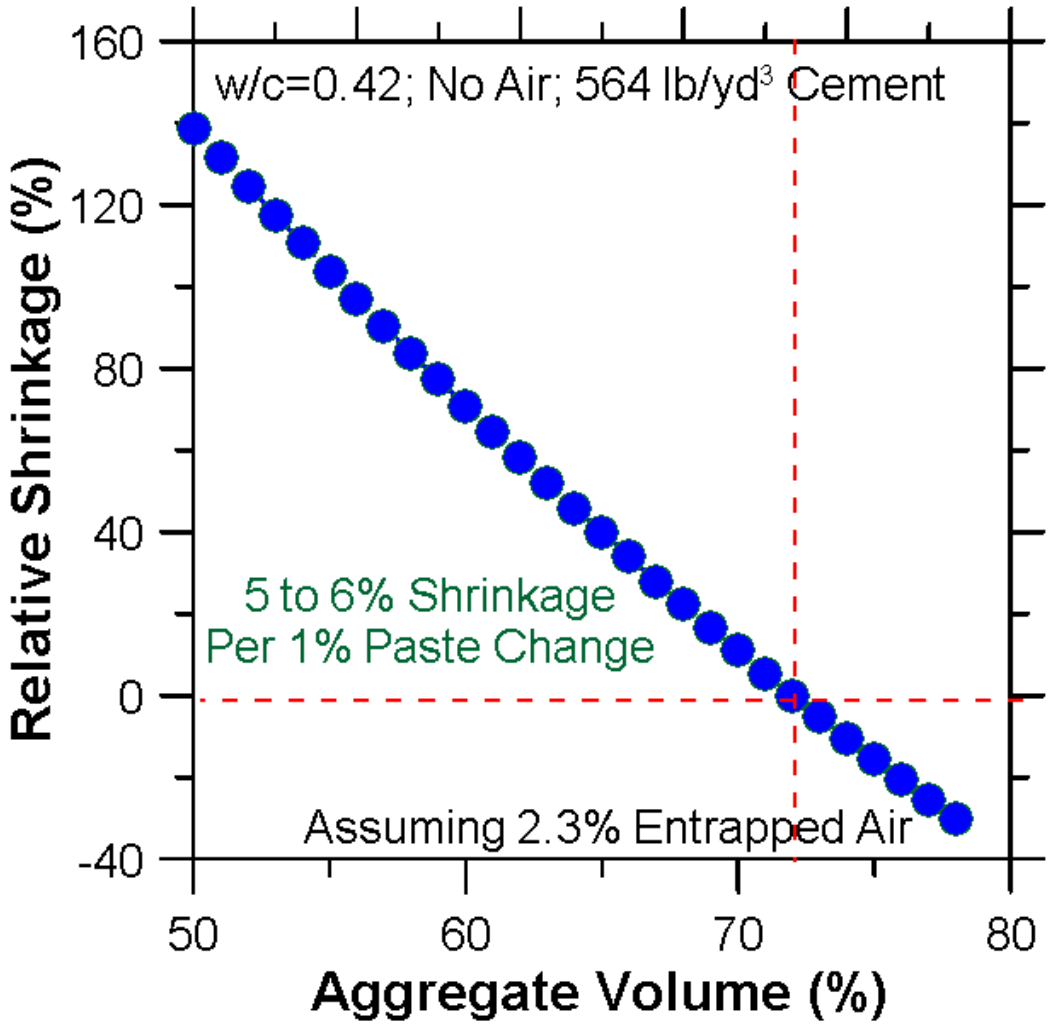


n 1.2 to 1.7

$$\varepsilon_{Concrete} = \varepsilon_{Agg} \cdot V_{fAgg} + \varepsilon_{Paste} \cdot V_{fPaste}$$

$$\varepsilon_{Concrete} = \varepsilon_{Paste} \cdot (1 - V_{fAgg})^{n}$$

Shrinkage and Paste Volume



Kelvin Young Laplace Theory

$$p_{cap} = -\frac{2\gamma \cdot \cos\theta}{r}$$

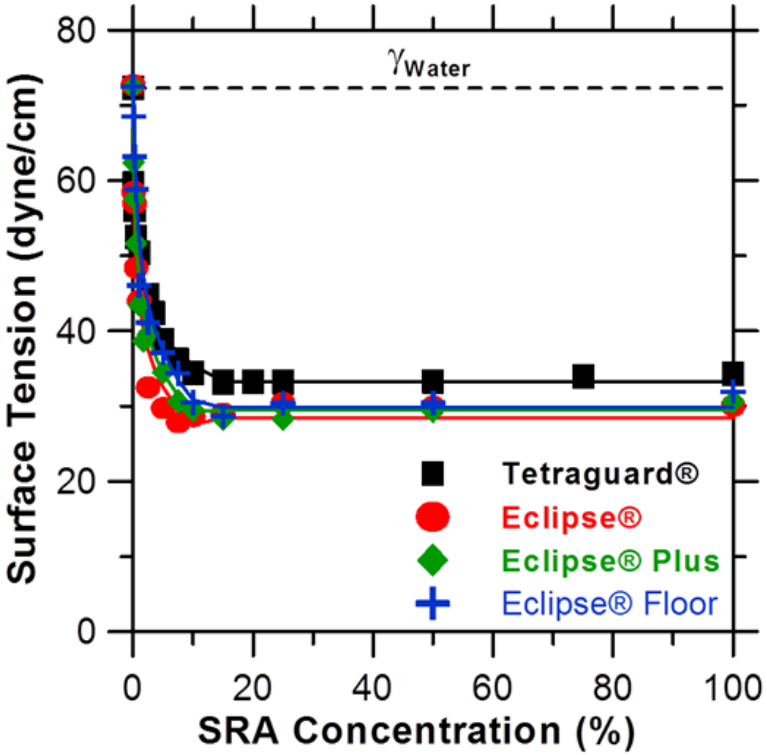
- Concrete is Made of Little Tiny Holes, Called Pores
- Size of the Pore Matters
- Pressure (p_{cap}) is related to surface tension (γ) and inversely related to radius of the meniscus that forms (r)
- Big Pores – Low Pressure, Low Shrinkage
- Water is a clingly material – High Shrinkage

