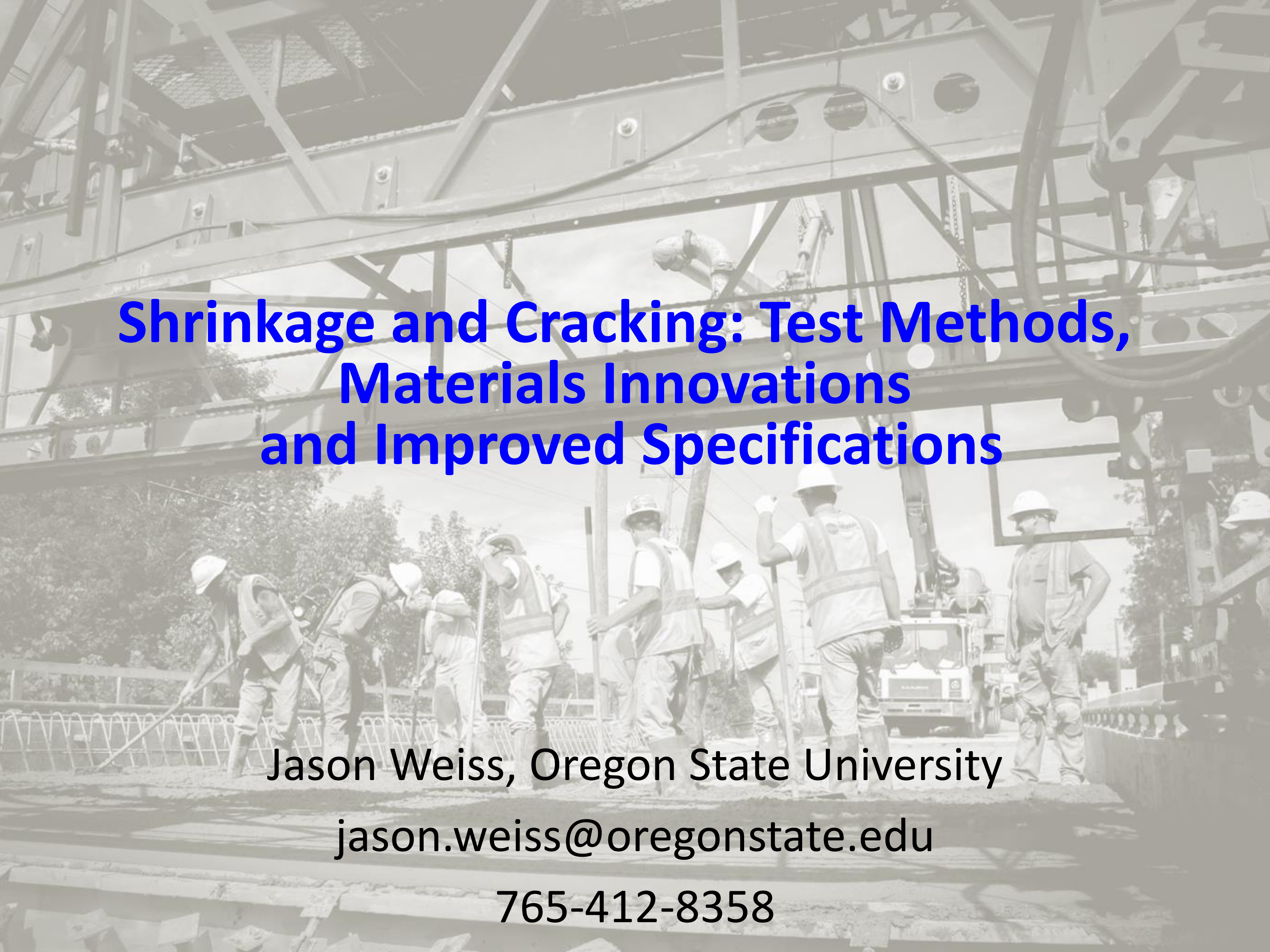

Shrinkage and Cracking: Test Methods, Materials Innovations and Improved Specifications

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The 1980-90's usher in Higher Strength

- "**High-strength** concrete is one of the most significant new materials available to federal, state, and local highway agencies………… With its improved **impermeability, durability, and accelerated strength** gain …….. an ideal material ….."
- HSC **may be slightly more expensive** than normal concrete initially, but its greater strength means that HSC bridges may require **fewer supports**, which could **reduce overall costs**.

Benefits of High Strength Concrete

Advantages

- Higher Strength
- Rapid Strength Gain
- Low Permeability
- Improved Durability
- Costs
- Less Members
- Ease of Placement
- Volume Stability
- Toughness
- Higher Modulus
- Lower Creep

Disadvantages

- Costs

Benefits of High Strength Concrete

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- Less Members
- Ease of Placement
- Volume Stability
- Toughness
- Higher Modulus
- Lower Creep

Disadvantages

- Costs

It’ll knock your socks off..
And it'll get’em whiter

Asking for Higher Strength with the Best of Intentions….

True or False:
Increasing Strength
Improves Performance

Asking for Higher Strength with the Best of Intentions….

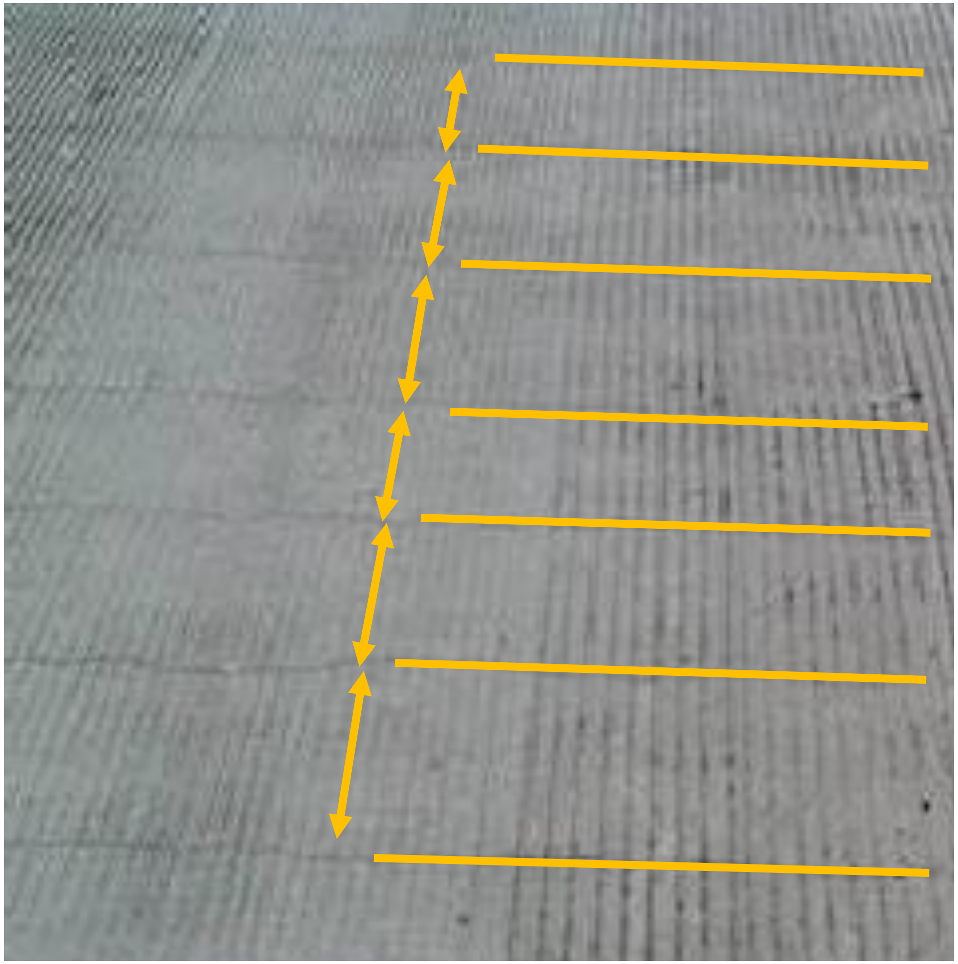
True or False:
Increasing Strength Improves Performance

………Misconceptions of Using Lower W/C, Higher Strength Concrete

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

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

Lets Look at the Fundamentals

- What causes cracking?

Initial Specimen

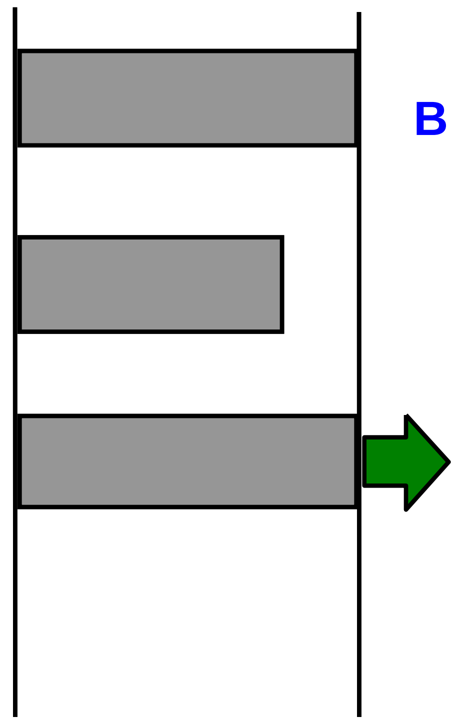
Initial Pavement
Bridge Deck or Industrial Floor

Conceptual View of Stress Development

Initial Specimen

Shrinkage Effect

Restraint Effect



Initial Pavement
Bridge Deck or Industrial Floor

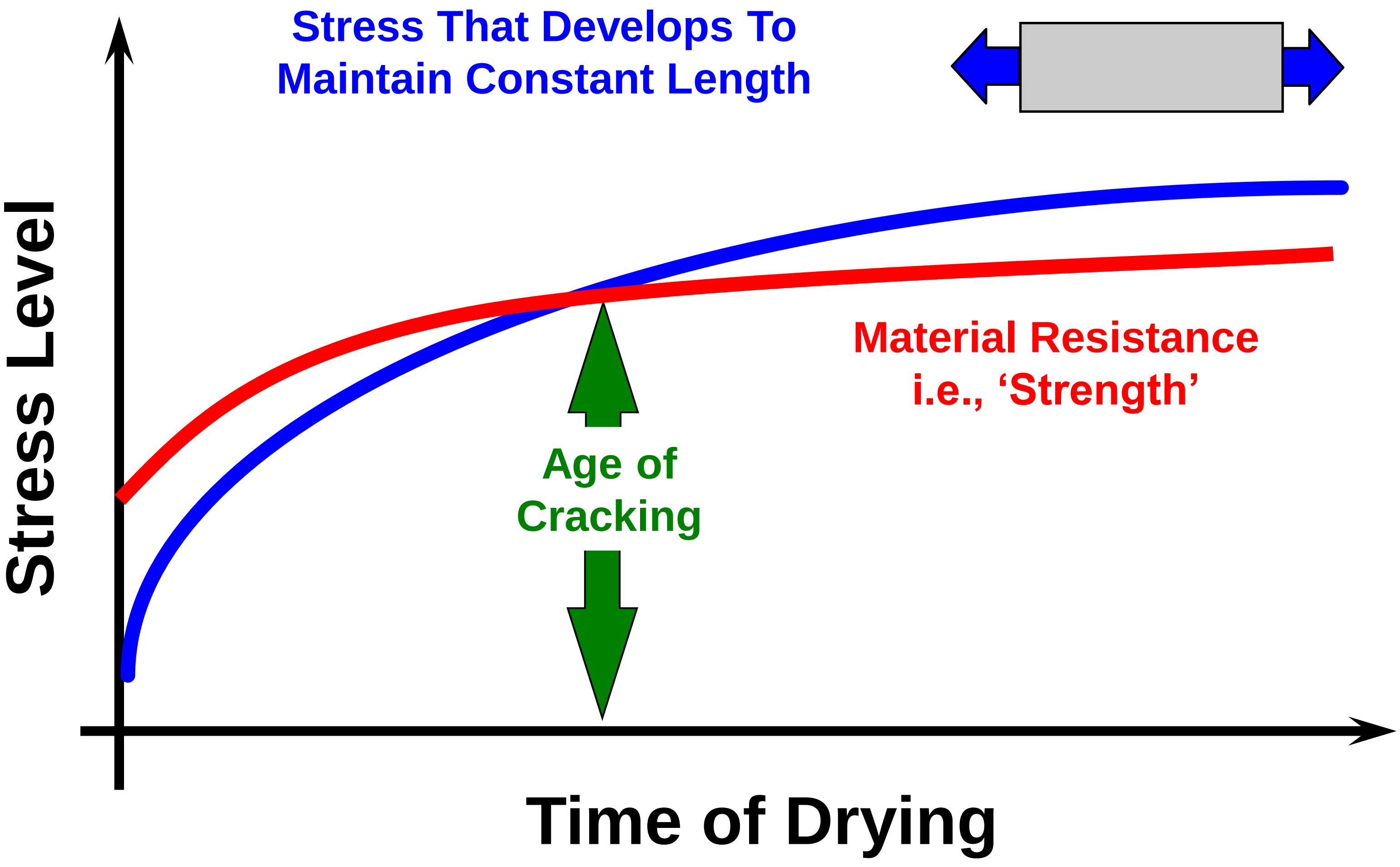
Disconnect it From
The Subgrade

Apply Force to
'Simulate' Subgrade

Maintain "Zero"
Displacement

(In real-life actually
not complete but…)

