Durability Knights of the Round Table - Performance Specs -

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KING
ARTHUR

Prescriptive Specifications

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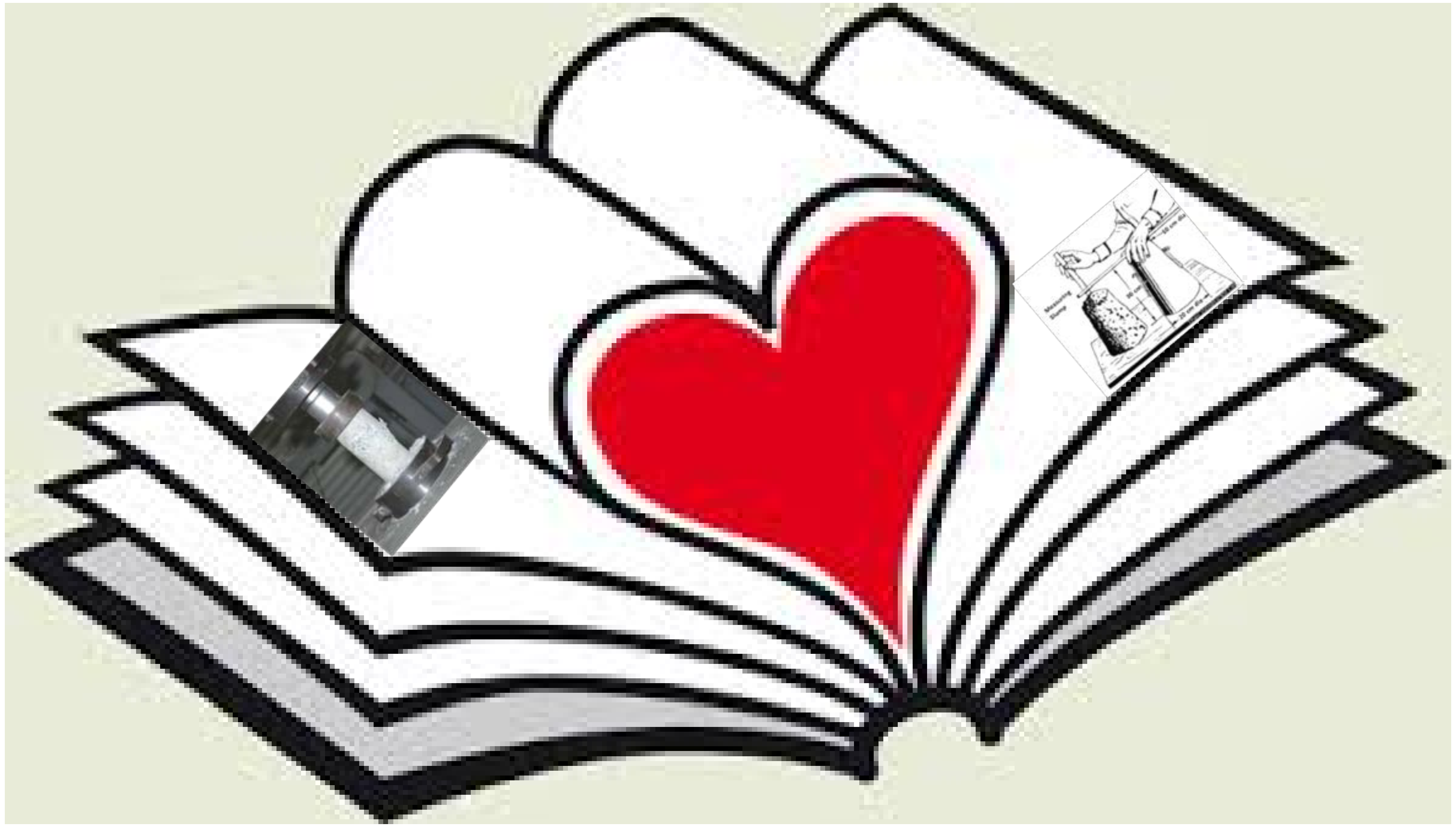
- Some people love their prescriptive specifications
- They are referred to some as recipe specifications
- Frequently they focus on slump, air and compressive strength
- If this works for you that's fine
- The problem is there are cases it does not



Is Concrete Durable

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Alkali Silica Reactivity (www.fhwa.dot.gov)

Shrinkage Cracking (www.carasquilloassociates.com)

Freeze-Thaw Damage (www.cement.org)

Joint Damage (Weiss et al. 2005, Byers 2015)

OSU ETG Contributions

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TARGET: Improve Long-Term Durability

- Freeze-Thaw
- Salt Damage
- Chloride Ingress
- ASR

- Shrinkage & Cracking

Worked to develop an overall framework

Identified sections

- 6.5
- 6.6
- 6.7
- 6.8

Weiss et al. 2015

This is work done prior to the current pooled fund and led to a large portion of AASHTO PP-84

Four Step Approach Toward Performance

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Assess Performance w/ Standard Tests

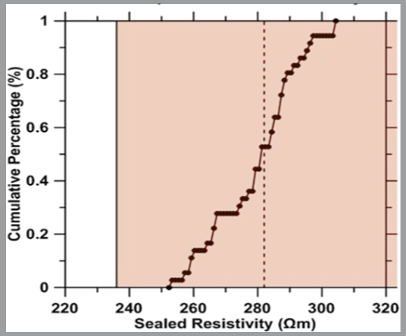
Tests should be:
- easy to perform
- economical
- repeatable

Convert Test Results to Fundamental Properties

Example:
- Measure ρ
- Account for Pore Solution
- Determine F- Factor

Relate Properties w/ Exposure Conditions

Use Exposure, Material Properties, and Models to Estimate Performance



Establish Performance Grade and Measure

Set Performance Limits and Use Tests to Measure to Insure That You Received What you Specified

Barde et al. 2007

Four Step Approach Toward Performance

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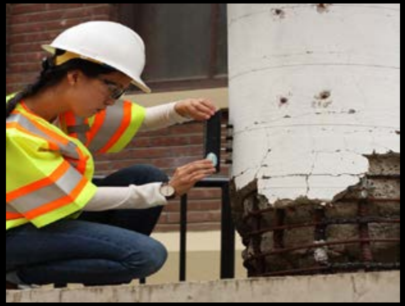

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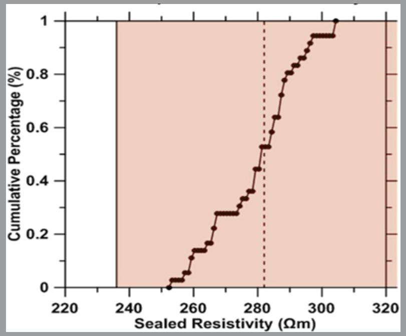