SRA and Surface Tension

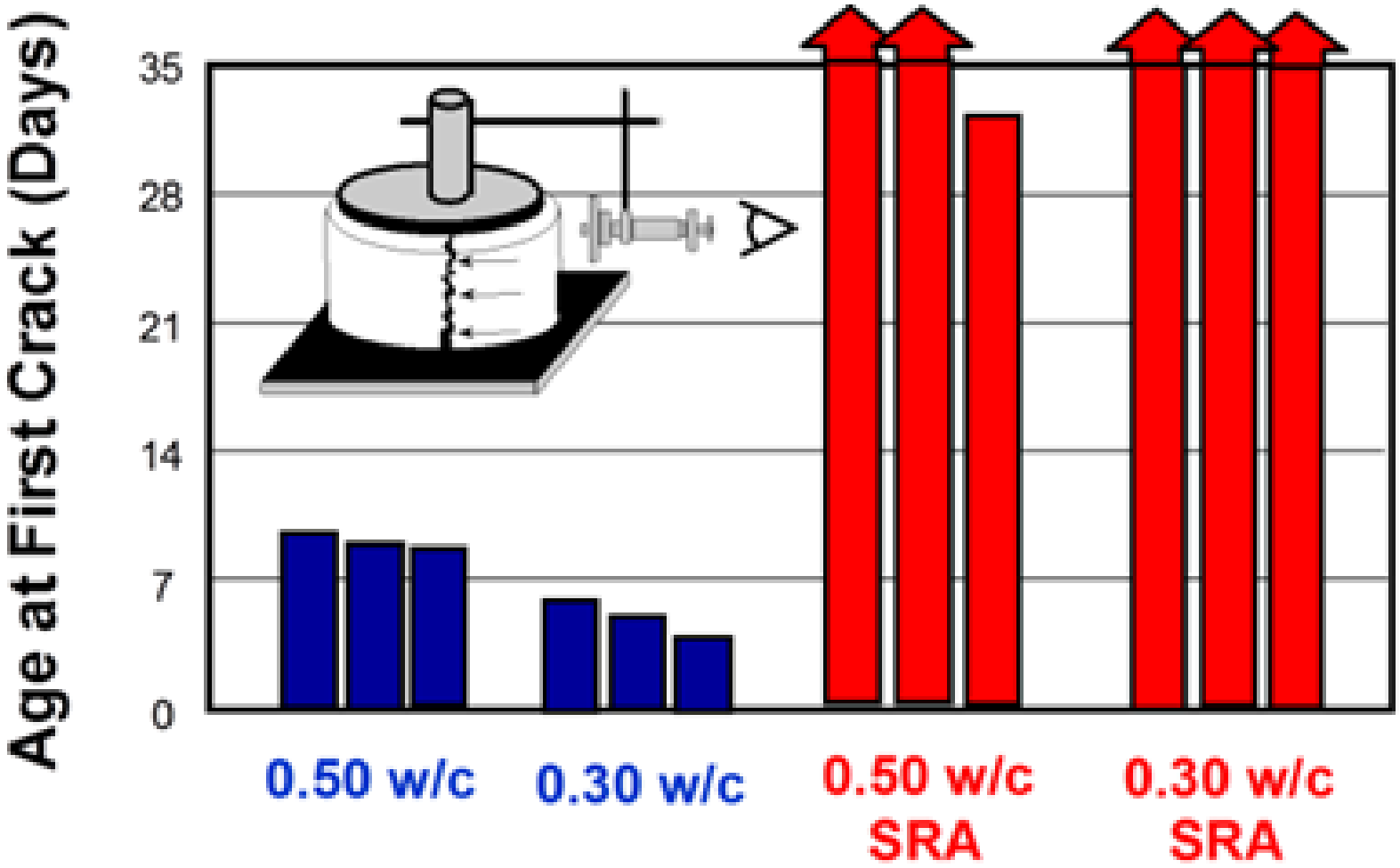
- To reduce shrinkage we reduce pressure, this means we either… reduce surface tension