Condition for Cracking

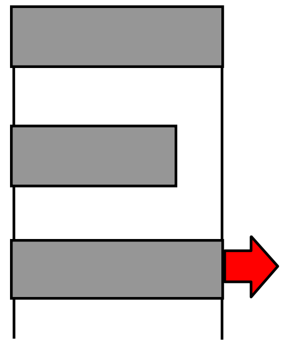


Reality is a Bit More Complex

Initial Specimen

Shrinkage Effect

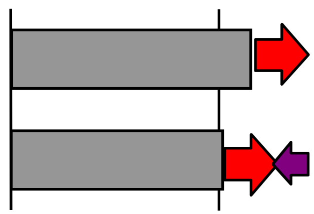
Restraint Effect



$$d\varepsilon(t,\xi) = \frac{d\sigma(\xi)}{E_\sigma(\xi)} + d\varepsilon_{SHR}(\xi)$$

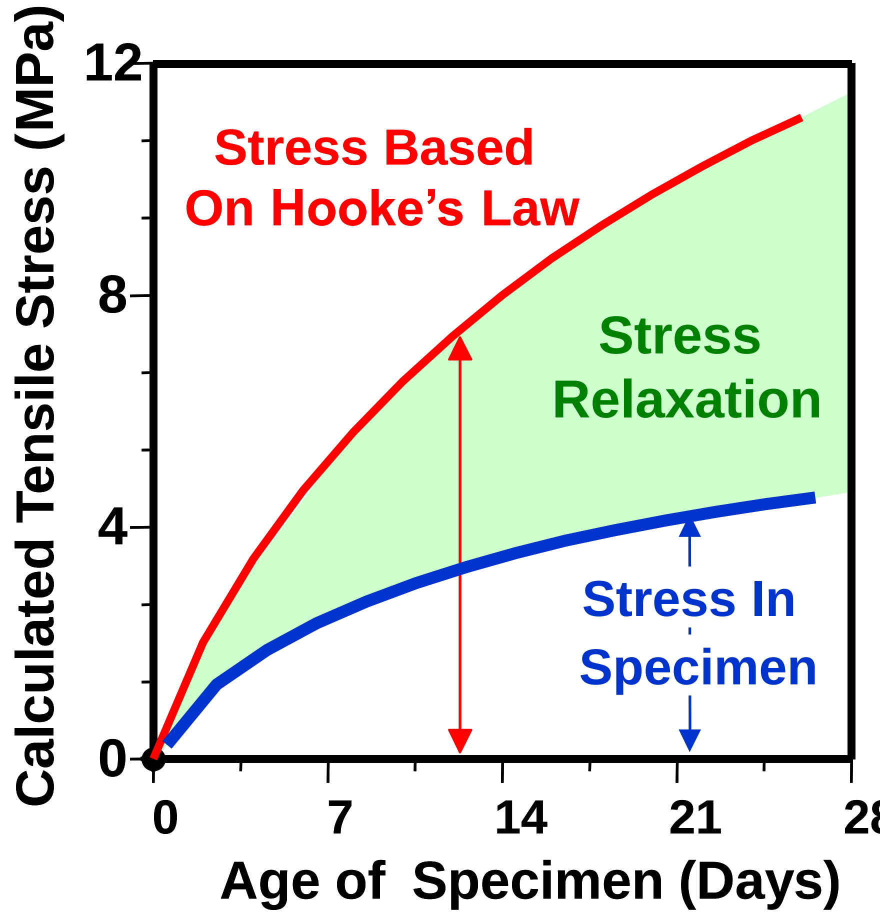
Creep/Cracking Effect

Stress Relaxation



$$d\varepsilon(t,\xi) = \frac{d\sigma(\xi)}{E_\sigma(\xi)} + d\varepsilon_{SHR}(\xi) + d\sigma(\xi)\left[\frac{\phi(t,\xi)}{E_{28}}\right]$$

Final Stress State



Weiss et al. 1998, JEM

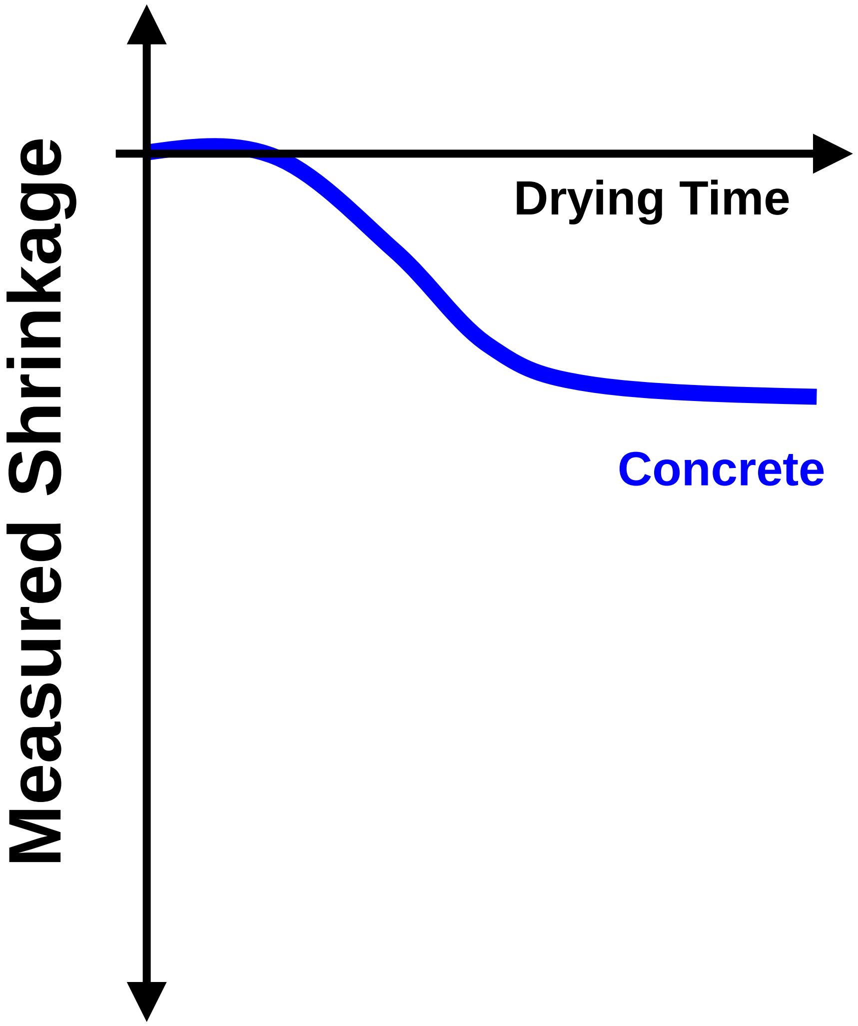
Lets Look at the Fundamentals

- What causes cracking? - Concrete Shrinks, Stress Develops if Restrained

- Why does concrete shrink ?

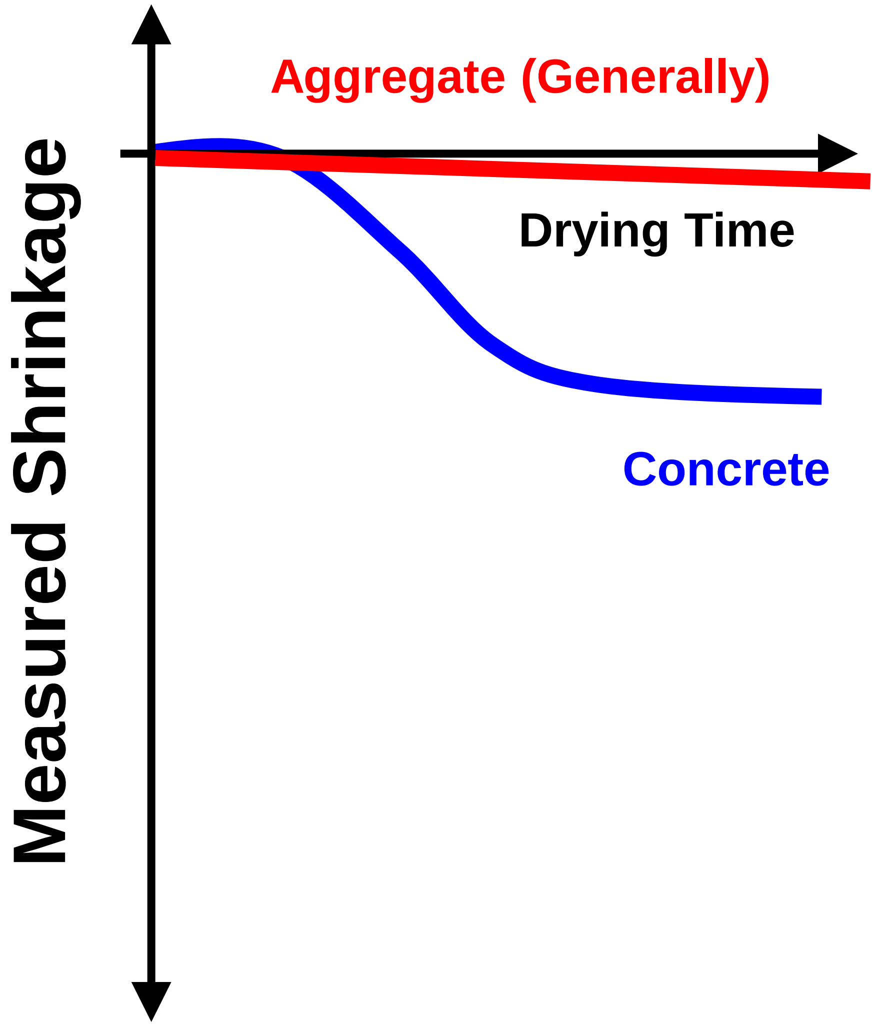
Shrinkage of Different Cement Based Materials

- **Shrinkage - Volumetric Change Associated With A Loss Of Water**



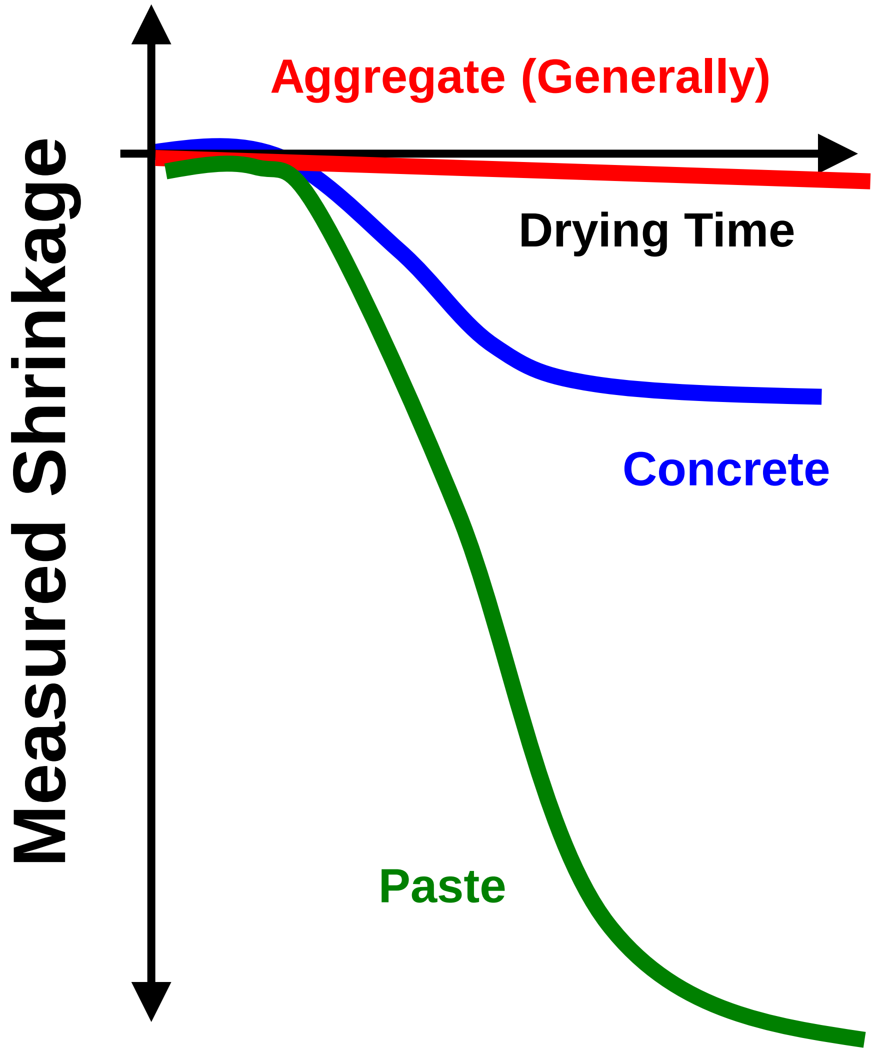
Shrinkage of Different Cement Based Materials

- Shrinkage - Volumetric Change Associated With A Loss Of Water
- Aggregate Generally Does Not Shrink (In the US)