Establish Performance Grade and Measure

Shrinkage Cracking/Probability of Cracking

Formation Factor and Corrosion

Freeze-Thaw Saturation Model

Salt Damage in Pavements

Barde et al. 2007

Shrinkage and Shrinkage Cracking

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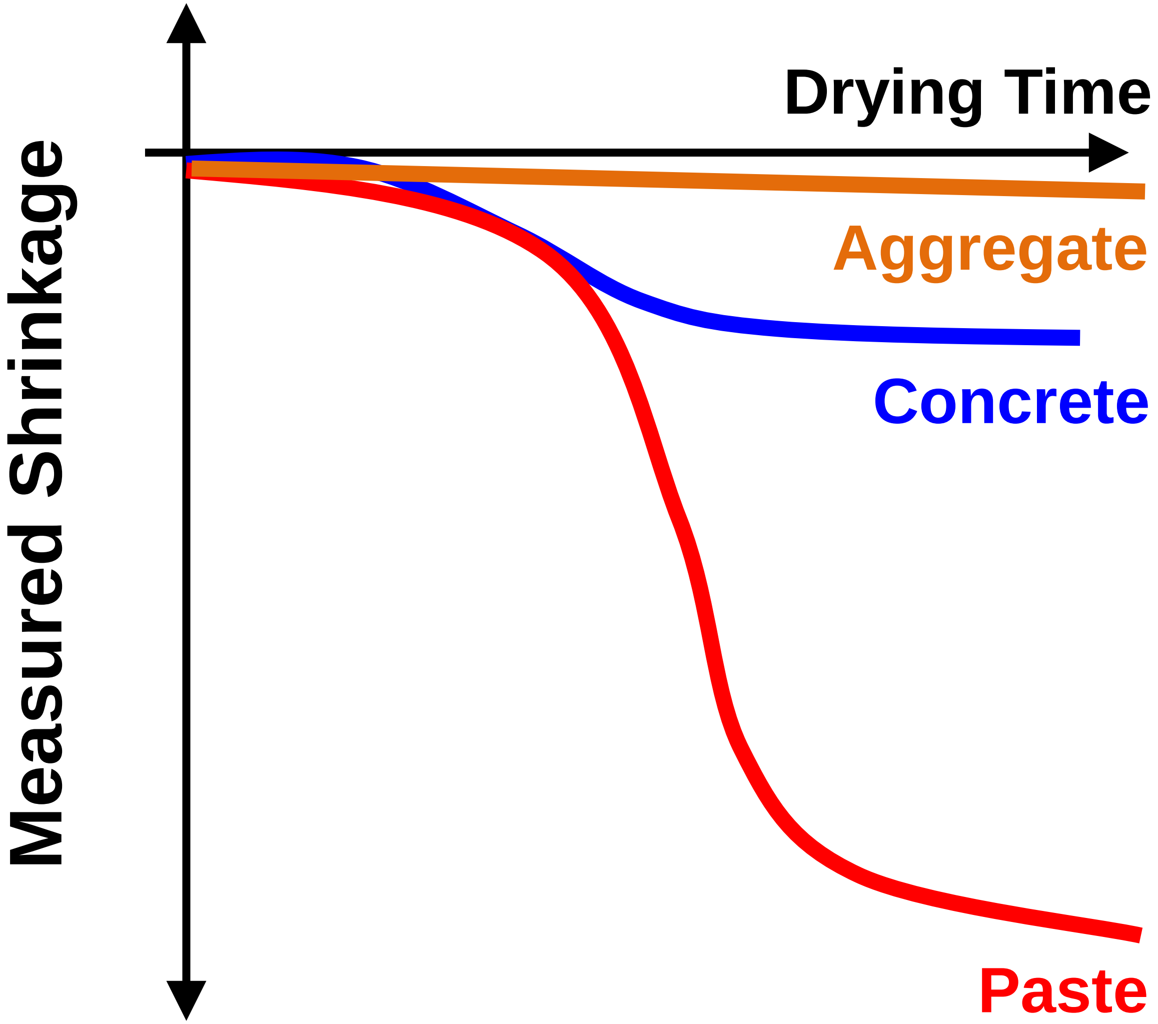
- Durability is key
- Transverse cracking in 100,000+ bridges
- 62% of DOT's consider cracking as a problem (NCHRP)
- Cracks shorten service life, increase maintenance, and accelerate corrosion
- Increase in HSC

Here we see cracks spaced at 2.5 ft on the approaches to a bridge

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

Shrinkage of Components

- Looking at shrinkage of the components
- Aggregate generally don't shrink
- Paste is the portion that shrinks
- Shrinkage is a paste property
- SRA/IC different