- 1983 – Japan
- 1997/99 – US
- US Product 1999

$$p_{cap} = -\frac{2\gamma}{r}$$

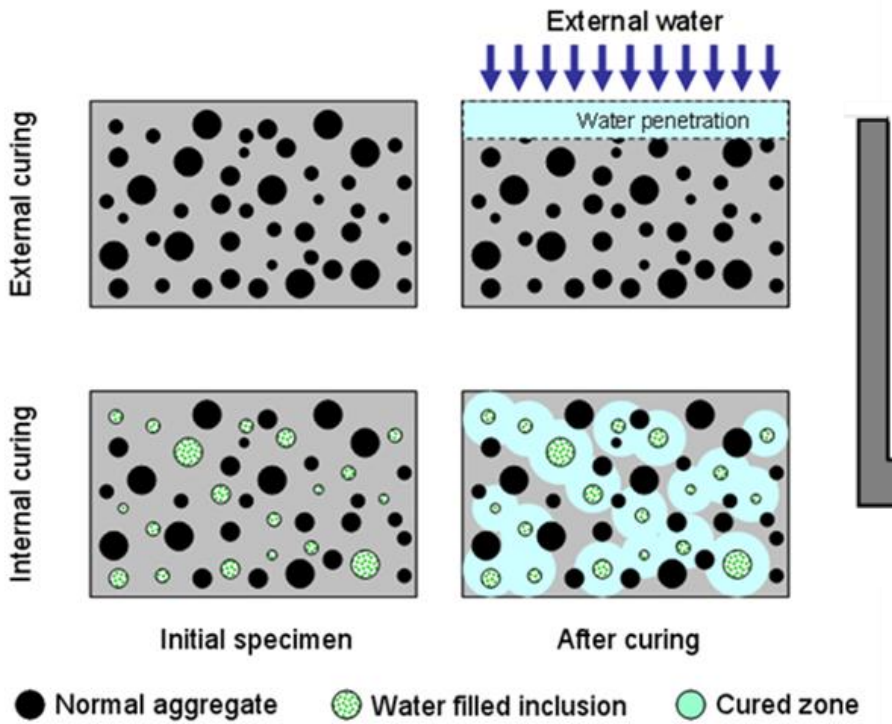


Shrinkage Reducing Admixtures

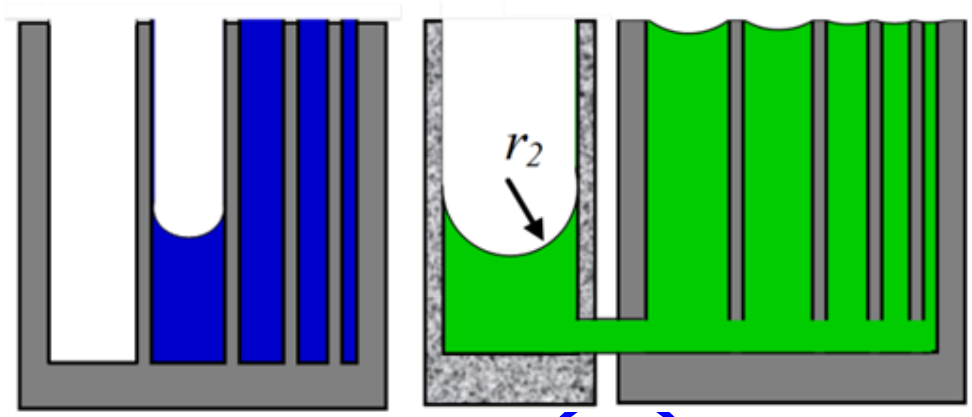


Internal Curing Approach

- To reduce shrinkage we reduce pressure, we can increase the size of the pore



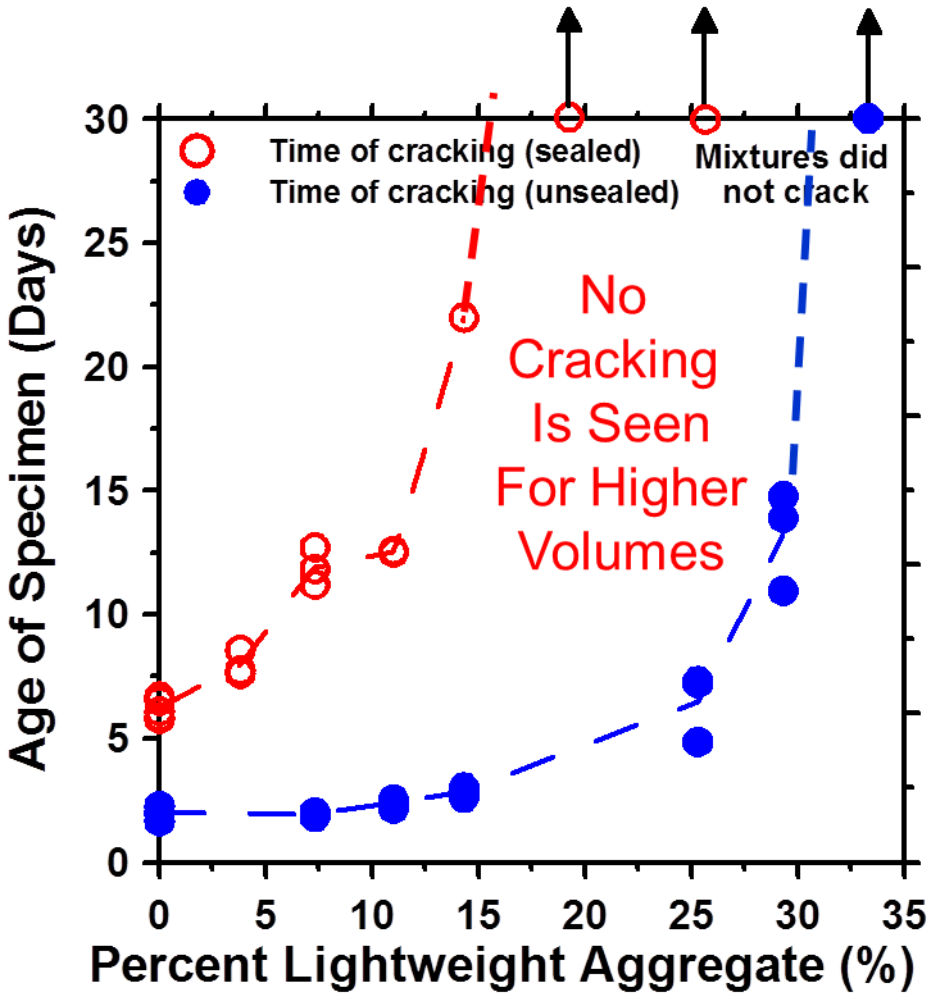
Castro et al. 2009



$$p_{cap} = -\frac{2\gamma}{r}$$

Shrinkage Cracking and IC

- Restrained tests results on IC concrete (explained in more detail later)
- Increasing the use of LWA leads to a great reduction in cracking
- 24% LWA is typ. des.



Henkensiefken et al. (2008)

Field Trials and Applications

- Becoming More Widely Used
- INDOT, NYDOT, IL Tollway Cities and Towns, Others
- Reducing Cracking

Outline

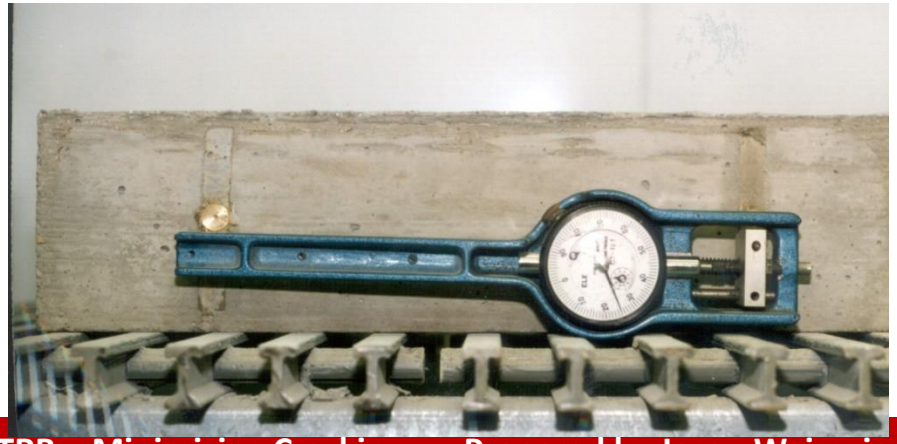
- Materials Approaches to Reduce Cracking
  - Aggregate Volume
  - Shrinkage Reducing Admixtures
  - Internal Curing
- Tests to Evaluate Shrinkage and Cracking
  - New Shrinkage Tests
  - Dual Ring Test Has Merit and is Fast
- Performance Based Specifications
  - Model Based on Risk of Cracking