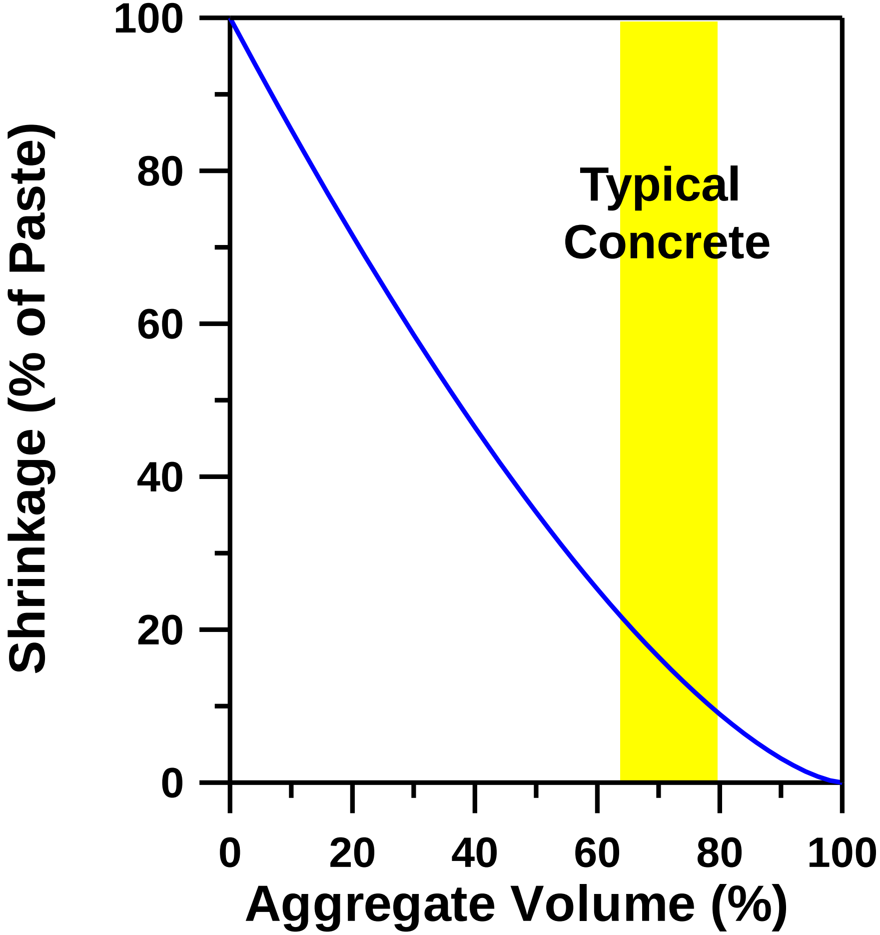


Shrinkage of Different Cement Based Materials

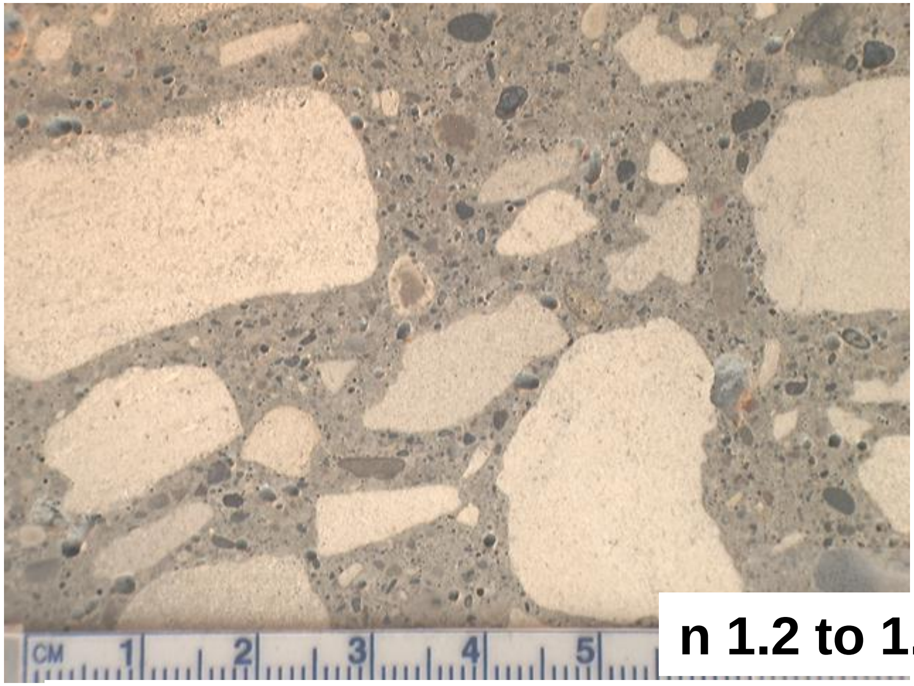
- Shrinkage - Volumetric Change Associated With A Loss Of Water
- Aggregate Generally Does Not Shrink (In the US)
- It's the Paste That Shrinks



Shrinkage is a Paste Property



Stiffer Aggregate More Effective In Restraining Paste Shrinkage

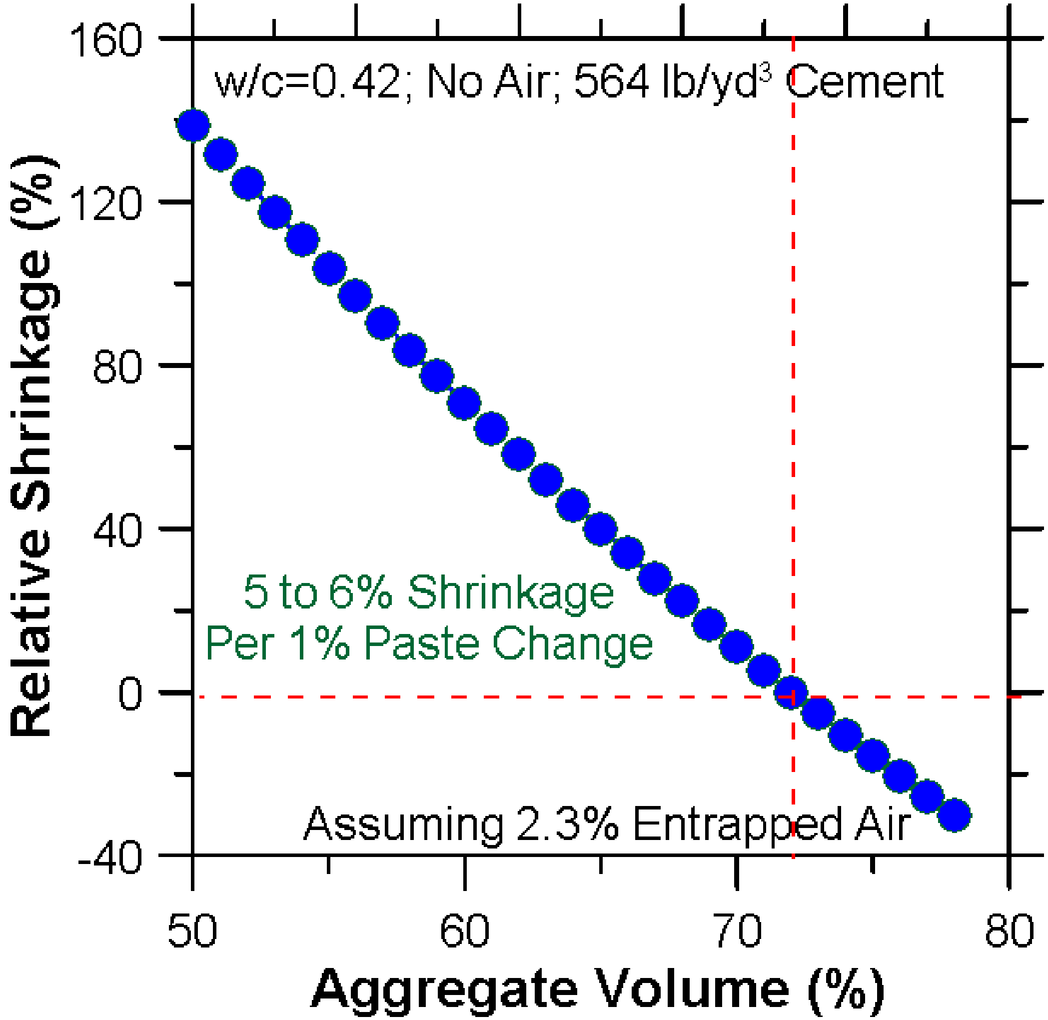


n 1.2 to 1.7

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

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

A Look at Shrinkage and Paste Volume



Lets Look at the Fundamentals

- What causes cracking? - Concrete Shrinks
- Why does concrete shrink ? Loss of water from the paste (we will come back to this)
- More Importantly, Controlling Aggregate Volume is the First Key Step not w/c
- Loss of water from the paste you say…. Lets talk theory

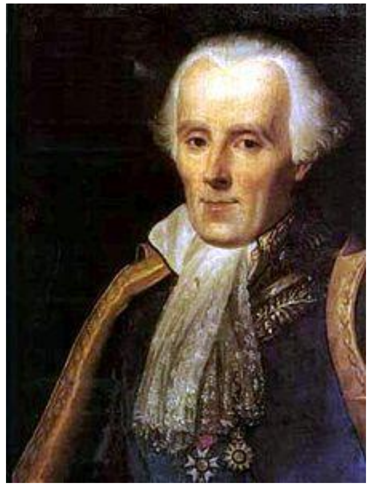
Kelvin-Laplace-Young-Gauss

- Some insights on the factors influencing shrinkage

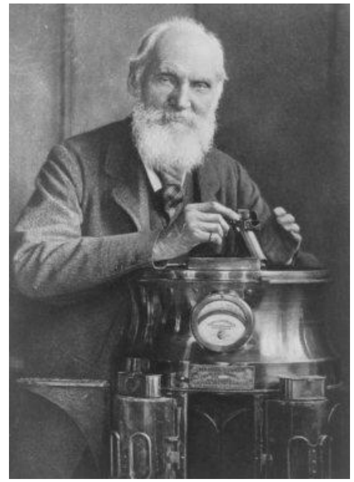
$$p_{cap} = -\frac{2\gamma \cdot \cos\theta}{r}$$

Thomas Young (1773 – 1829)

Carl F. Gauss (1777 - 1855)



Marquis de Laplace (1749 - 1827)



Lord Kelvin (1824 - 1907)

$$\ln\left(\frac{p}{p_0}\right) = \ln(RH) = -\frac{2\gamma \cdot \cos\theta \cdot}{r}\frac{V_W}{RT} = p_{cap}\frac{V_W}{RT}$$

Lets Make This Useful

- Concrete is Made of Little Tiny Holes, Called Pores
- Size of the Pore Matters

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

- 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

Lets Look at the Fundamentals

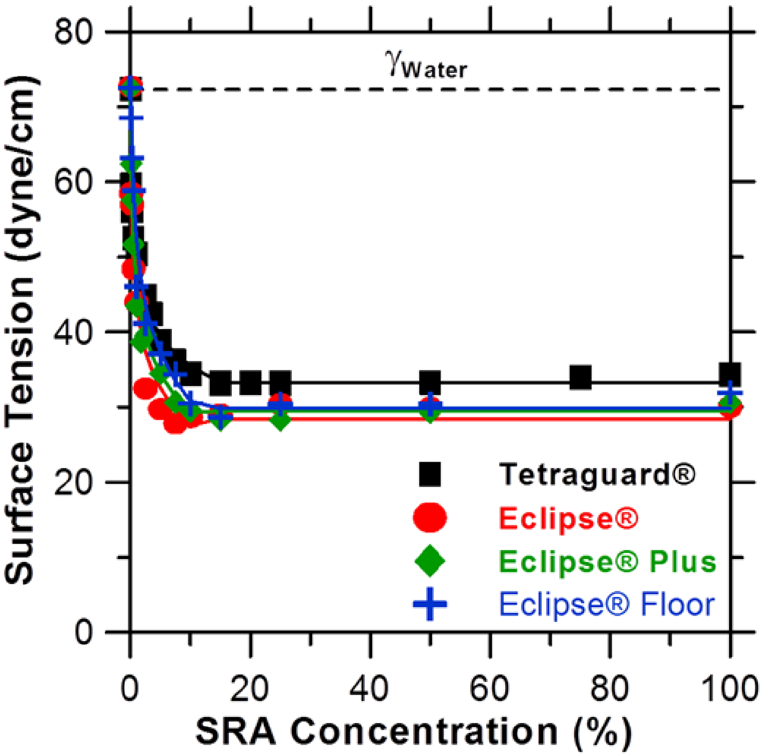
- What causes cracking? - Concrete Shrinks
- Why does concrete shrink ? Loss of water from the paste, but the size of the pores matters
- Can I Reduce Shrinkage by knowing KLYG