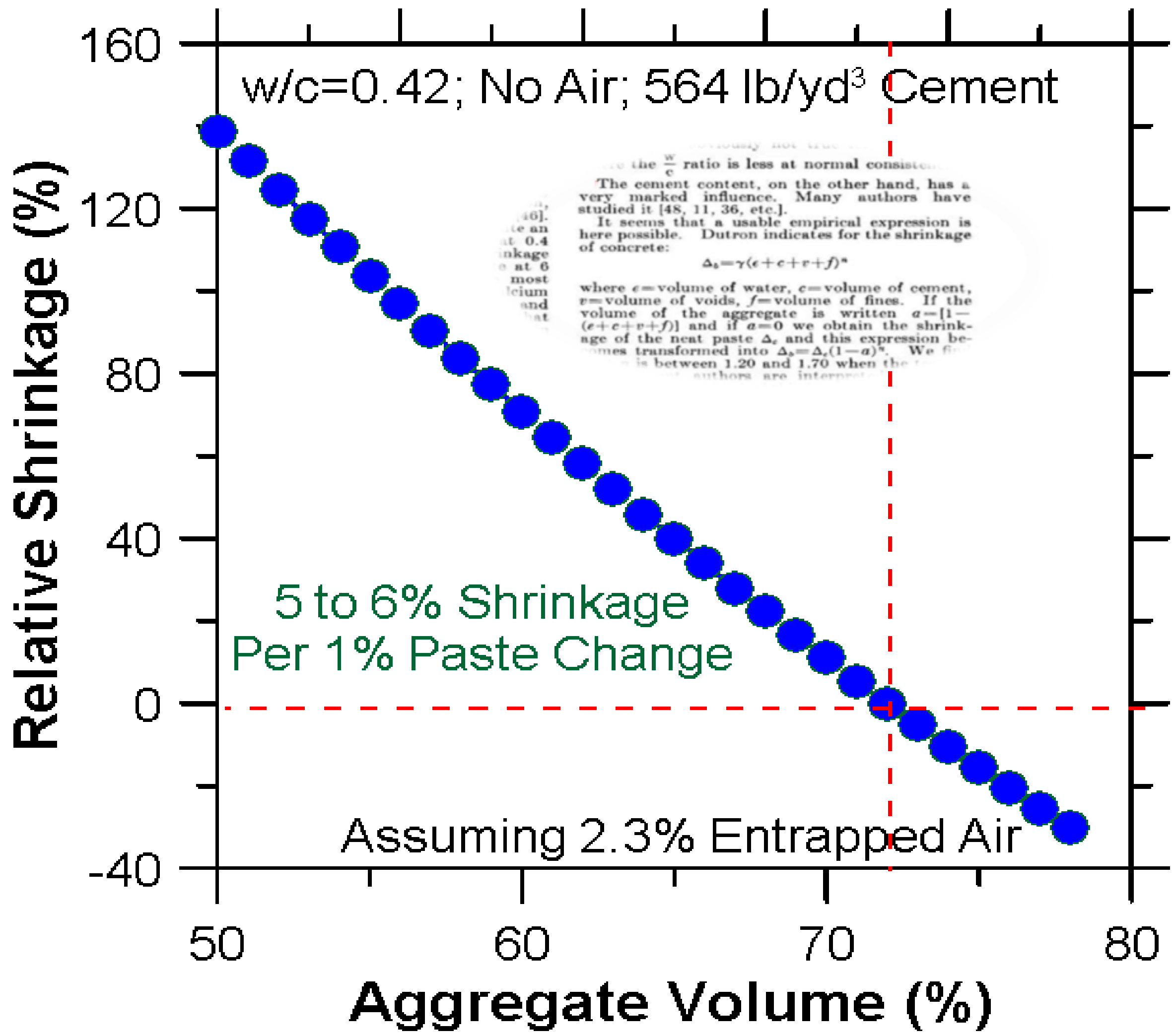


Volume of Paste is One Approach – V $_{Paste}$

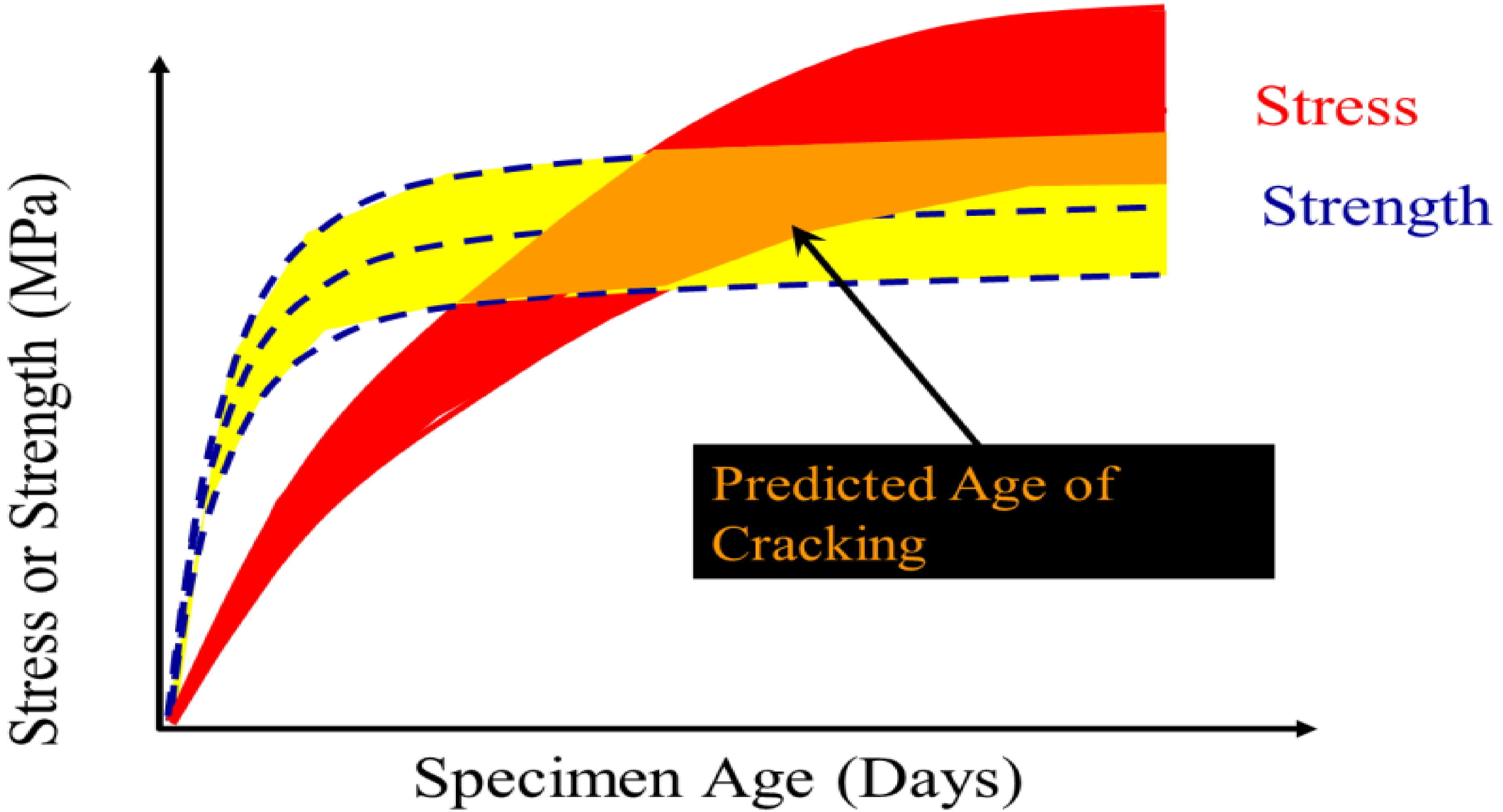
- Dutron (1956) shares data
- L'Hermite (1960 no influence of the w/c) (We can shown this is due to PSD)
- Pickett ('65) and others work on eqn

$$\varepsilon_{Concrete} = \varepsilon_{Paste}\left(1 - V_{Agg}\right)^{n}$$

- SRA, IC change this approach doable)

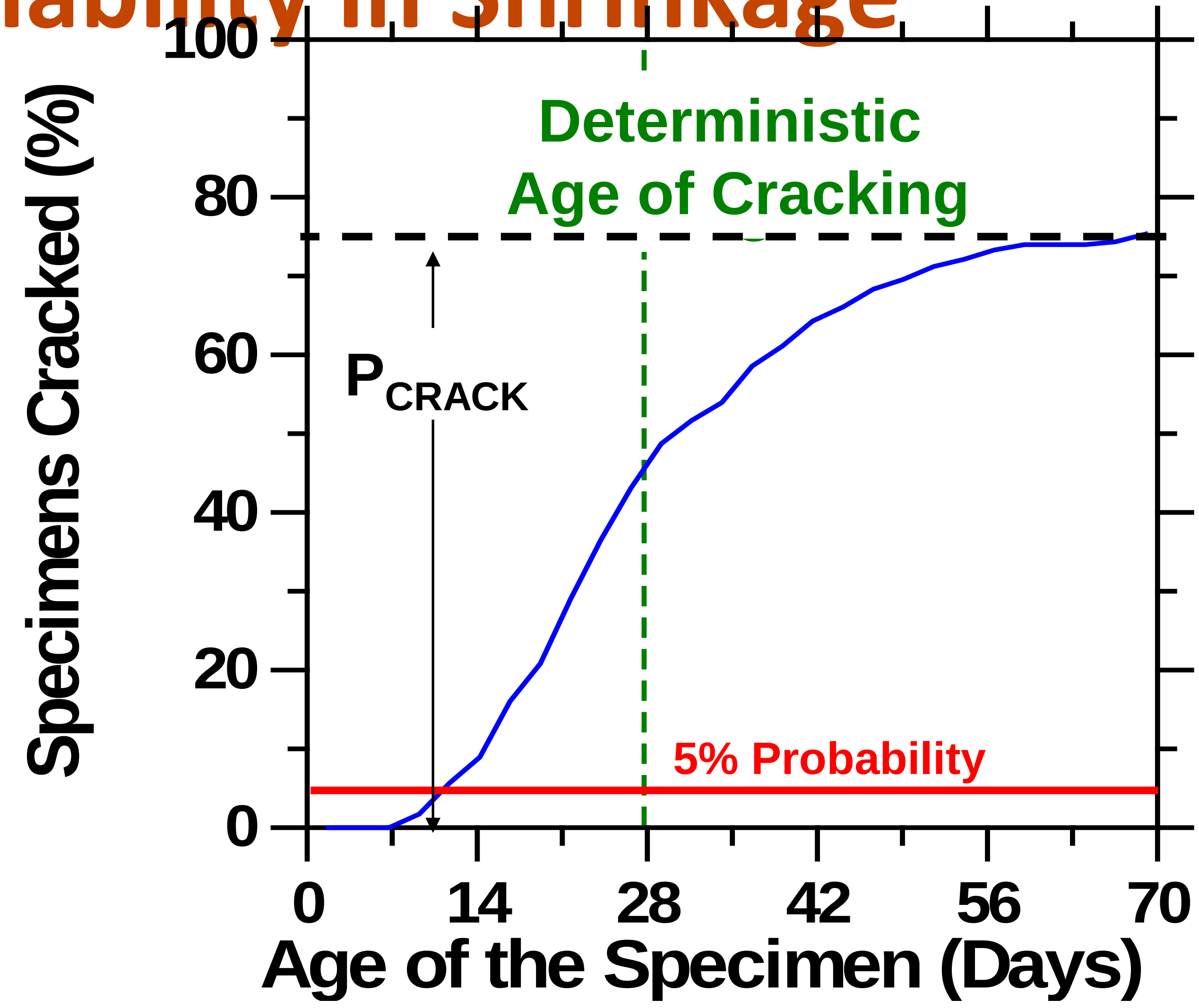


Probability of Cracking



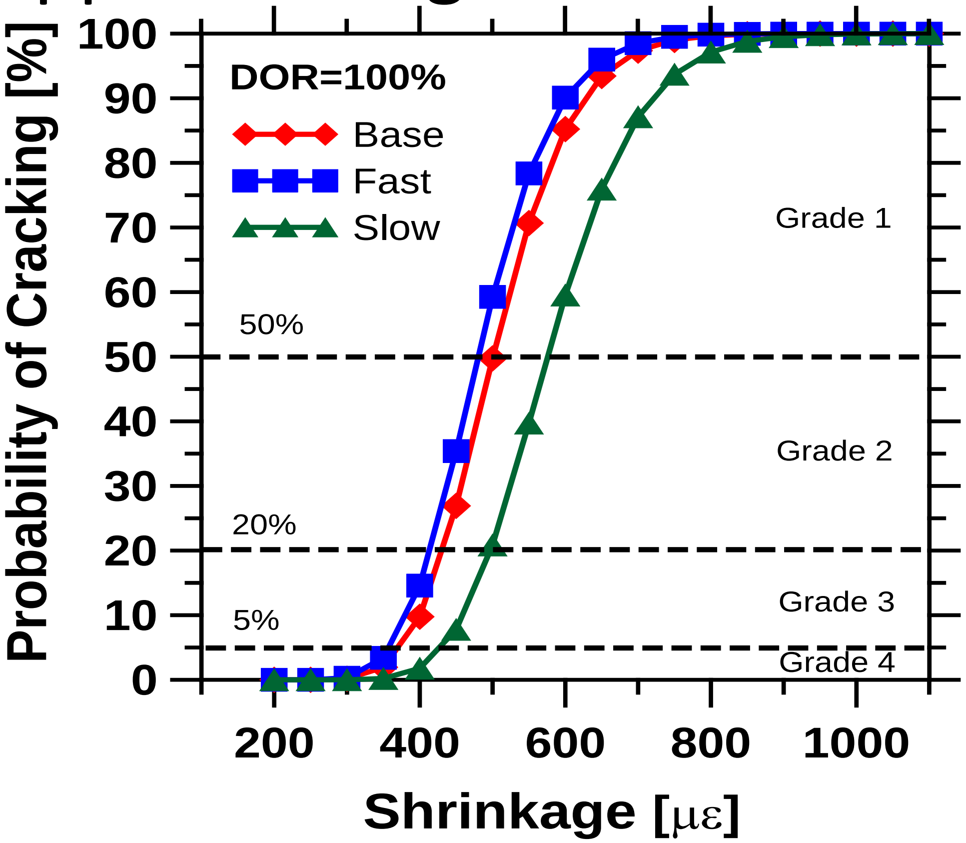
Results Of An Alternative Approach to Consider Variability in Shrinkage