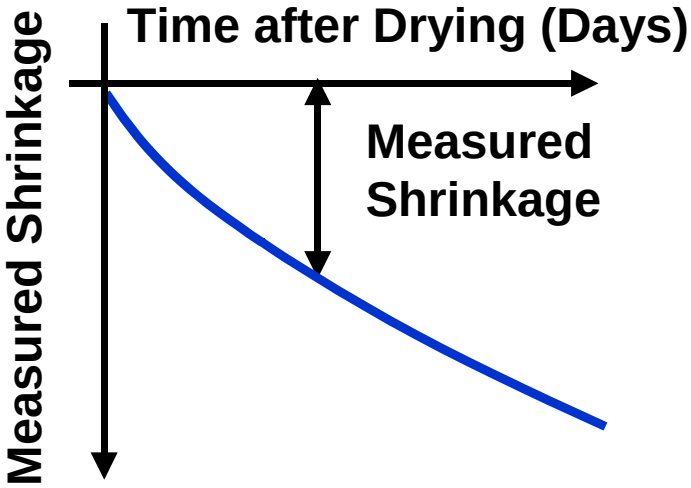
Laboratory Tests to Measure Shrinkage

- ASTM C-157

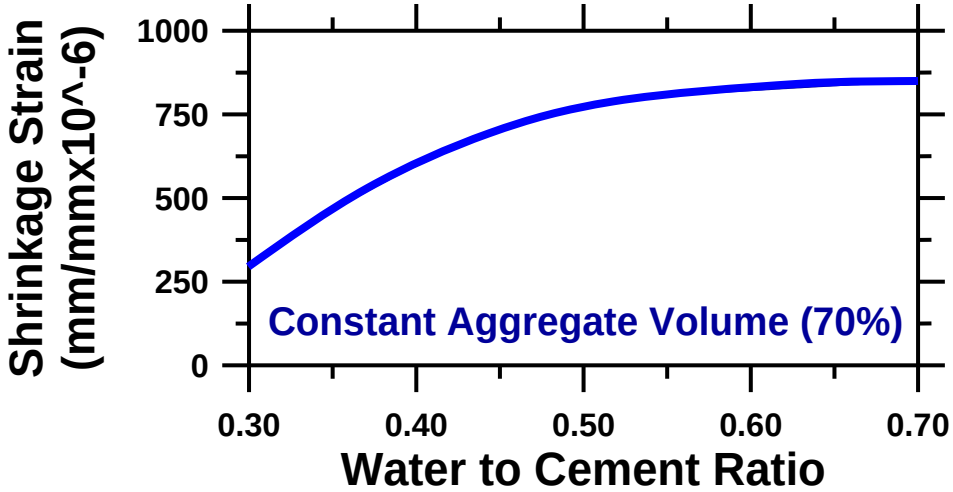
$$\varepsilon = \frac{\Delta l}{l_0}$$

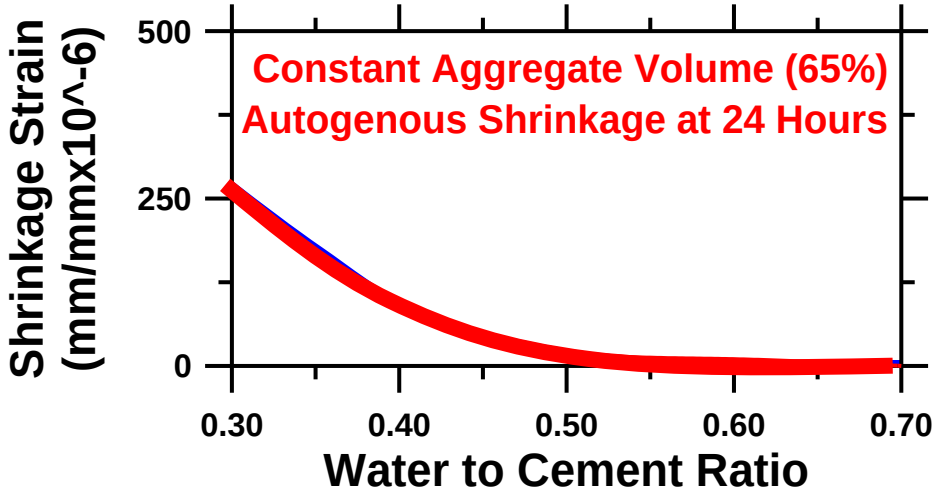
- ASTM C-341

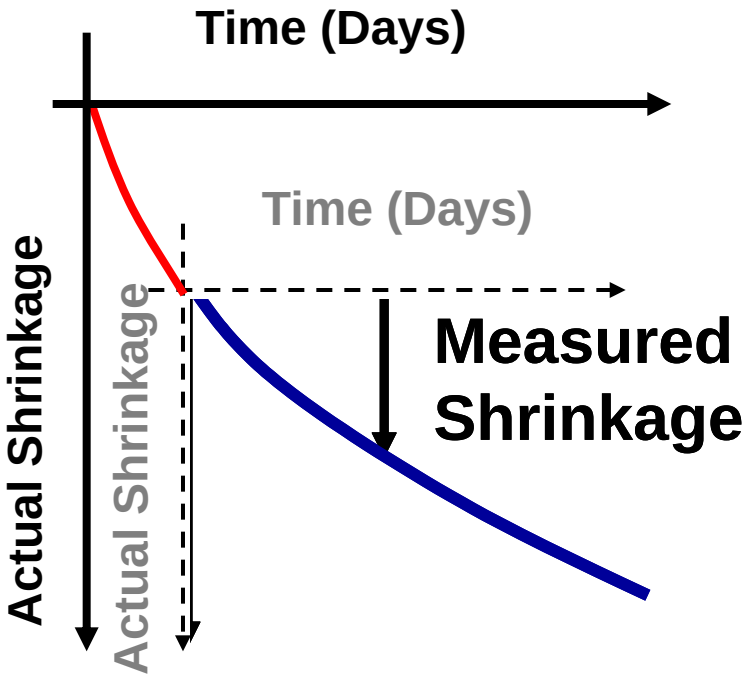




Measuring Shrinkage
Starting Time is Critical



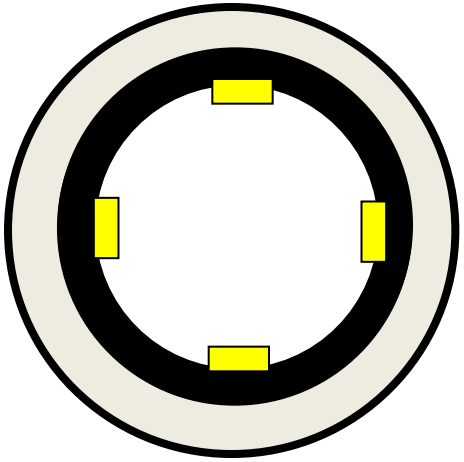




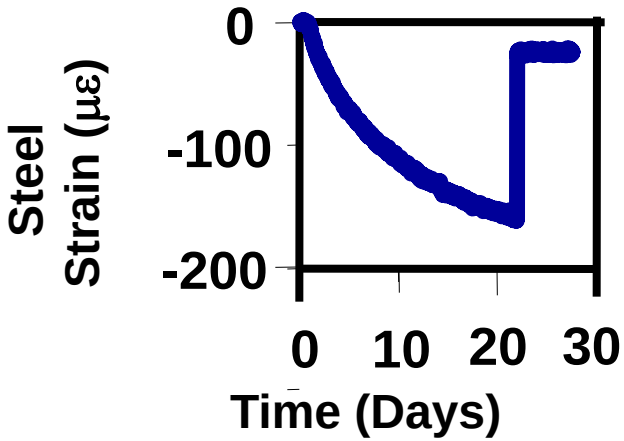
New Test – ASTM C1698

Stress Development Approach

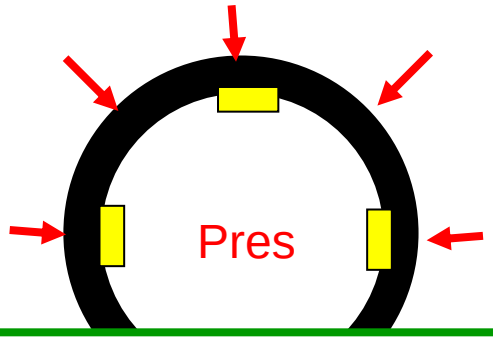