Using the KLPG Theory For Good

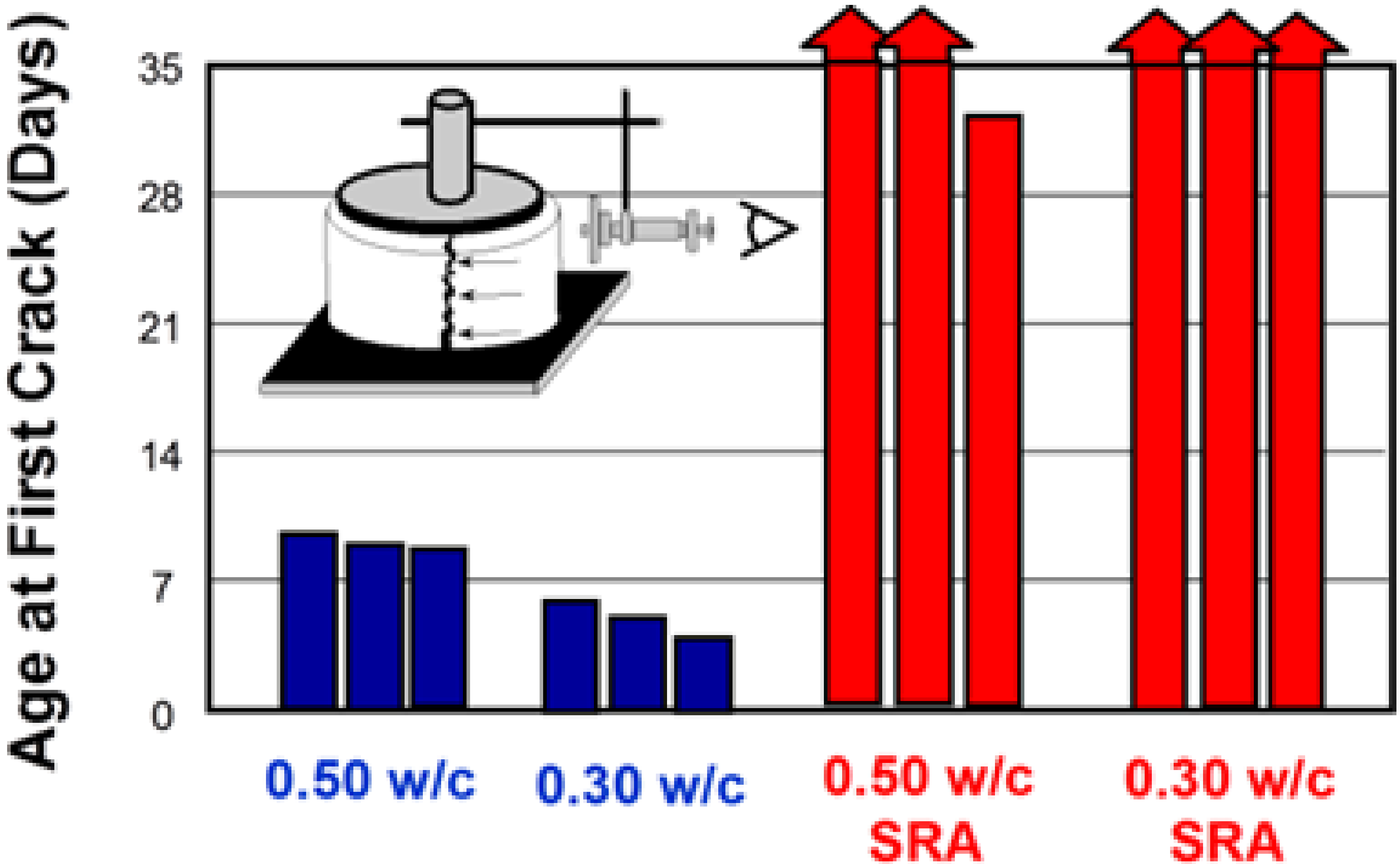
- To reduce shrinkage we reduce pressure, this means we either… reduce surface tension

- 1983 – Japan
- 1997/99 – Weiss
- US Commercial Product in 1999 from Grace

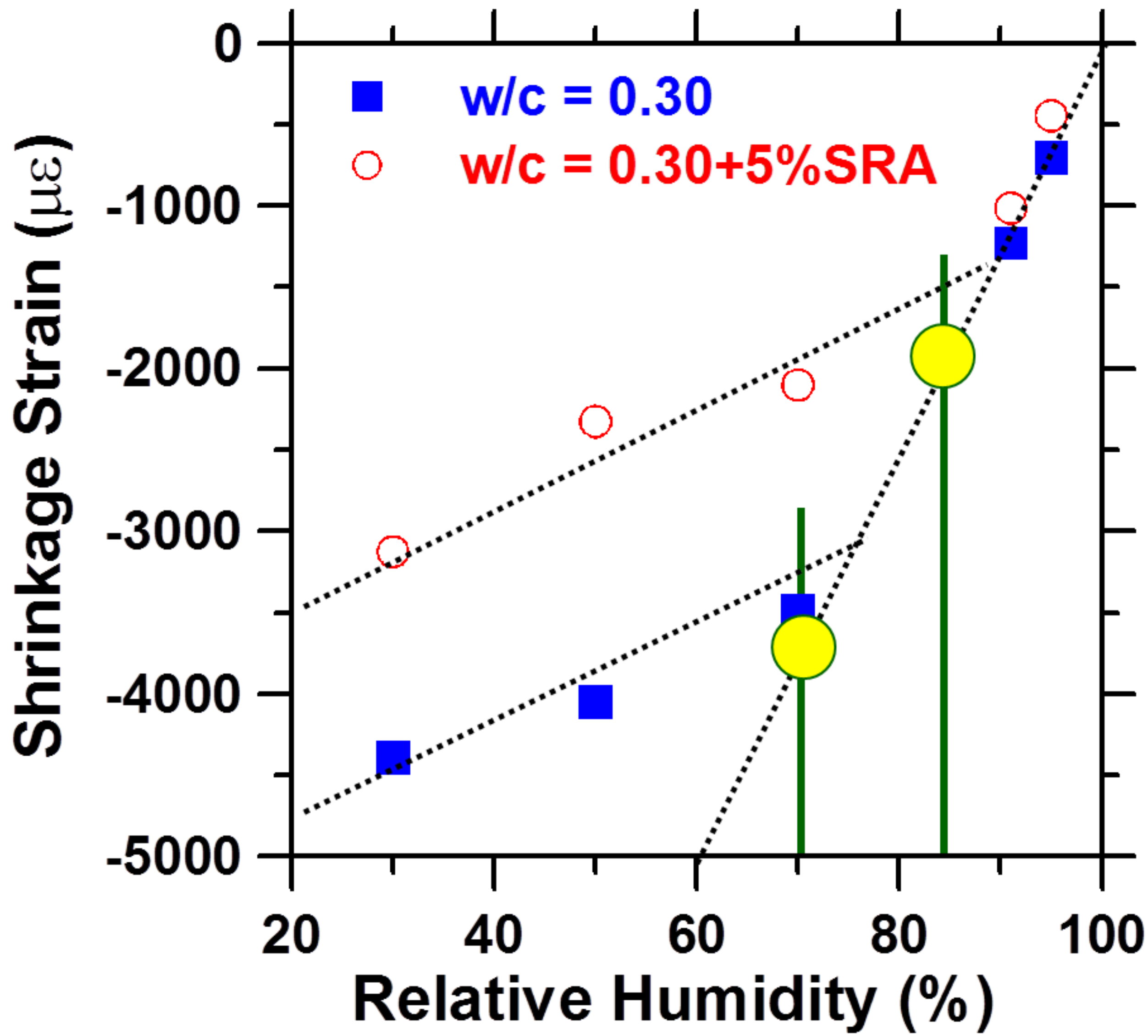
$$p_{cap} = -\frac{2\gamma}{r}$$



Shrinkage Reducing Admixtures



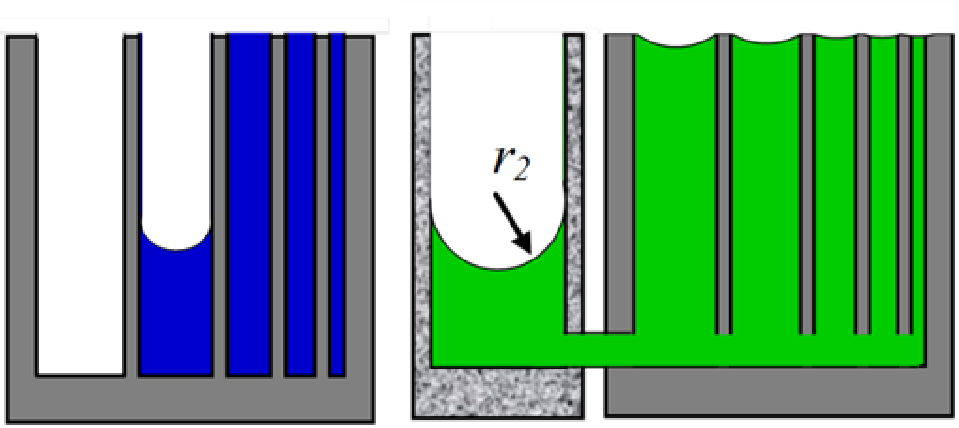
Some SRA Observations



Using the KLPG Theory For Good

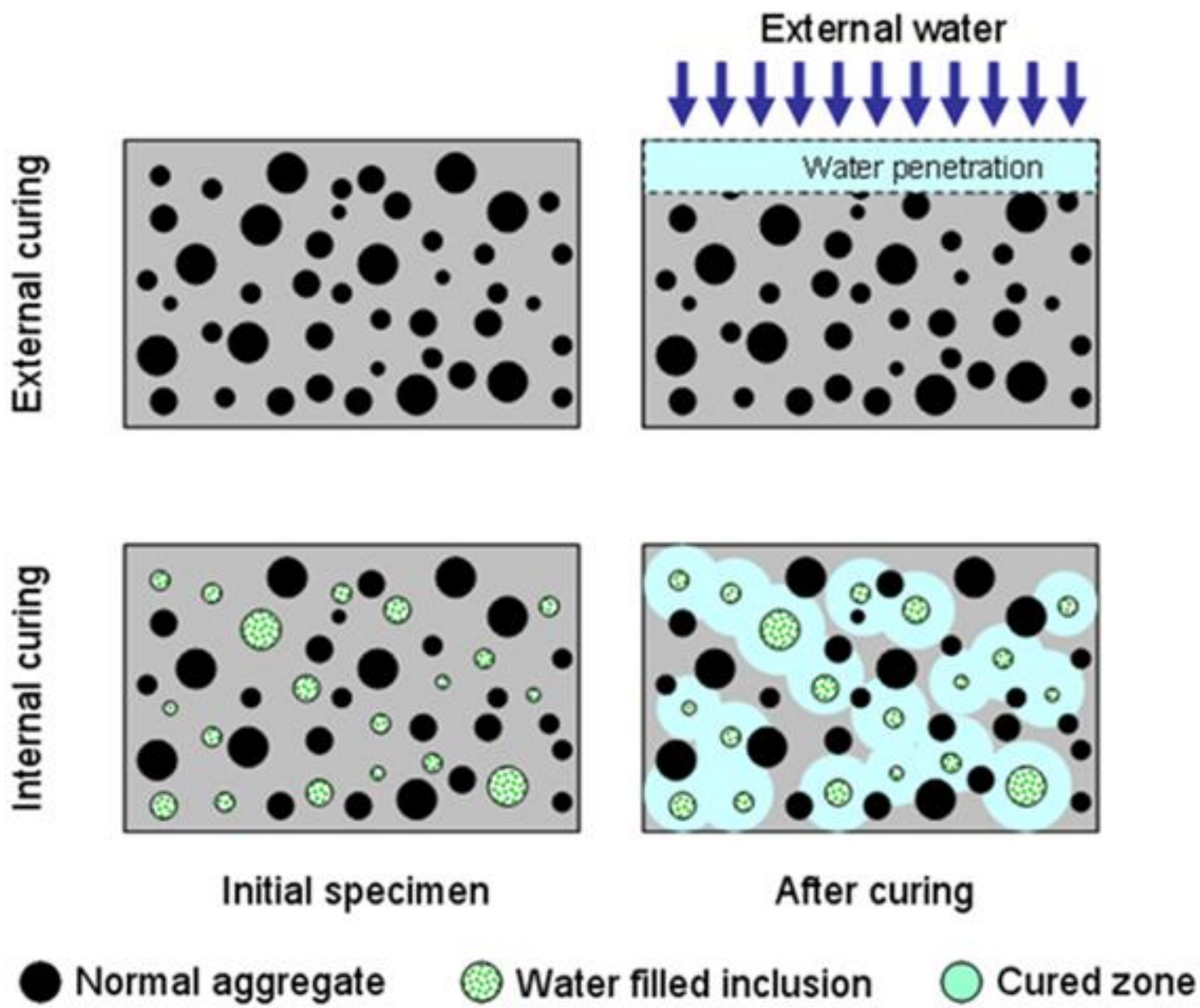
- To reduce shrinkage we reduce pressure, this means we either… reduce surface tension and/or we increase the size of the pore