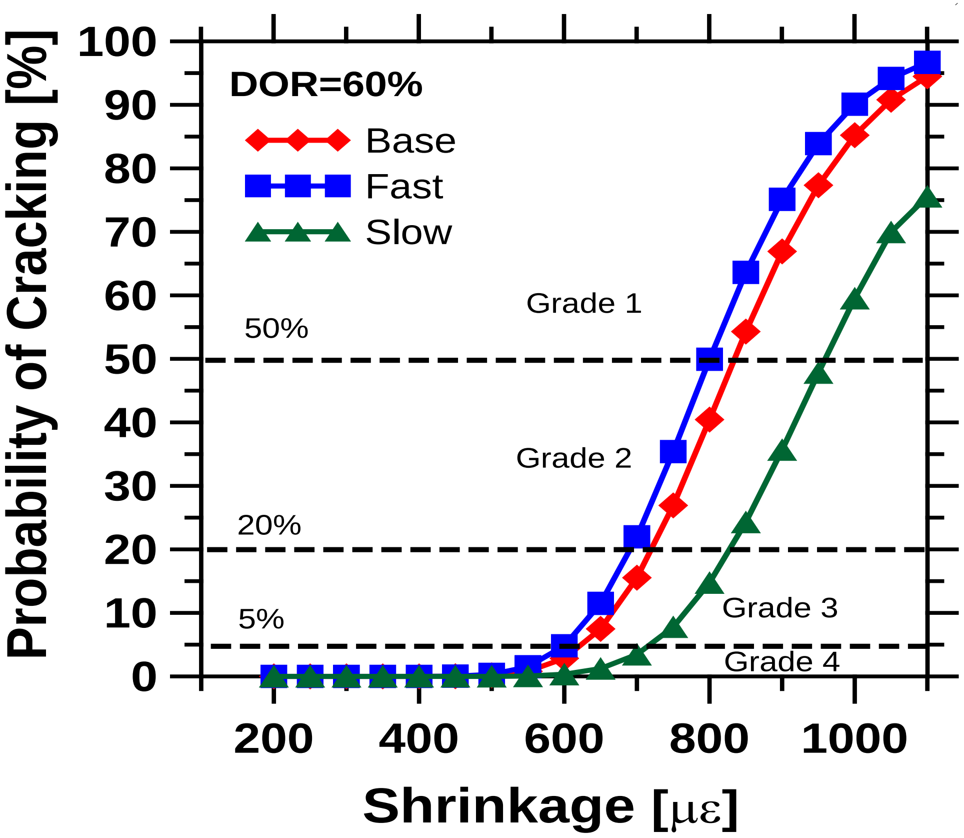
- Plotted the percentage of specimens cracked by a specific age
- Results of 10,000 simulations
- Can quantify risk or total probability



Probability Based Shrinkage Specification

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





Dual Ring Test (AASHTO Approved)

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Standard Method of Test for

Evaluating Stress Development and Cracking Potential due to Restrained Volume Change Using a Dual Ring Test

AASHTO Designation: T XXX-12

1. SCOPE

1.1. This test method covers the evaluation of stress development and cracking potential in concrete when volume changes caused by shrinkage and temperature changes are restrained. The procedure is comparative for the degree of restraint of the ring and is not intended to determine the time of initial cracking of a concrete cast in any specific type of structure.

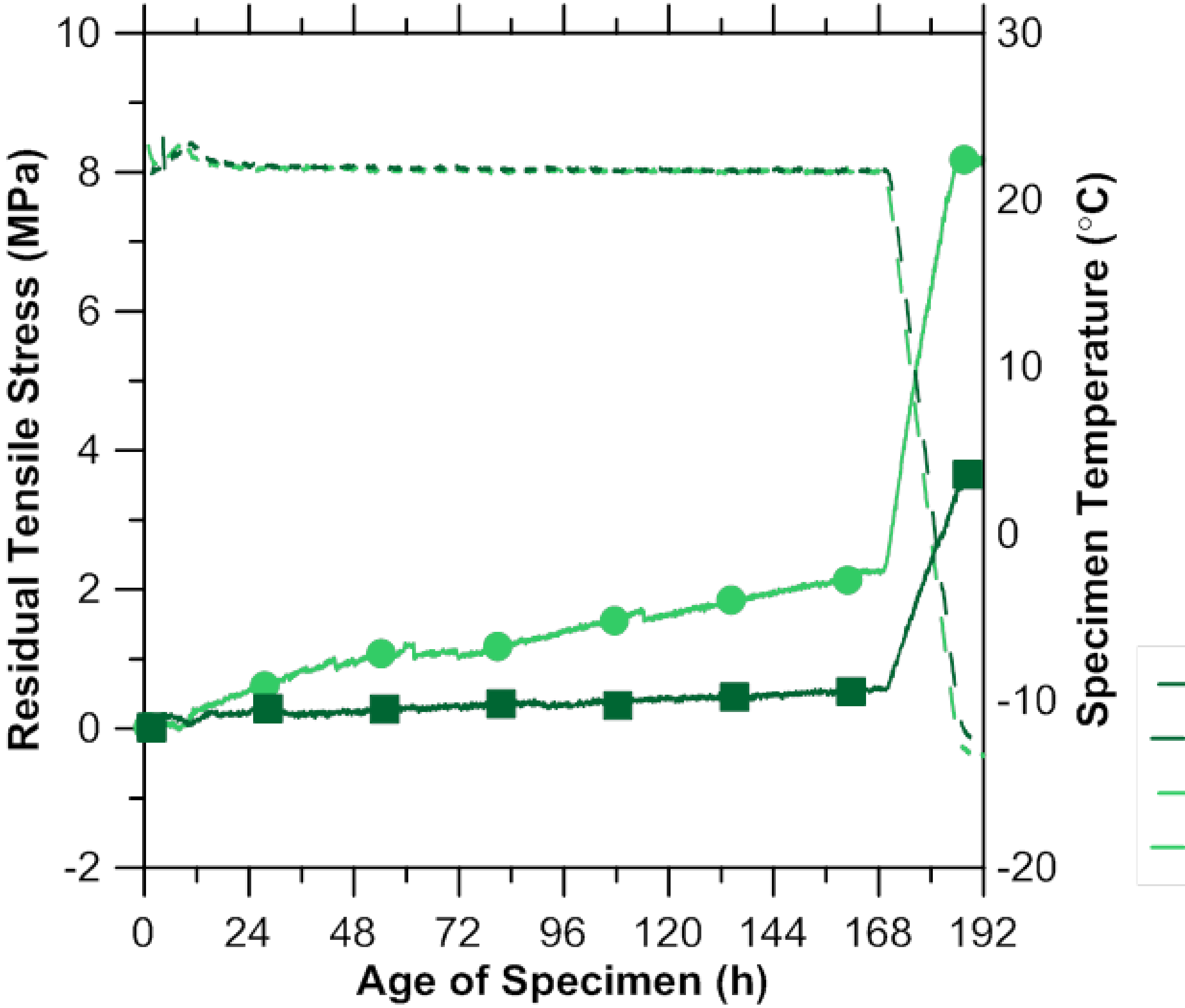
1.2. The values stated in SI units are to

1.3. *This standard does not purport to a use. It is the responsibility of the health practices and determine the a*

2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards:*
R 39, Making and Curing Concrete

2.2. *ASTM Standards:*
C 305, Practice for Mechanical M



Four Step Approach Toward Performance

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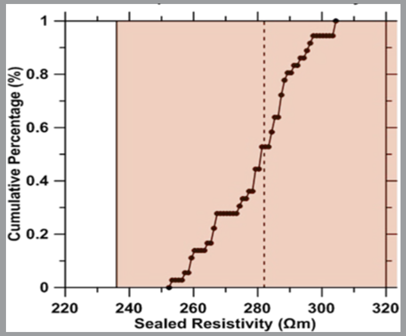

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Barde et al. 2007

Toward FT SLM

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Develop the Sorption Based Modeling Concept

Relating the saturation level in concrete to a theoretical critical limit of saturation