- Using an Instrumented Ring
- Measure Strain that Develops in Steel
- Determine the Pressure Required to Obtain that Strain
- Apply Pressure to Concrete and Obtain Tensile Stress

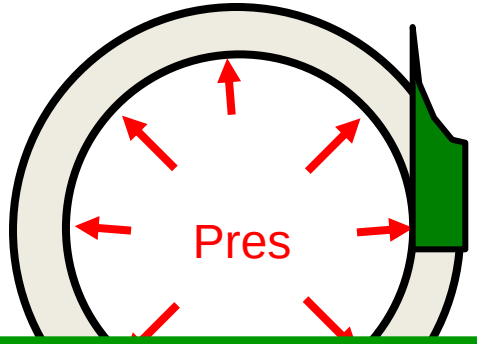


Original Ring



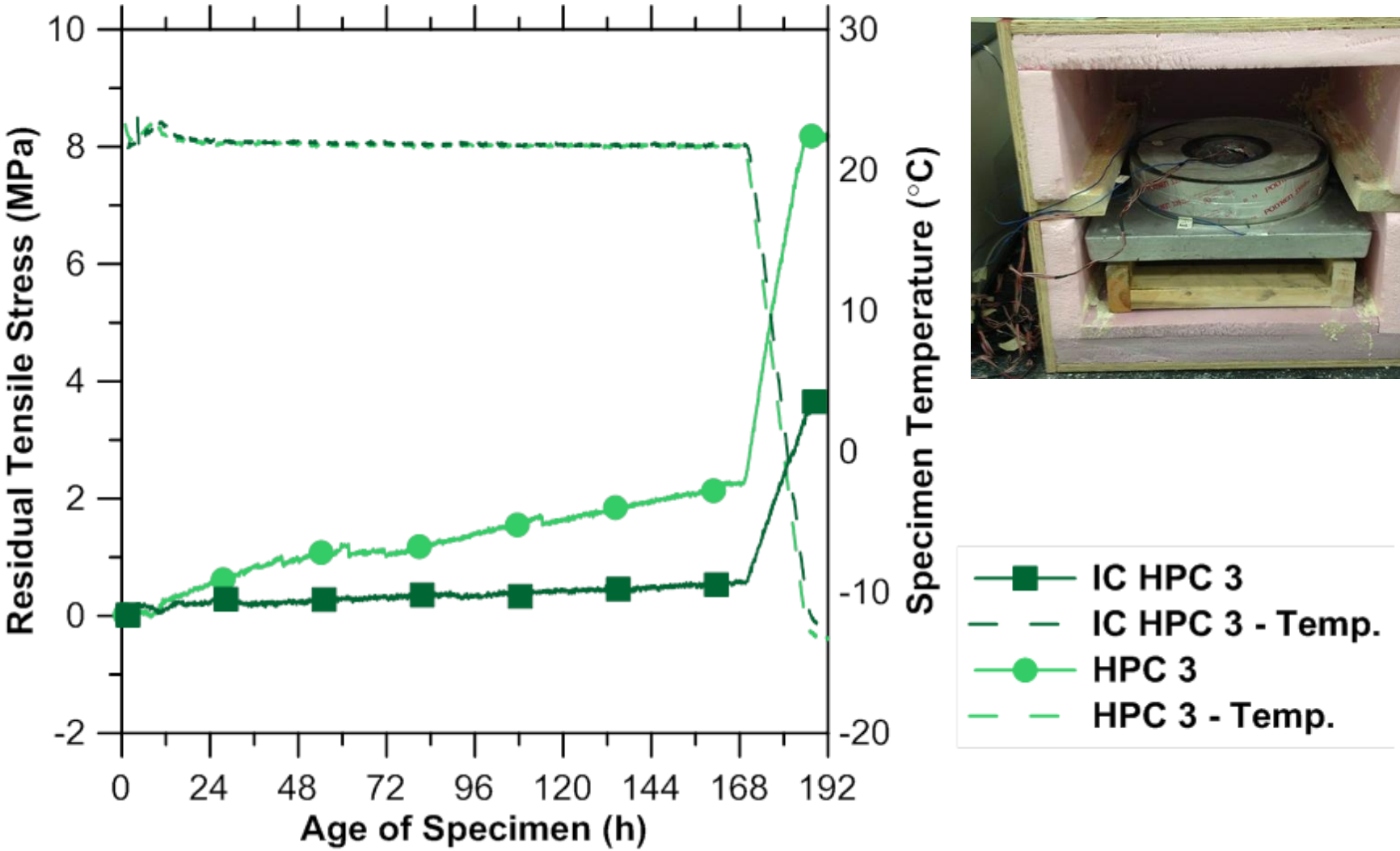
Measured Strain





$$\sigma_{Concrete}(t)\Big|_{r=R_{IC}} = \varepsilon_{Steel}(t)E_S \frac{\left(R_{OS}^2 - R_{IS}^2\right)}{2R_{OS}^2}\frac{\left(R_{OC}^2 + R_{IC}^2\right)}{\left(R_{OC}^2 - R_{IC}^2\right)}$$