- Not really impacted by w/c .. Long story
- We want to keep pores filled up



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

Internal Curing

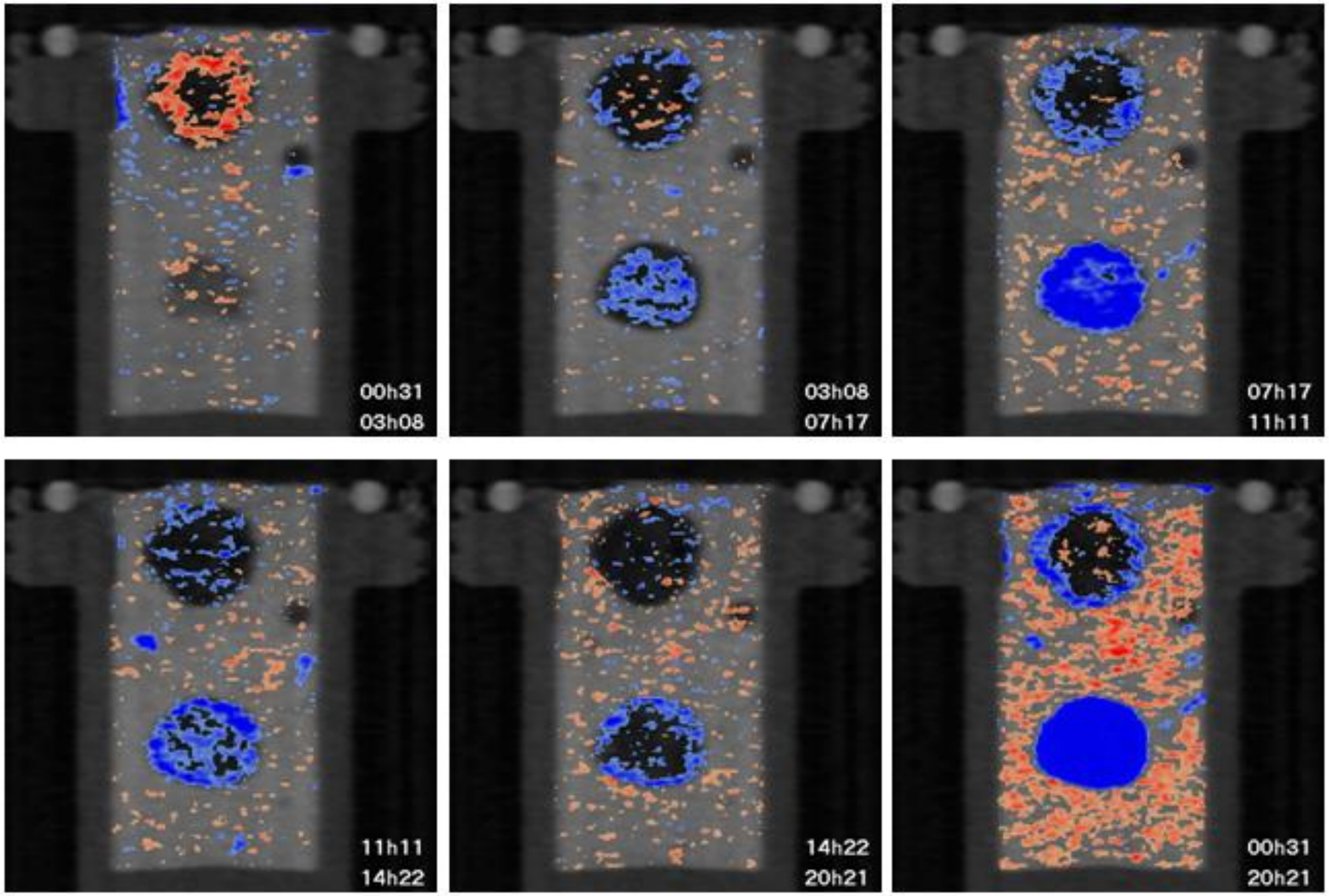


Castro et al. 2009

Things Professors Think About

Dry LWA
Absorbs
Water

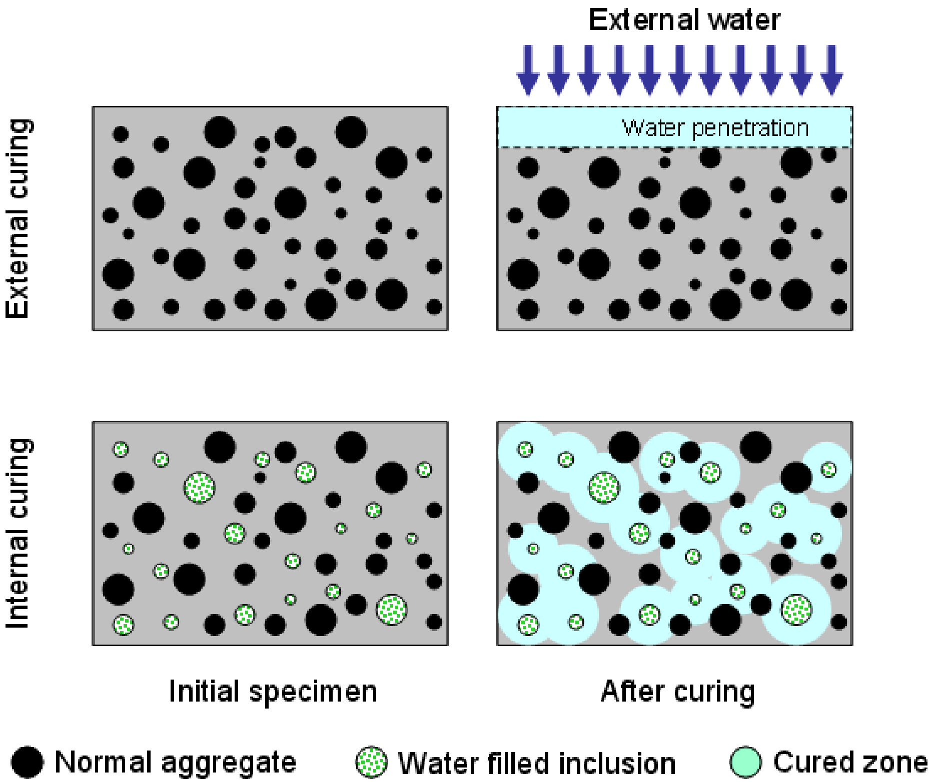
Wet LWA
Gives off
water



Trtik et al. 2010

What is Internal Curing?

- Its Concrete 101 with a twist
- Add water to cure concrete properly
- The twist… the water comes from inside the concrete
- Water held in LWA or SAP
- Magically released



Is This Practical ?

Lots of Confusion Around Proportioning – Its Really This Simple

- Based on theory
- Need a current set of mixture proportions you really like
- Enter them in orange
- Enter an aggregate's properties you really like, in green
- Wait 1 second….. voila

Project: Date:

Mixture ID:

Operator:

Plain Mixture Design

Target Air, %	6.5%
w/c	0.421

Legend

Ready Mix Input
LWA Input

Materials	Weight	SG (SSD)	Volume, ft^3
Cement	455	3.15	2.315
GGBFS	130	2.99	0.697
Fly Ash	0	2.64	0.000
Silica Fume	25	2.2	0.182
Sand	1231	2.623	7.521
Coarse Aggregate 1	1795	2.763	10.411
Coarse Aggregate 2	0	2.763	0.000
Water	257	1	4.119
Air	0	0	1.755
Σ	3893	-	26.999

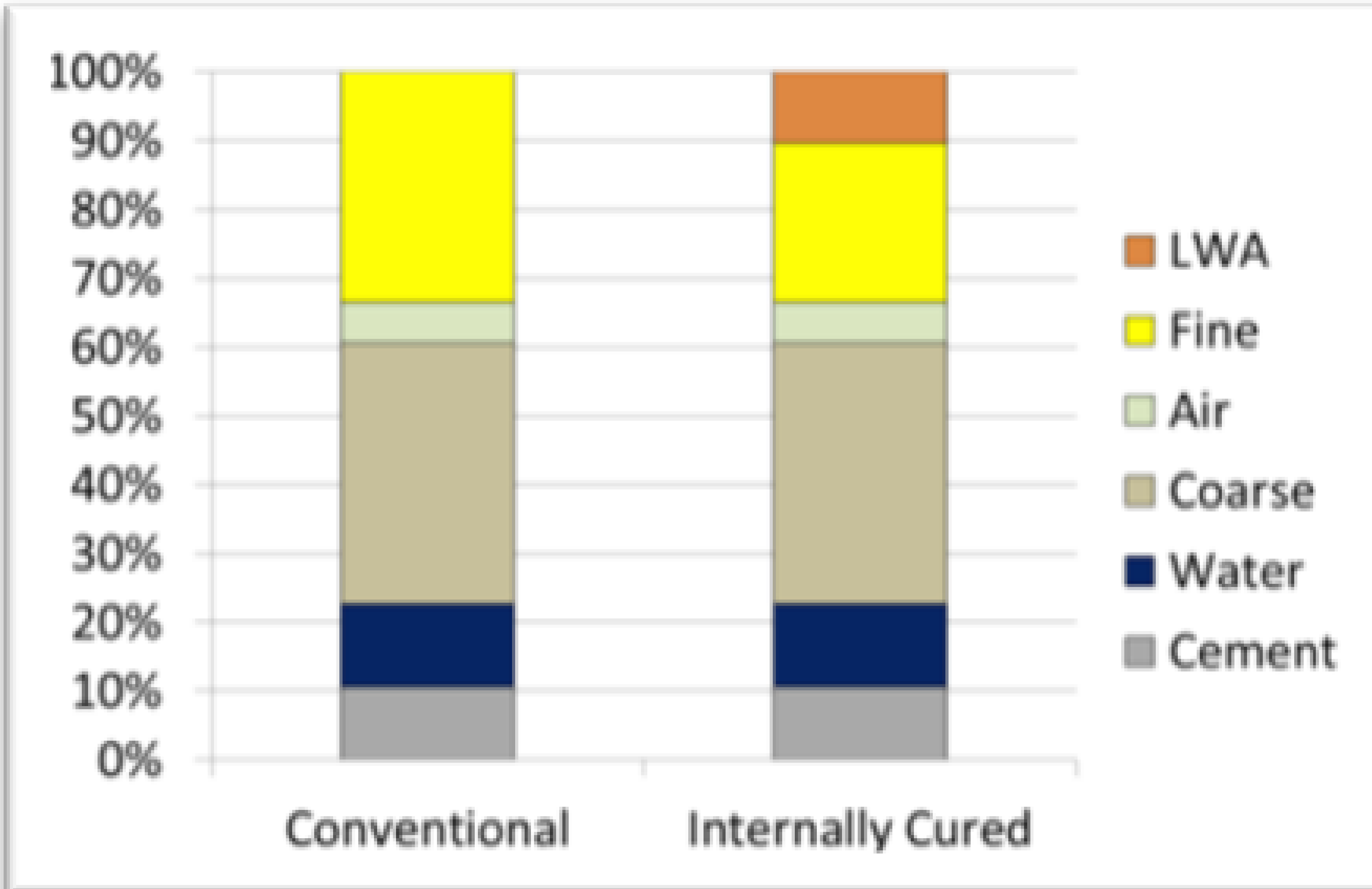
Internal Curing Properties

LWA Absorption:	15.0%	←This is 24 hour design absorption
LWA Desorption:	85.0%	←If unknown, use 85%
LWA PSD Specific Gravity	1.750	←This is 24 hour pre-wetted surface-dry specific gravity for preliminary
Cement Factor	610	
Chemical Shrinkage:	0.07	
Degree of Hydration	1	
PSD LWA Replacement	385	
SSD Sand Replaced	577	
% Volume Replacement	46.9%	

IC Mixture Design

Materials	Weight	SG (SSD)	Volume, ft^3
Cement	455	3.15	2.315
GGBFS	130	2.99	0.697
Fly Ash	0	2.64	0.000
Silica Fume	25	2.2	0.182
Sand	654	2.623	3.994
Lightweight Aggregate	385	1.750	3.527
Coarse Aggregate 1	1795	2.763	10.411
Coarse Aggregate 2	0	2.763	0.000
Water	257	1	4.119
Air	0	0	1.755
Σ	3701	-	26.999