Develop Testing Procedures to Evaluate Concrete Mixtures

Developed Testing for Critical Saturation, Absorption, and Degree of Saturation

Evaluate Properties of Typical Paving Mixtures

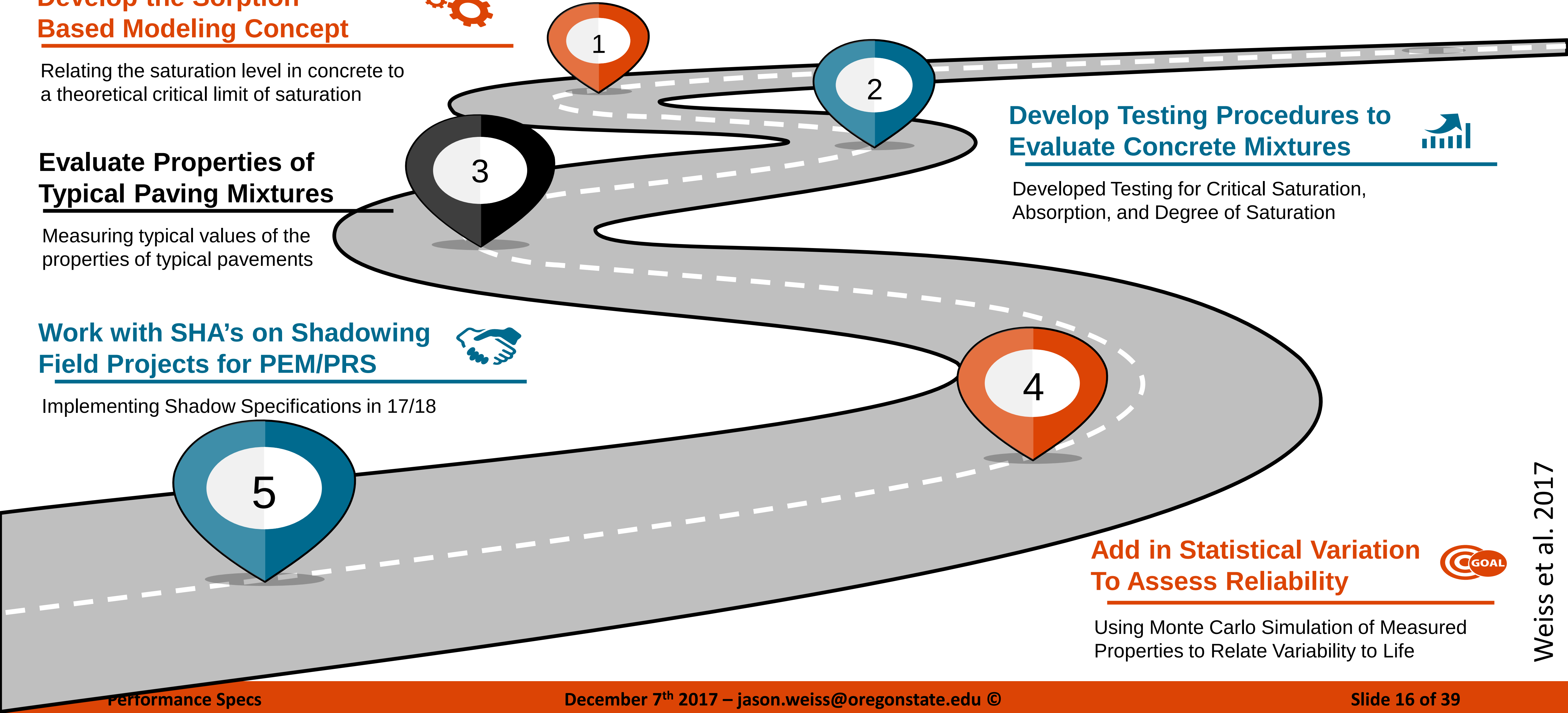
Measuring typical values of the properties of typical pavements

Work with SHA's on Shadowing Field Projects for PEM/PRS

Implementing Shadow Specifications in 17/18

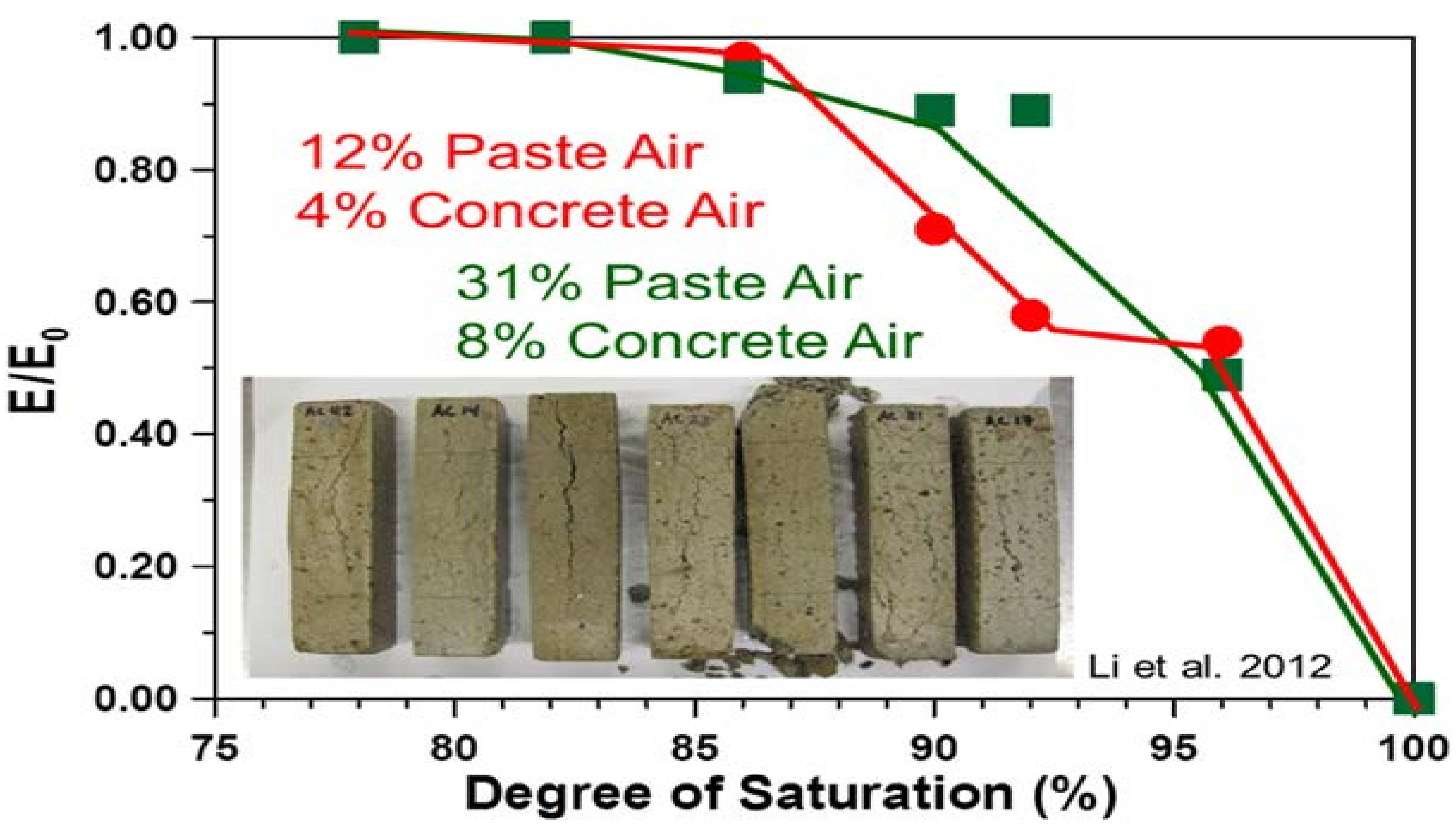
Add in Statistical Variation To Assess Reliability

Using Monte Carlo Simulation of Measured Properties to Relate Variability to Life