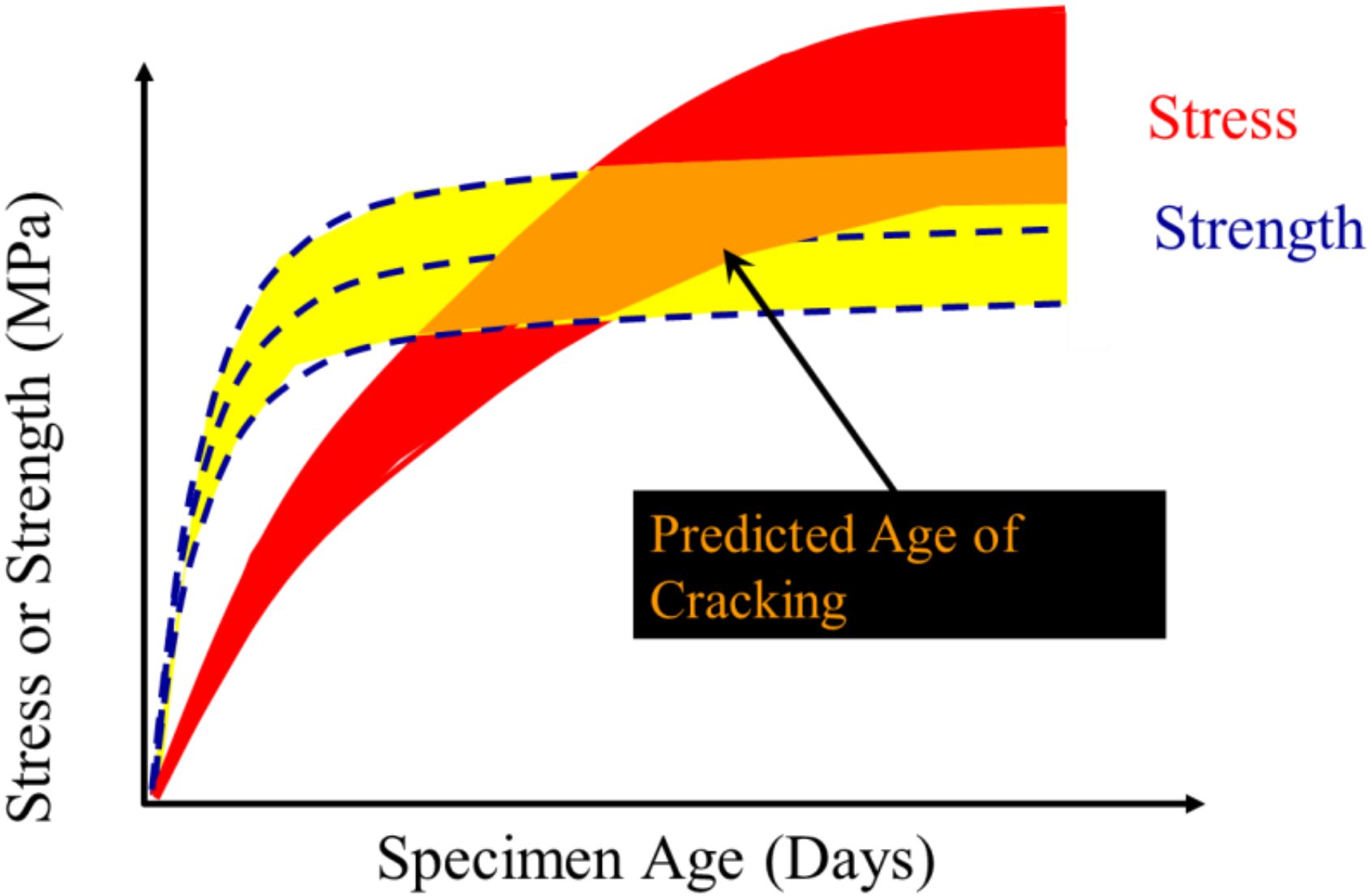
The Dual Ring Test



Outline

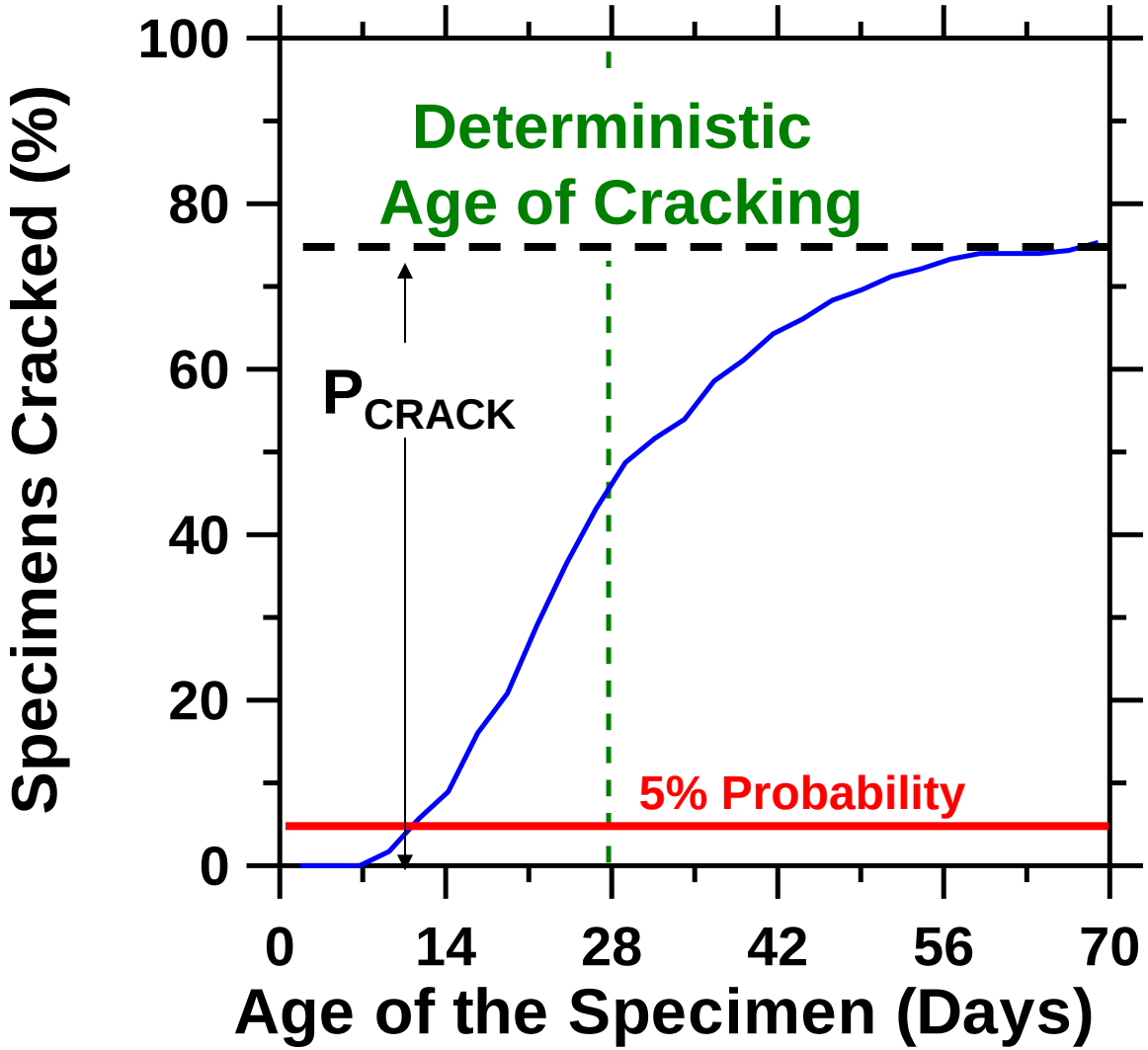
- Materials Approaches to Reduce Cracking
  - Aggregate Volume
  - Shrinkage Reducing Admixtures
  - Internal Curing
- Tests to Evaluate Shrinkage and Cracking
  - New Shrinkage Tests
  - Dual Ring Test Has Merit and is Fast
- Performance Based Specifications
  - Model Based on Risk of Cracking