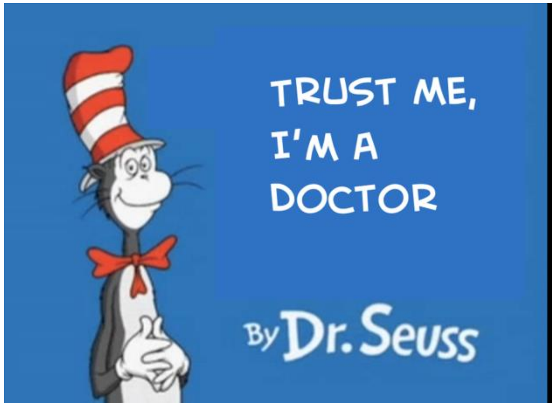
Volumetric Proportions

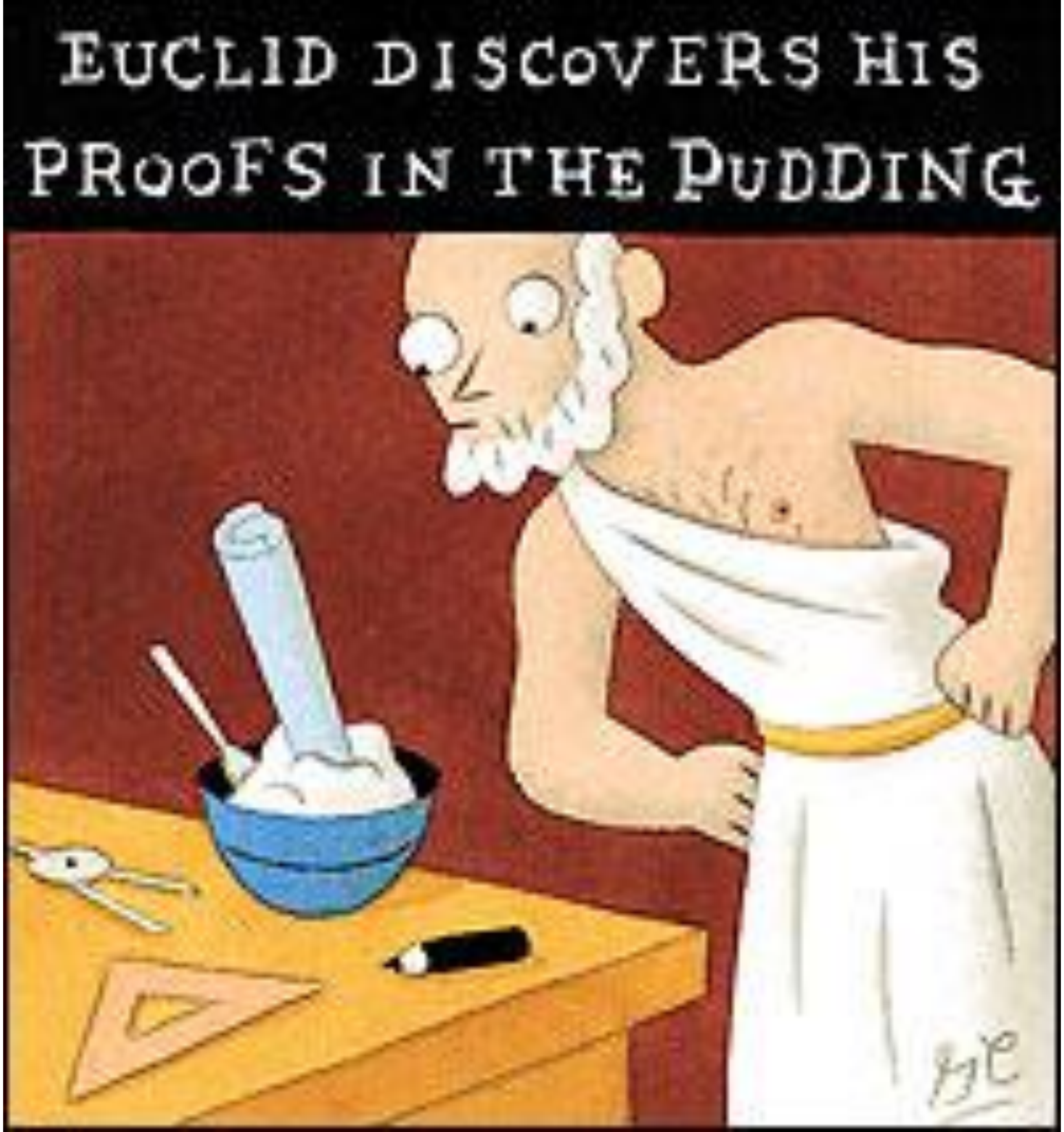


How Do I know If It Works

- Compressive Strength – Generally no change, especially if water cured
- Slump – Generally no change (depends on aggregate FM and angularity)
- Air Content – Generally no change
- Transport Properties – Generally no change or a slight reduction

- Shrinkage Cracking Reduced



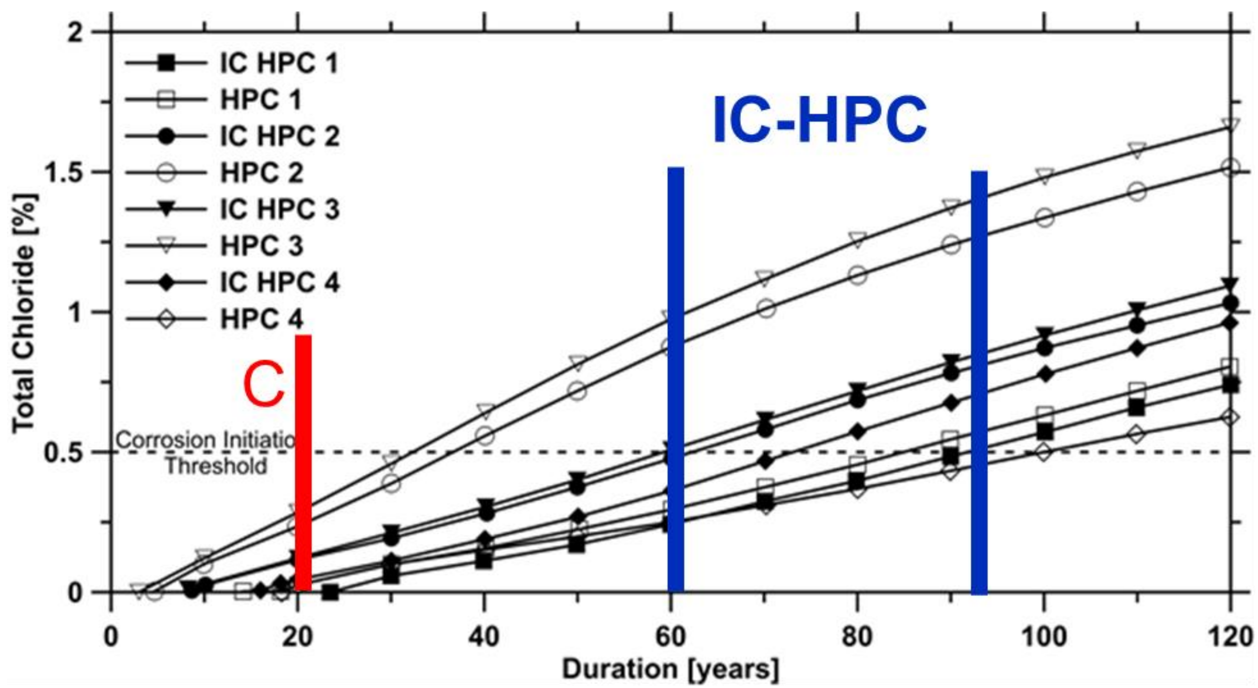

EUCLID DISCOVERS HIS
PROOFS IN THE PUDDING

Bloomington Indiana Decks - 2010

- At 18 months Plain (3 cracks) IC (none)
- At Year three very small crack in the IC

Internal Curing in Indiana 2013-15

- 10+ ICHPC Bridge Decks (All specs achieved)
- Very limited cracking (at most negative moment region due to settlement – construction Issue)
- Typical INDOT design 18 years
- ICHPC 60-90 yrs



Internal Curing in New York

- NYDOT using internal curing in bridge decks (map showing bridges as of 2012)
- General experience is positive
- Reduced cracking with no problems to contractor or supplier

Streeter et al. 2012

Internal Curing in Colorado

- Building large slabs is complex
- Denver Water 10-Million Gallon Lone Tree Tank No. 2
- Negligible differences in placing & finishing
- Opinion – less cracking and maintenance

Bates et al. 2012

Internal Curing in Texas

Friggle et al. 2008

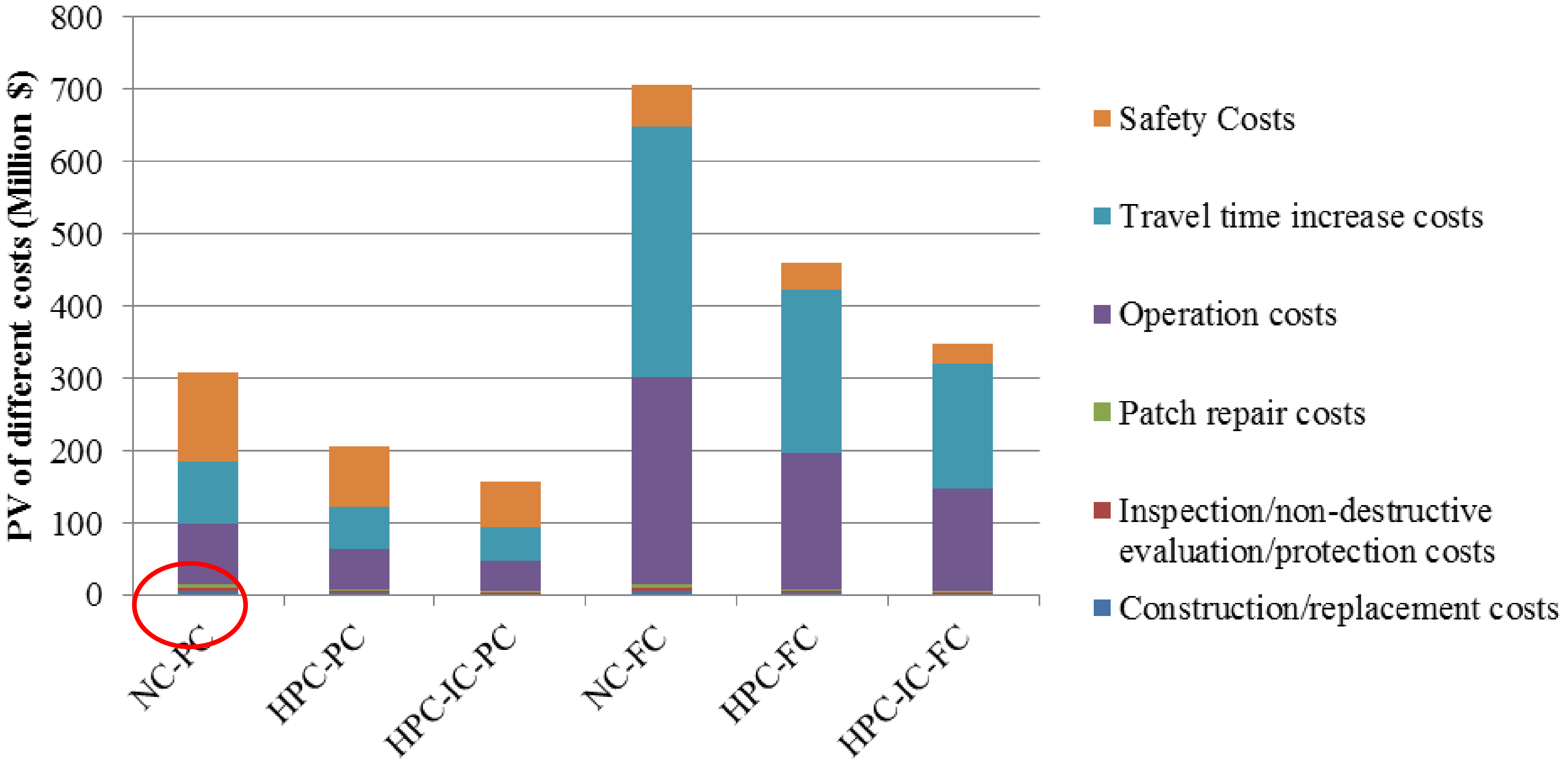
- RR intermodal facility
  - 250,000 yd^3 of low slump IC material
- CRC Paving for TxDOT
  - 6 months 1 crack, 5.5 years minor drying or plastic shrinkage cracking

Internal Curing in Illinois

- Tollway has used a SRA or IC Option
- Very happy with current experience and reduced cracking
- A neighboring states photo to fill the page …
- No change in construction

Cost Implications

- 1 bridge not three, 5% materials, 1% project
- Sustainable, Safety, Public Benefits



Lets Look at the Fundamentals

- What causes cracking? - Concrete Shrinks

- Why does concrete shrink ? Loss of water from the paste, but the size of the pores matters – Kelvin Equation

- Shrinkage Reducing Admixtures – (γ)
- Internal Curing – Supplies Water to increase r

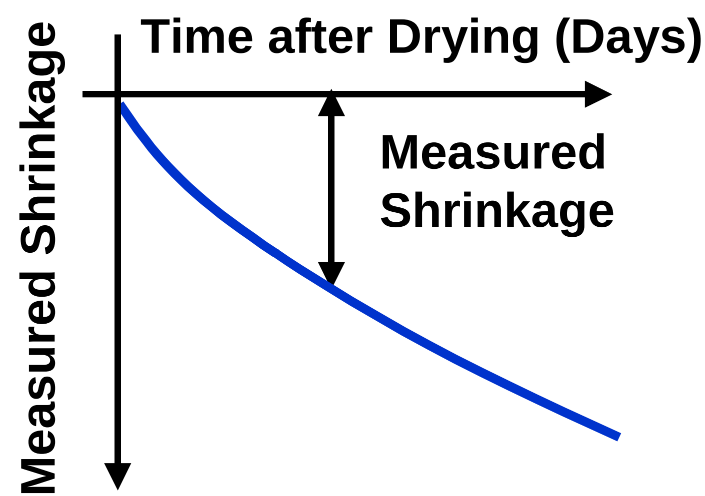
- What Tests Should I Do?