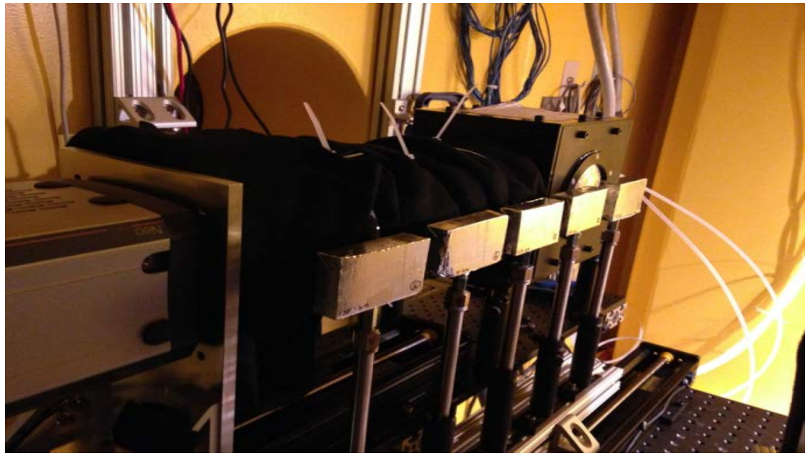


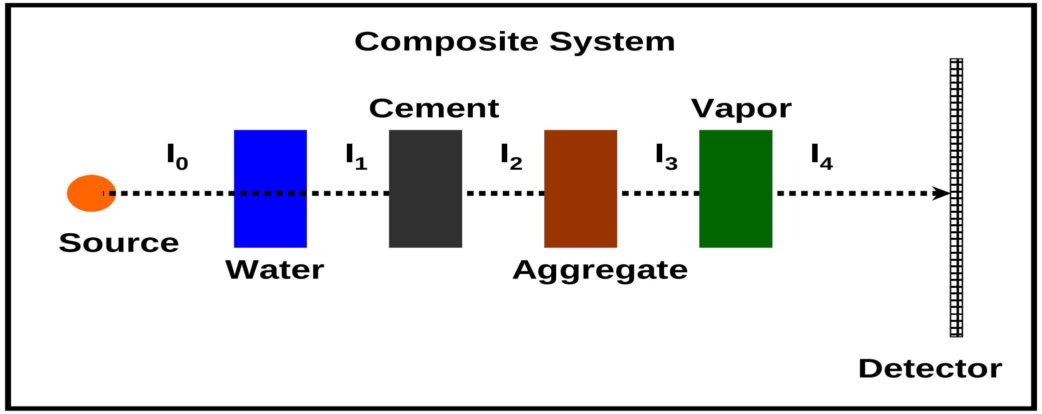
Weiss et al. 2017

High Saturation - Damage



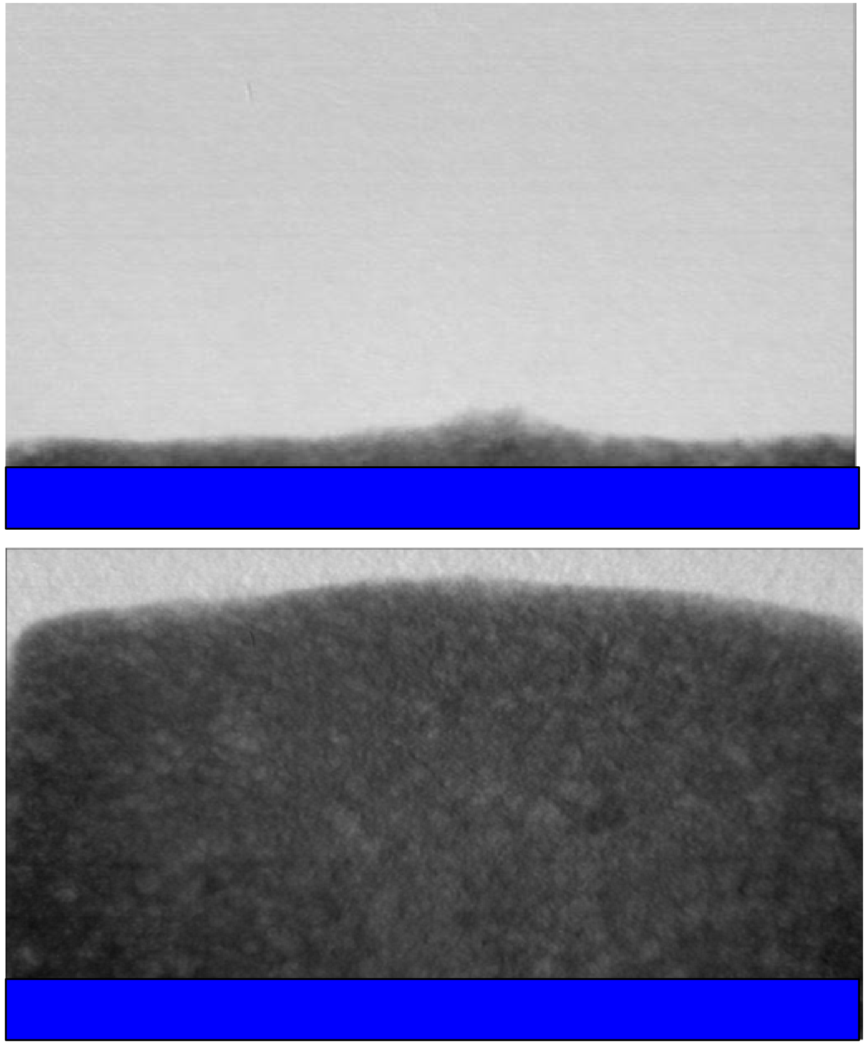
Neutron Radiography





$$I(t) = I_0 \exp^{-\left(\left(\sum_{i=1}^{N}(\mu_i V_i)\right)t\right)}$$