Including 'Random Variation'



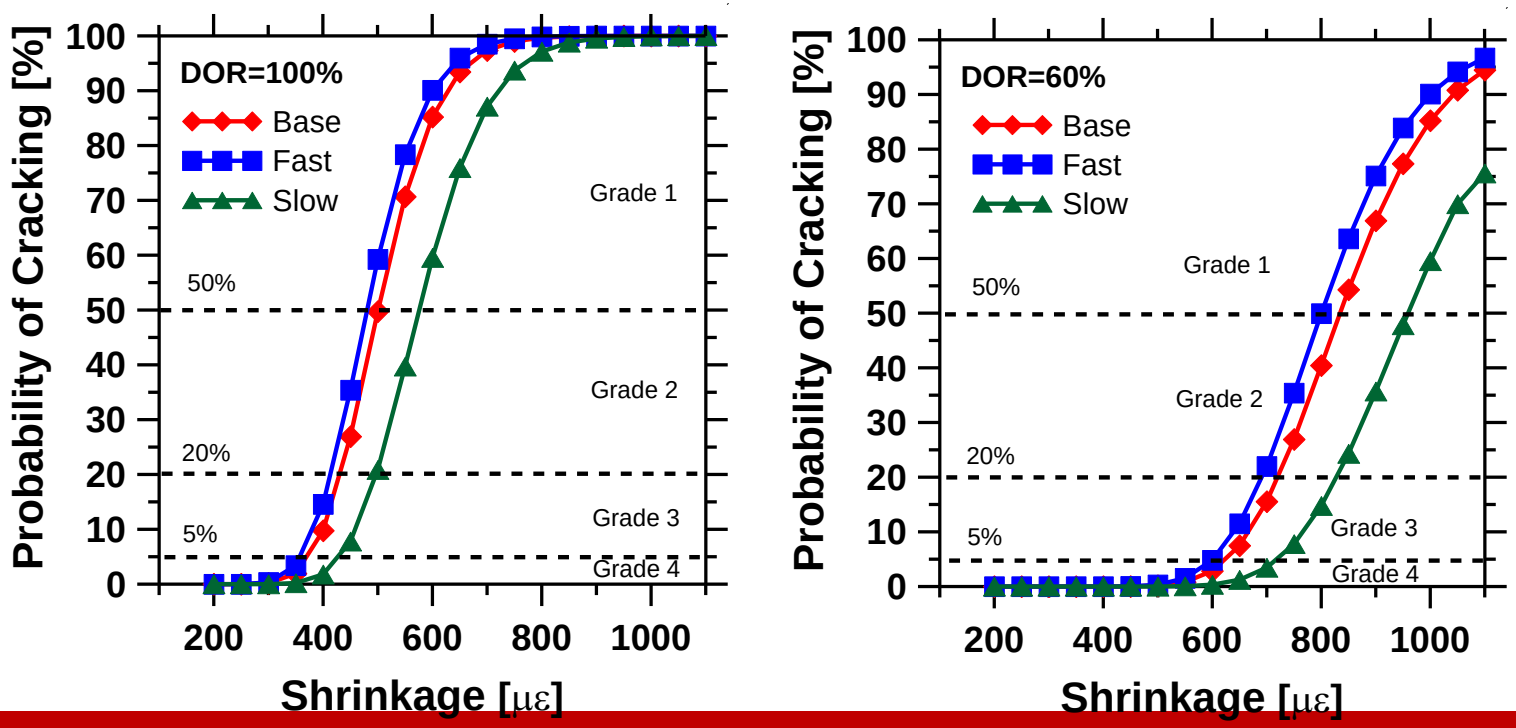
Results Of An Alternative Approach to Consider Variability in Shrinkage

- Plotted the percentage of specimens cracked by a specific age
- Results of 10,000 simulations
- Can quantify risk or total probability



Toward a Shrinkage Specification

- Shrinkage can be related to cracking potential and this simple approach begins to relate a simple test to performance



A Summary of Thoughts

- Concrete Shrinks but We Have Three Defenses
  - Aggregate Volume – Change Shrinking Proportion
  - Shrinkage Reducing Admixtures – Change Fluid
  - Internal Curing – Change Pore Emptying
- Current Tests are Lacking However
  - New Tests Exists – 4+ New Shrinkage Tests
  - Dual Ring Test Has Merit and is Fast
- Specifications can Be Performance Based
  - Model Based on Risk of Cracking

Thank you
Are There Any Questions

Jason Weiss , Edwards Distinguished Professor

jason.weiss@oregonstate.edu

Practical Applications to Minimize Cracking

Donald Streeter, P.E.

Concrete Problems

- American's spend 4.2 billion hours a year stuck in traffic
- Bridges (>25%) are structurally deficient or functionally obsolete
- Highways (>33%) are in poor or mediocre condition
- ASCE 2013 report D+
- Colbert Report
  - "Tiny Triumphs"

DRINKING WATER

Poor infrastructure fails America, civil engineers report

January 28, 2009

Share Twitter Email

Recommend 152 people recommend this. Sign Up t what your friends recommend.