Laboratory Tests to Measure Shrinkage

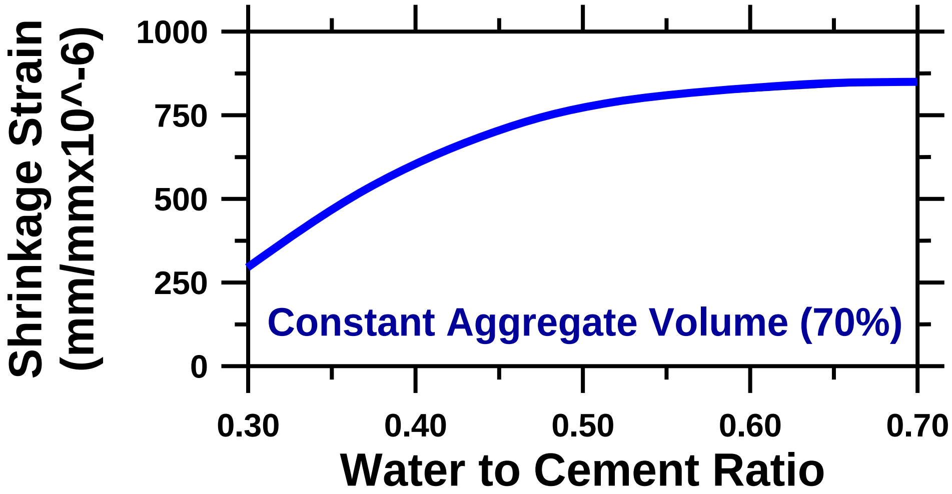
- ASTM C-157

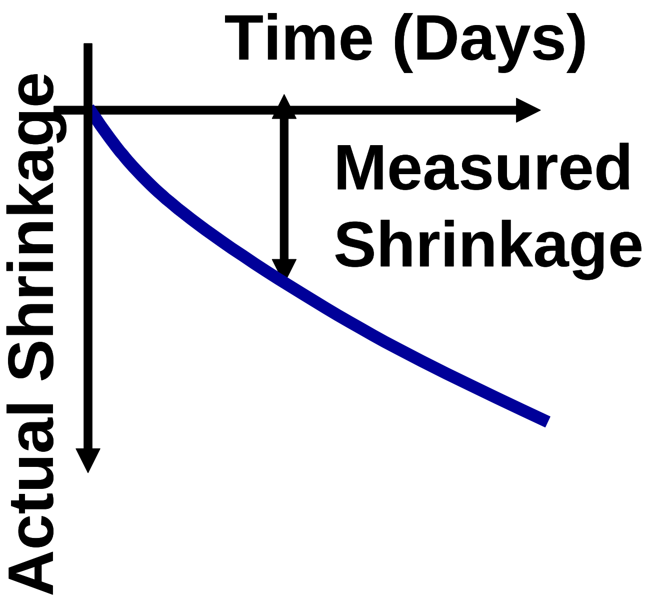
$$\varepsilon = \frac{\Delta l}{l_0}$$

- ASTM C-341



Measuring Shrinkage
Starting Time is Critical





Measuring Shrinkage
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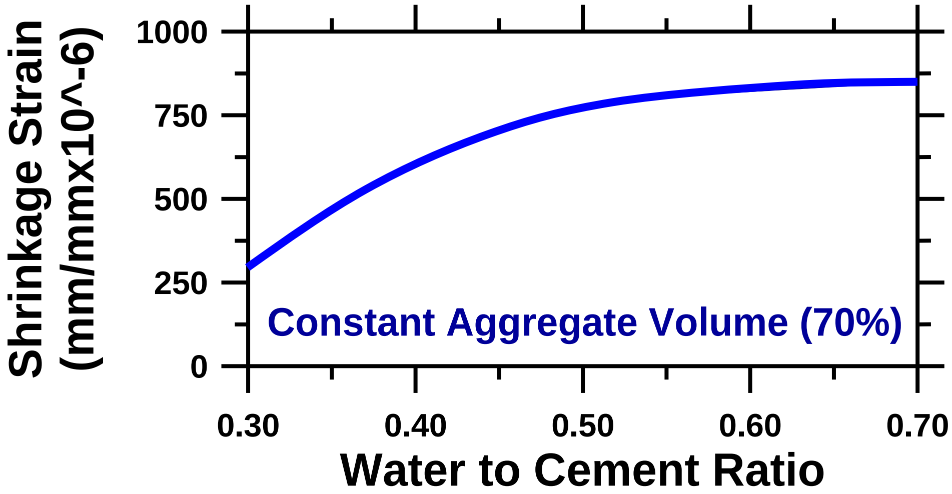
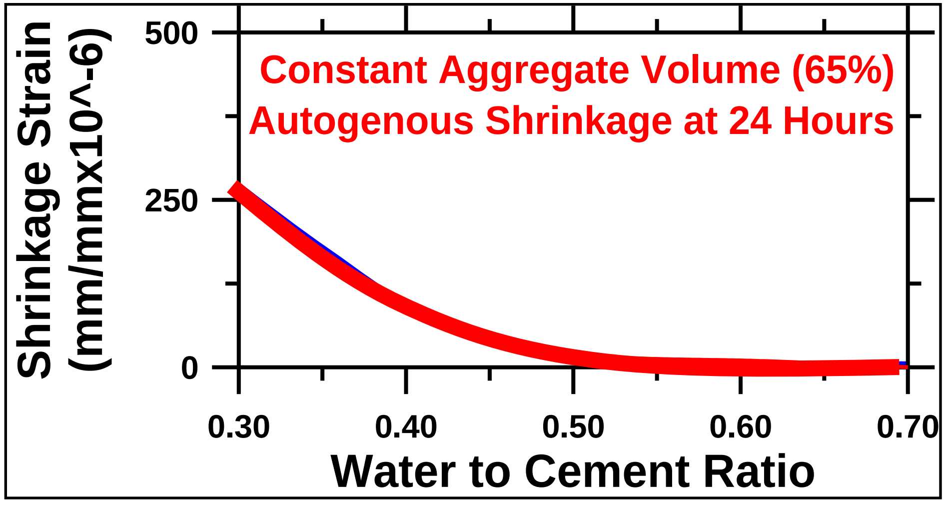
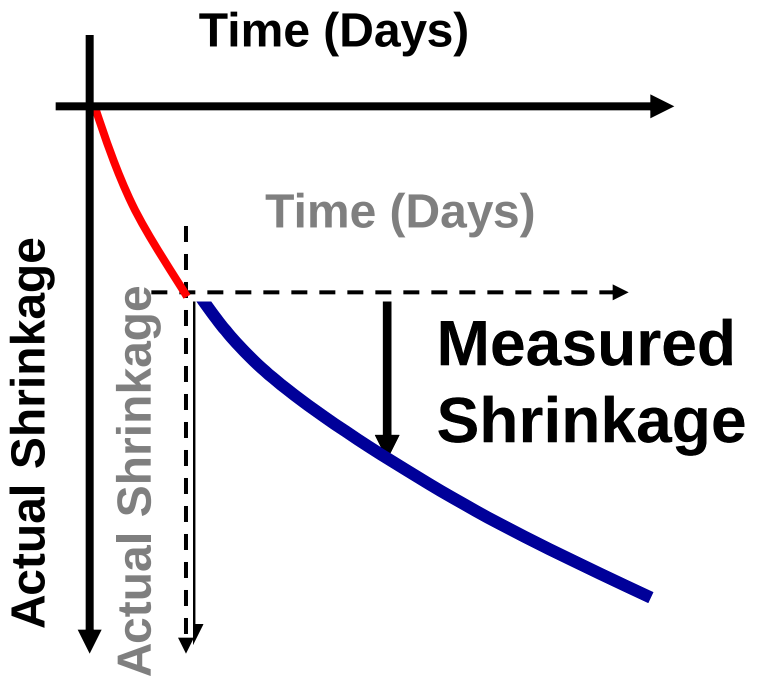


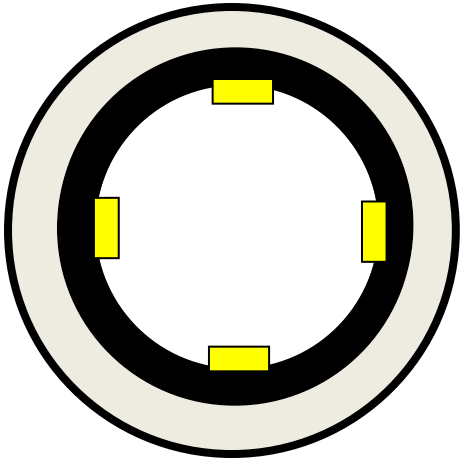




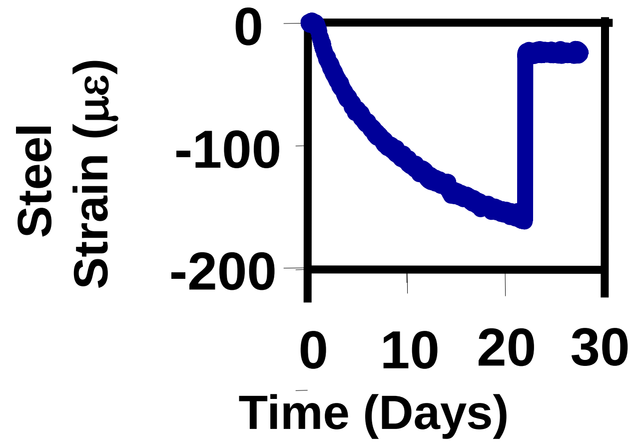
New Test – ASTM C1698

Stress Development Approach

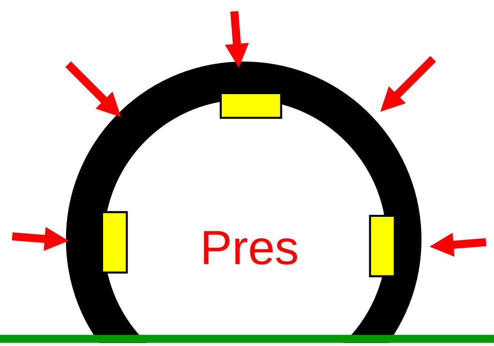
- Using an Instrumented Ring
- Measure Strain that Develops in Steel
- Determine the Pressure Required to Obtain that Strain
- Apply Pressure to Concrete and Obtain Tensile Stress

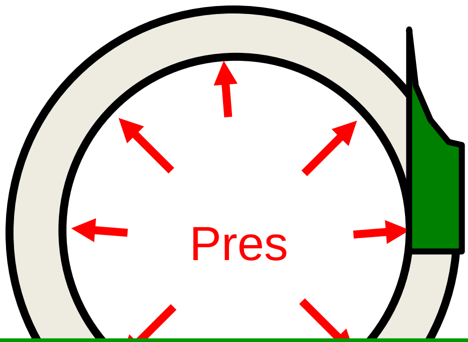


Original Ring



Measured Strain



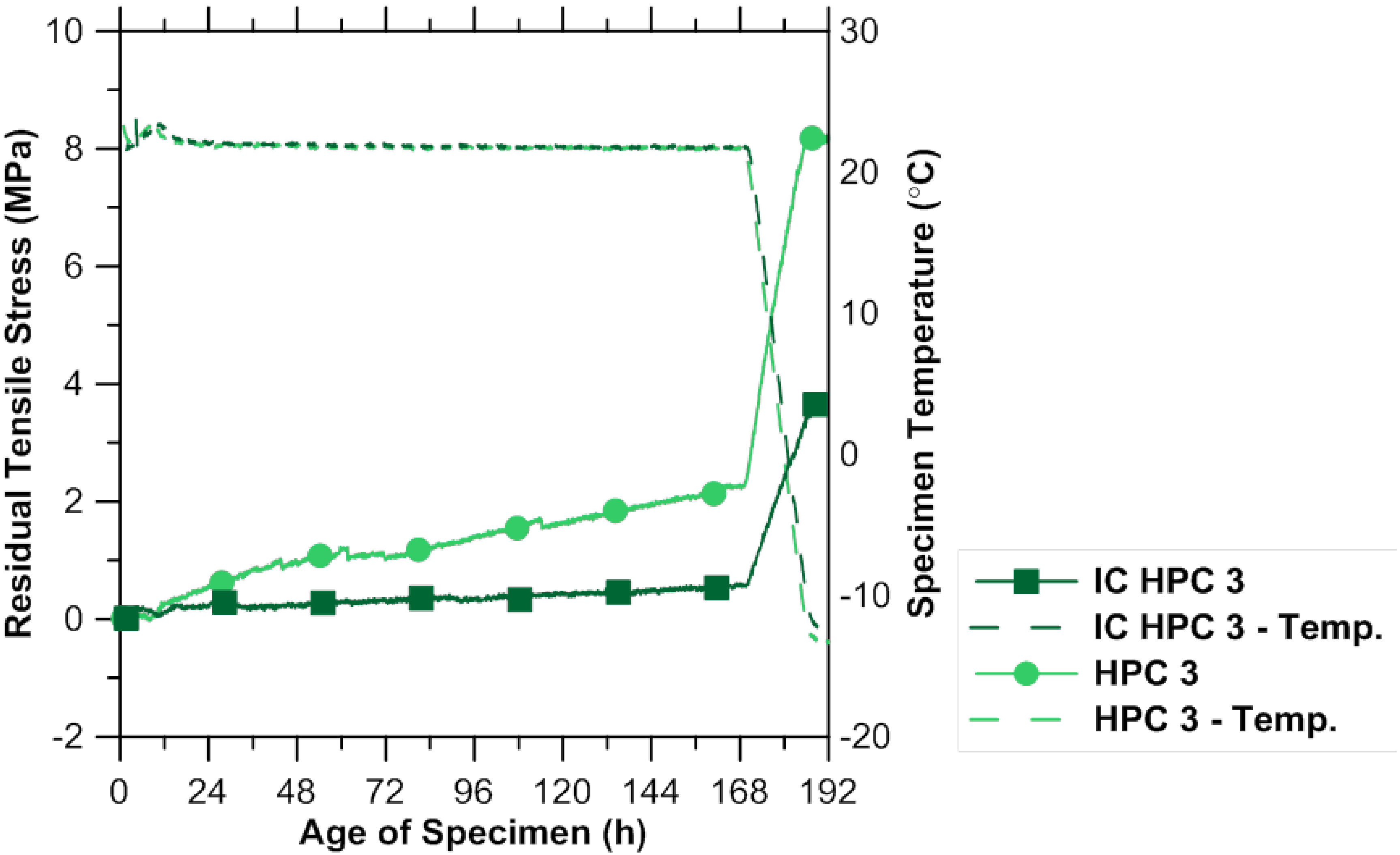


$$\sigma_{Concrete}(t)\Big|_{r=R_{IC}} = \varepsilon_{Steel}(t) E_S \frac{\left(R_{OS}^2 - R_{IS}^2\right)}{2R_{OS}^2} \frac{\left(R_{OC}^2 + R_{IC}^2\right)}{\left(R_{OC}^2 - R_{IC}^2\right)}$$