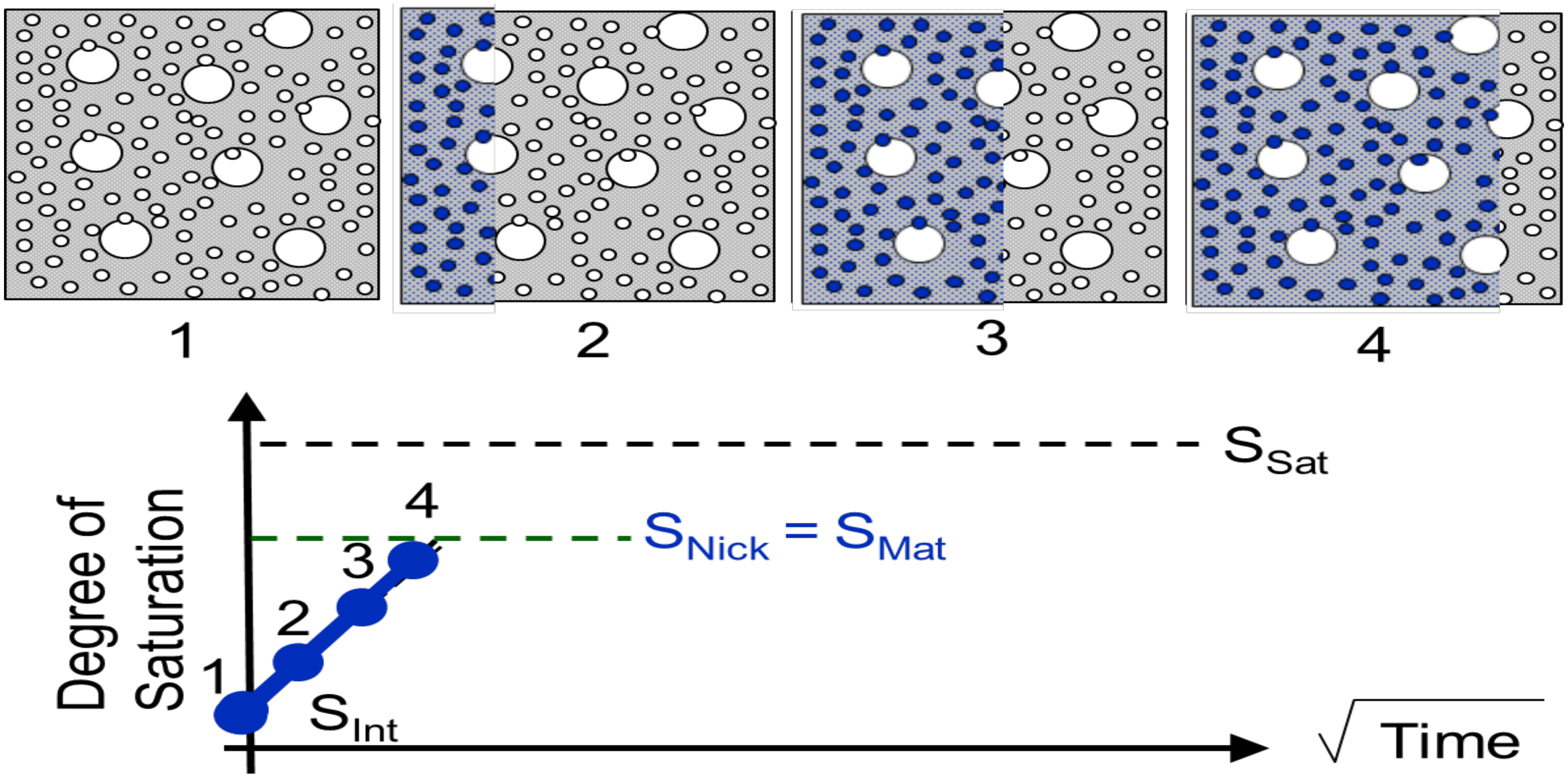
10 minutes



11 hours

Lucero et al. 2015

Sorption Based Freeze-Thaw Model



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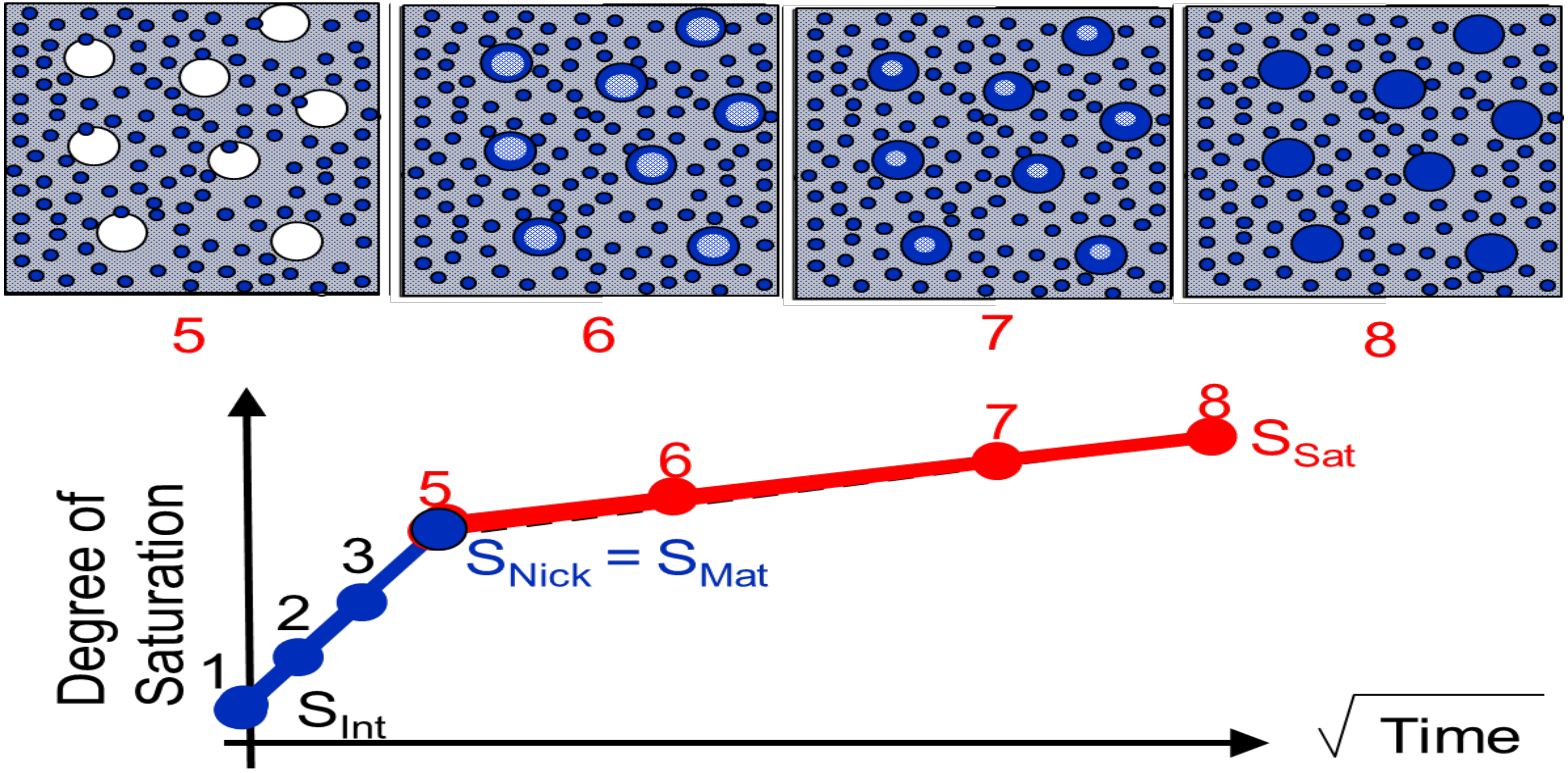
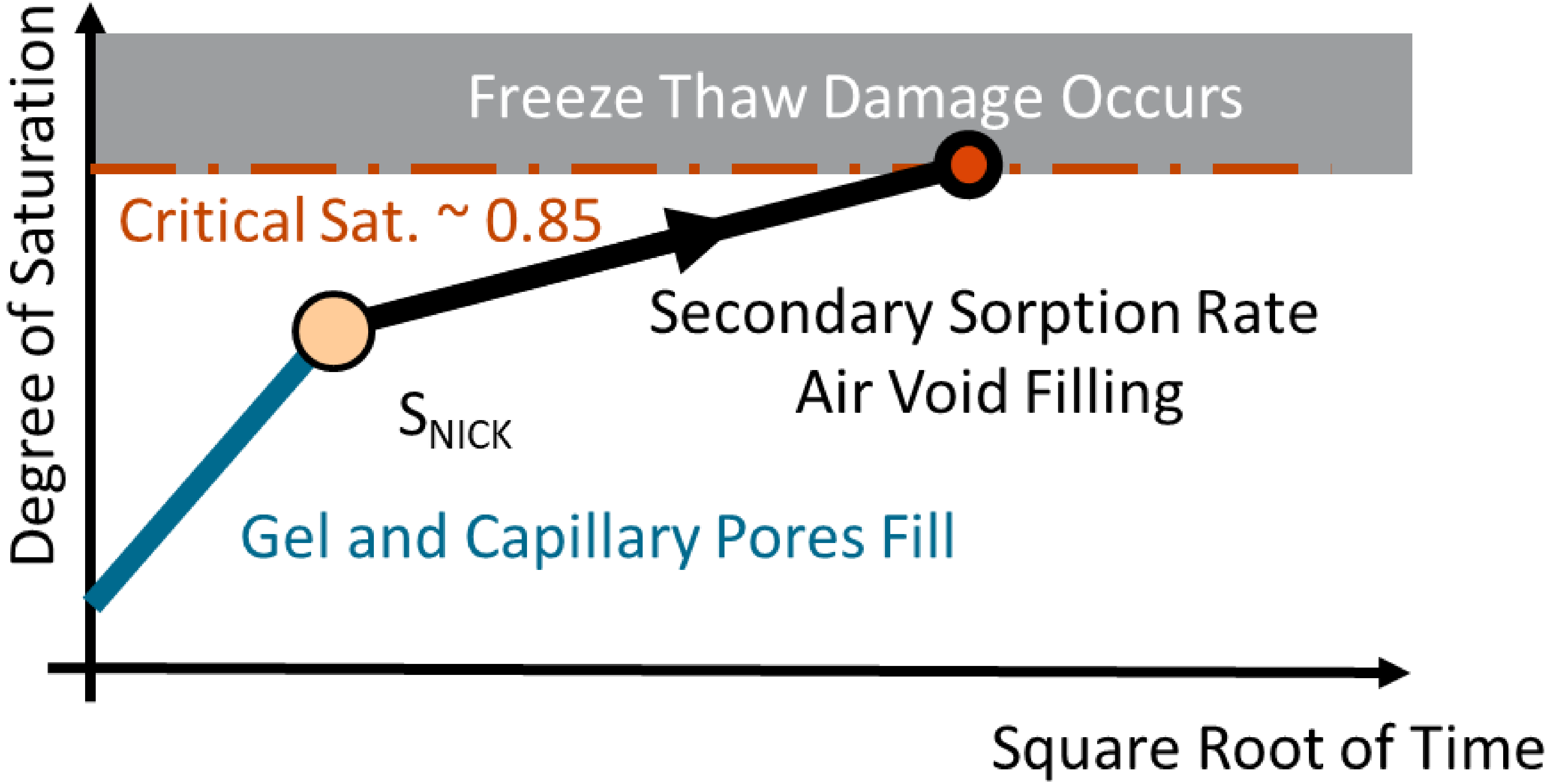