America's civil engineers think the nation's aging and rusty infrastructure is just not making the grade.

The American Society of Civil Engineers issued an infrastructure report card Wednesday giving a bleak cumulative ranking of D.

"We've been talking about this for many many years," Patrick Natale, the group's executive director, told CNN.

"We really haven't had the leadership or will to take action on it. The bottom line is that a failing infrastructure cannot support a thriving economy."

The civil engineers said the nation's D- roads cost motorists $67 billion a year in repairs and operating costs.

The ranking -- which grades the condition of 15 infrastructure entities such as roads, bridges and dams -- is the same as the the last time such a report was issued, in 2005. In 2001, the grade was D+, slightly better but still poor.

Constraints

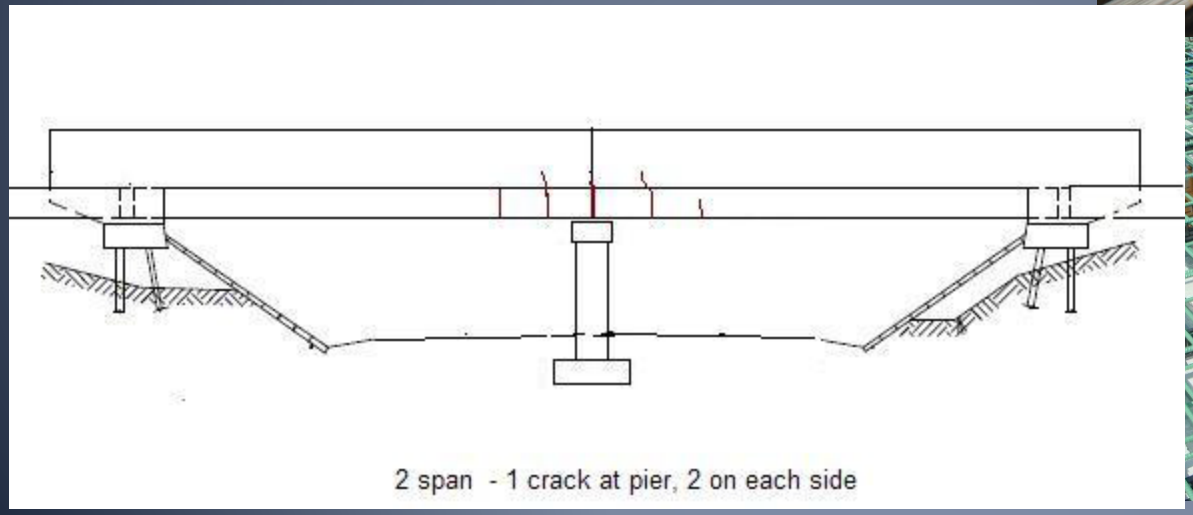
- Maintenance / preservation vs. Reconstruction ?
- Accelerated construction / traffic demands ?
- Durability / Service life expectations ?
  - Band-aid fix
  - Moderate service extension
  - Longer term service

What is your goal???

How will you achieve your goal???

Cracking - Design

- Flexure
  - simple vs. continuous
  - span length
- Beam type
- Geometry, skew



Cracking - Materials

- Materials
  - water demand / characteristics
- Mixtures
  - interactions

Cracking - Construction

- Construction
  - Time of placement, environmental conditions
  - Rate of placement
  - Curing
    - timing, duration

Where do we see cracking

- Large elements / Mass placements
- Accelerated construction
- Multi-span continuous decks
- Large surface areas / flatwork
- Long / thin placements

Potentially… everywhere!

Causes

- Shrinkage, Autogenous, Thermal
- Result of: design, materials, batching, environment, placing, finishing, curing

Crack mitigation practices as seen around the country…

Performance specification

- Owner defined parameters
  - Life cycle analysis
  - Consider permeability, strength, cracking
- QC Plan
  - Contractor defines
    - process, materials, mixtures
    - crack repair / treatment plan
    - Maintenance schedule

Mass Concrete

- Treating more placements as “Mass”

Mass Concrete

- Means to minimize cracking:
  - Mixture design
    - High pozzolan content

      30% – 70% SCM's
    - Low heat cements
  - Placement size / shape

Mass Concrete

- Means to minimize cracking (con't):
  - Cooling methods
    - Plastic PCC temp
    - Internal cooling
  - Environmental "controls"
  - Temperature monitoring
    - Max temp 160F
    - Max temp differential 35F

Mass Concrete

- Thermal Control Plan requirements
  - Mixture dependant
    - changes in mix = new TCP development
  - Method / duration of curing
  - Thermal development analysis
  - Temperature monitoring
    - sensor type / locations
    - Monitoring system plan / recording / reporting
  - Corrective action plan to control temp

Accelerated Concrete

- Precast / accelerated closures
- CIP accelerated PCC

  - Shrinkage requirements
  - Use longest set period allowed by work schedule

Superstructures

- HPC initiative in 1990's
  - Placing under improved environmental controls
  - Mix controls – strength, temps, etc…
  - Immediate wet curing – 30 minutes from placement
  - Extended wet curing – 14 days

- Internal curing
  - Use of l-w fine aggregates as a replacement for sand
  - 30% substitution by volume

IC Specification - construction

- Stockpile establishment
- SSD condition –
  - minimum 15% absorbed moisture
  - presoak minimum of 48 hours
  - Requires additional bin
- Handling, delivery, placement
  - Follows traditional practice
  - Similar characteristics

I-87 / Route 9 and Trout Brook

Comparison – I-87

Concrete Type	7 day Compressive Strength (psi)	14 day Compressive Strength (psi)	28 day Compressive Strength (psi)	28 day Tensile Strength (psi)	RCP Coulombs	F/T % loss
HPC	4420	5215	5910	569	1000	1.0
HPC-IC	4590	5790	6750	672	383	1.1
% Improvement	3.8%	11.0%	14.2%			

Cracking – no transverse cracking, map cracking SB

Barriers – used HPC NB, HPC-IC SB, both show cracking

Geometry

- Large surface areas
  - Construction practices
- Long – thin placements
  - SRA's
  - Fibers

Minimizing cracking

- Consider design:
  - Size, geometry, staging
- Materials selection to:
  - Minimize shrinkage, manage temps
- Construction practices:
  - Placement times
  - Environmental conditions
  - Placement, finishing, curing
  - Protections during / after curing

No 2 days of placement are the same!

Thank you