Hossain and Weiss, 2003

The Dual Ring Test

What Does Concrete Data Look Like



Lets Look at the Fundamentals

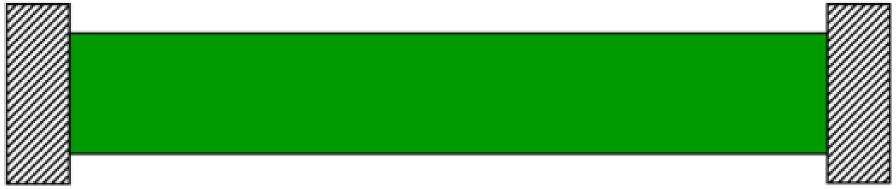
- What causes cracking? - Concrete Shrinks
- Why does concrete shrink ? Loss of water from the paste, but the size of the pores matters – Kelvin Equation
  - Shrinkage Reducing Admixtures
  - Internal Curing
- What Tests Should I Do? Ring, 1698, Dual Ring
- Thoughts on Prediction/Specification

A Simple Model

- Prediction of Stress Development

$$\varepsilon_{Permit}(t) = \int_0^t \left[\left(\frac{1}{E_\sigma(\xi)} + \frac{1}{E_c}\phi(t,\xi) \right) \frac{d\sigma(\xi)}{d\xi} + \frac{d\varepsilon_{Shr}(\xi)}{d\xi} \right] \cdot d\xi$$

(Weiss, 1997)

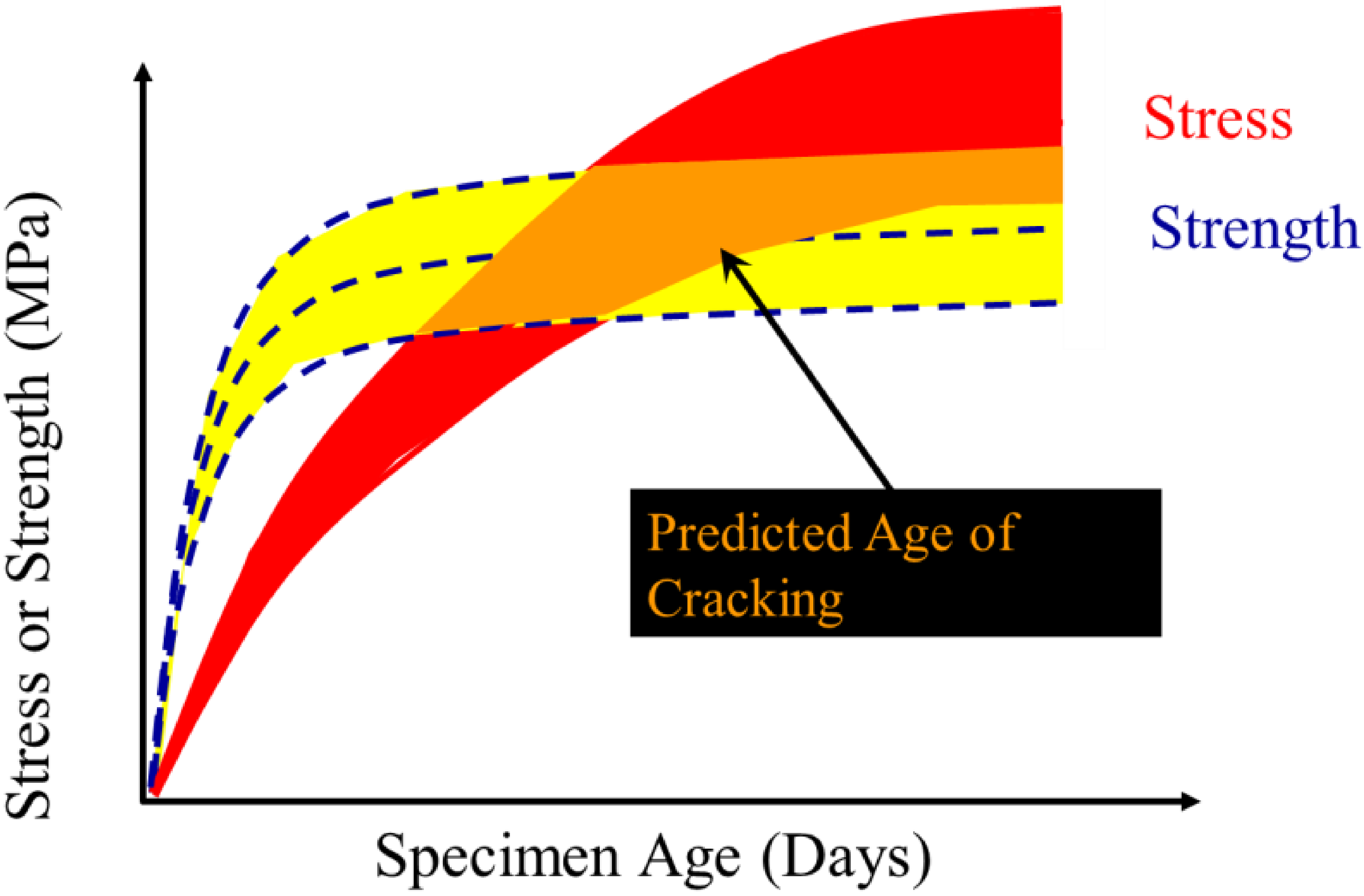


- Age/Time Dependent Material Properties

$$E_c(t) = E_\infty \frac{C_1(t-t_s)}{1+C_1(t-t_s)} \qquad f_{ten(t)} = f_{ten-\infty} \frac{C_2(t-t_s)}{1+C_2(t-t_s)}$$

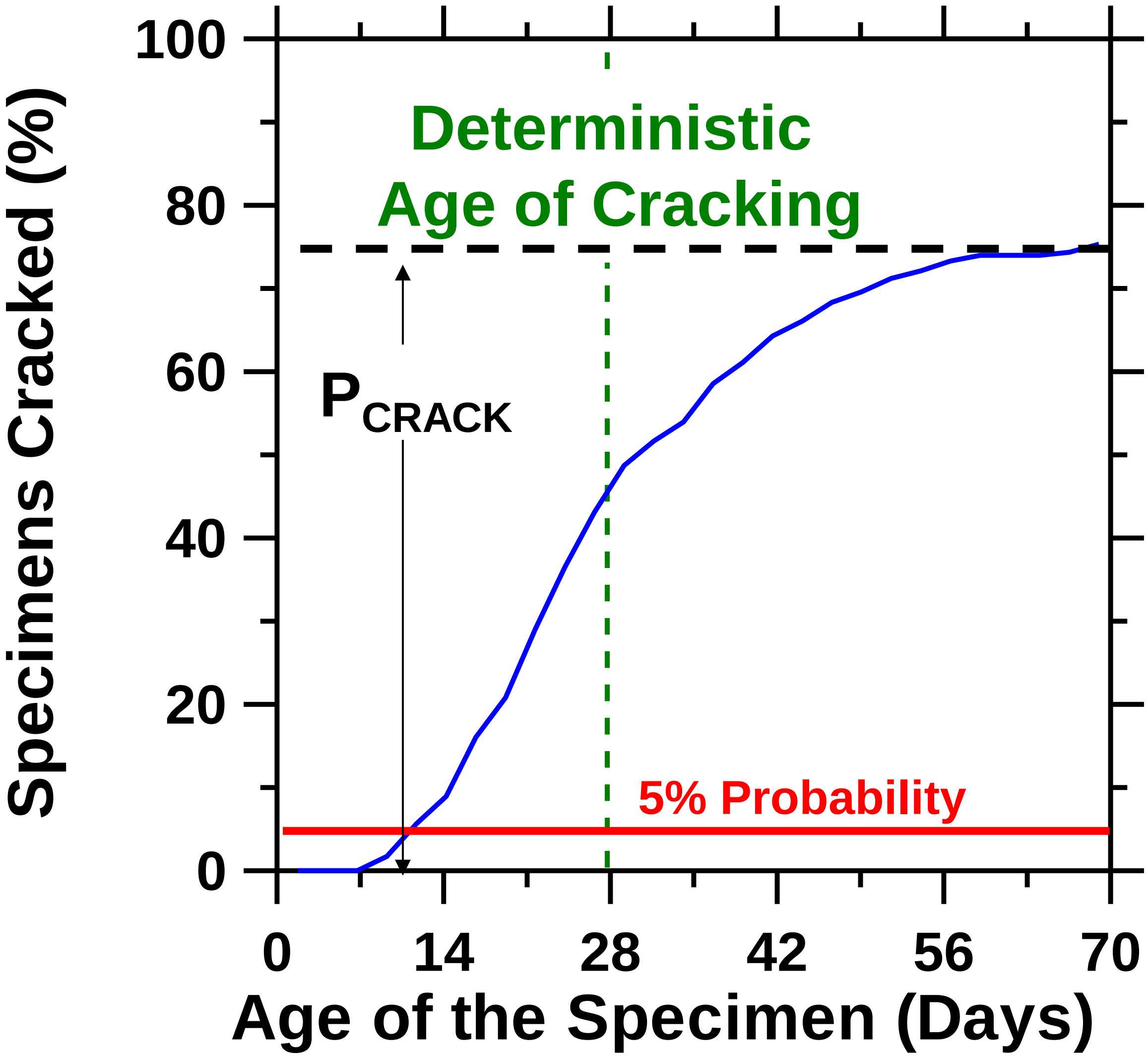
(McIntosh, 1956)

Including 'Random Variation'



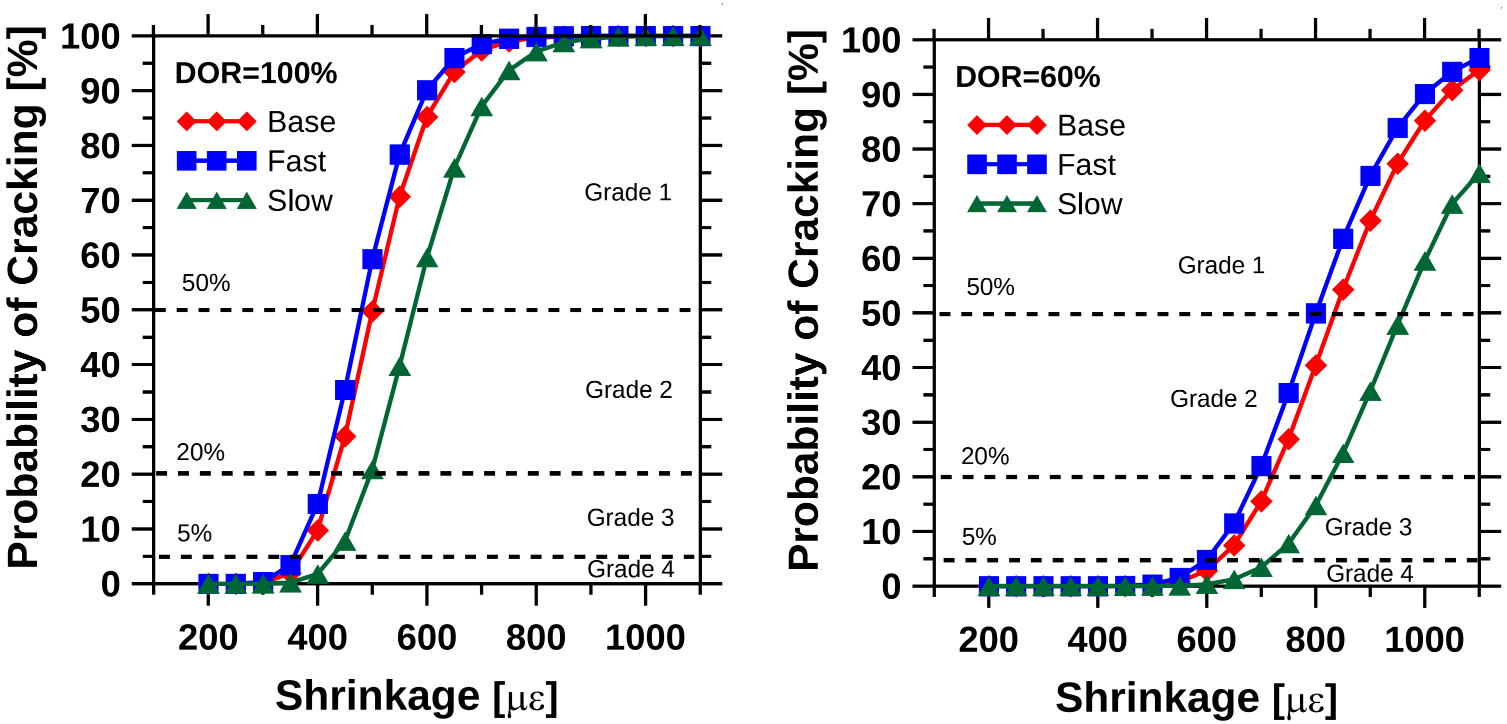
Results Of An Alternative Approach to Consider Variability in Shrinkage

- 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

Eager Beavers

- OSU - strong materials group wanting to help improve concrete performance
- Early age/shrinkage mitigation expertise (SRA, IC)
- SCM/Limestone/
- Durability Testing and Prediction
- Sustainability Related Research
- Non Destructive Testing
- Mechanical Properties and Reinforced Concrete
- Service Life Modeling – Corrosion, Freeze-Thaw
- Fluid Movement

Thank you
Are There Any Questions

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