Lucero et al. 2015

FT Service Life Model



Li et al. 2010

FT Service Life Model

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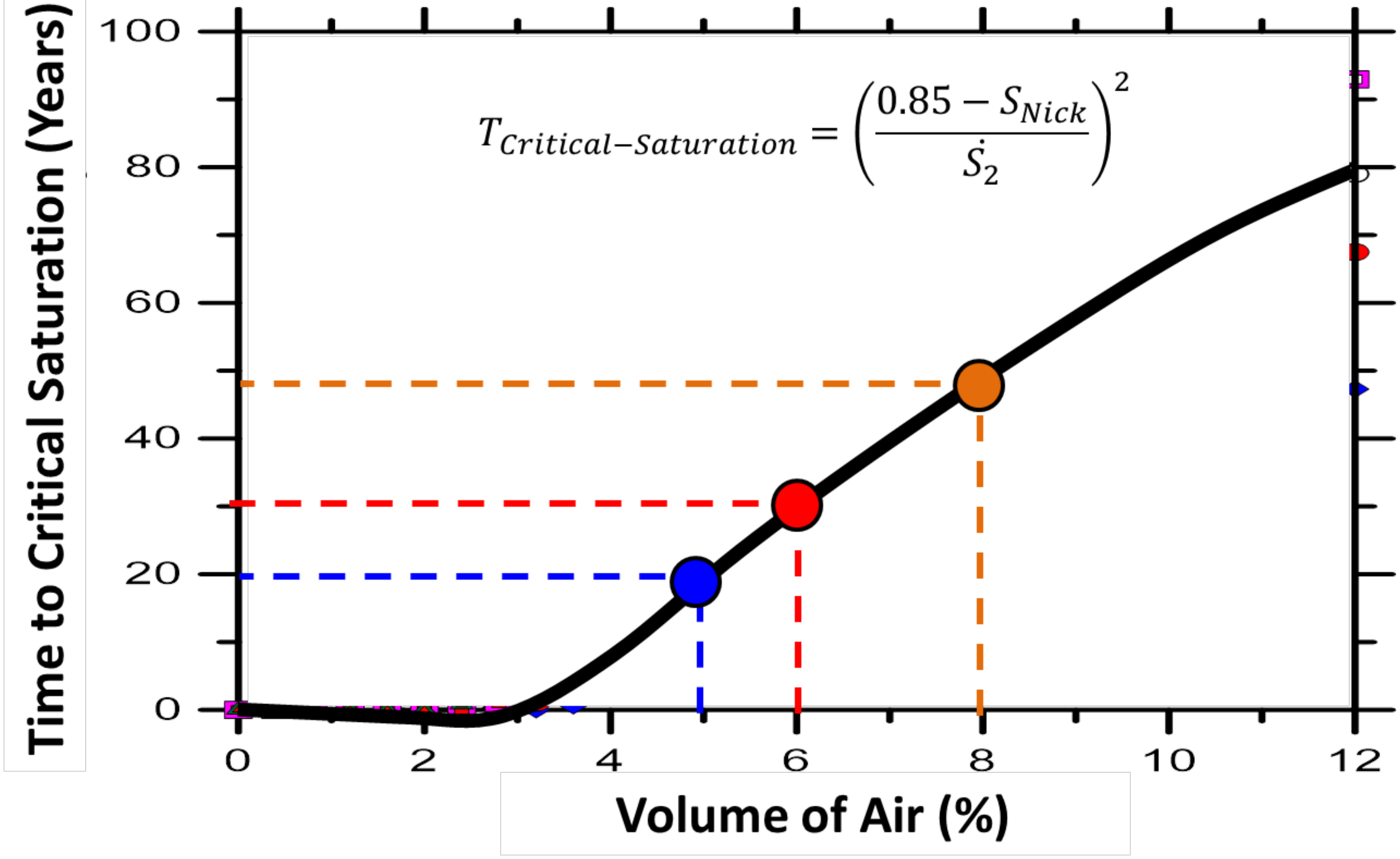
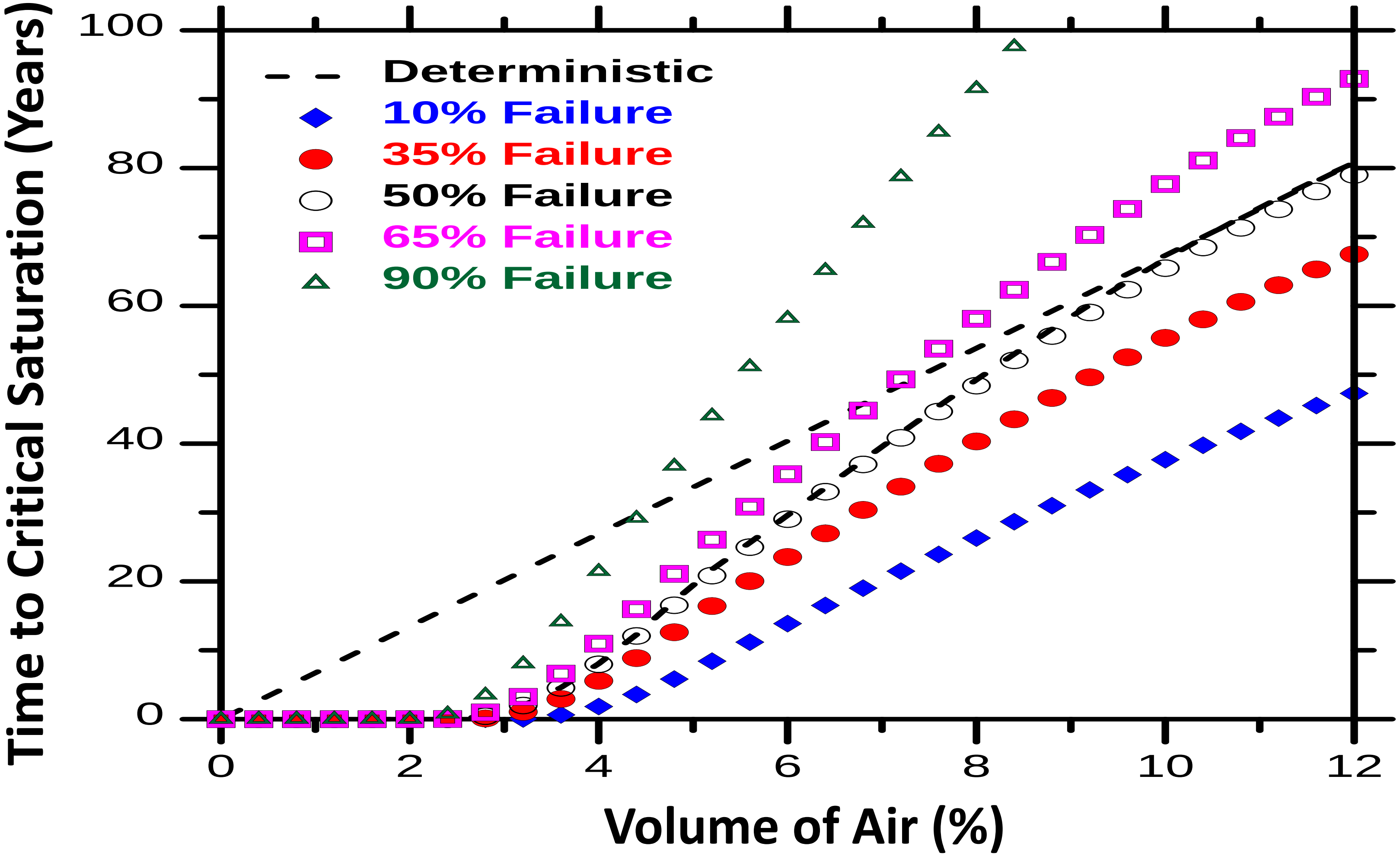


Weiss et al. 2014

What About Variability

- Design Mixture
  - 0.42 w/c
  - 6% Air
  - 564 lb cement
  - Fine Aggregate
- Lets Assume Variations
  - w/c 5% (0.38 to 0.46)
  - Air 15% (4.2 to 7.8)



Weiss et al. 2015

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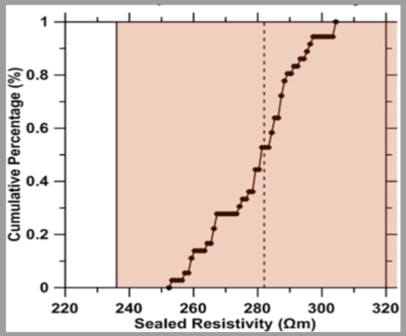

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Barde et al. 2007

Resistivity Test Becoming Popular

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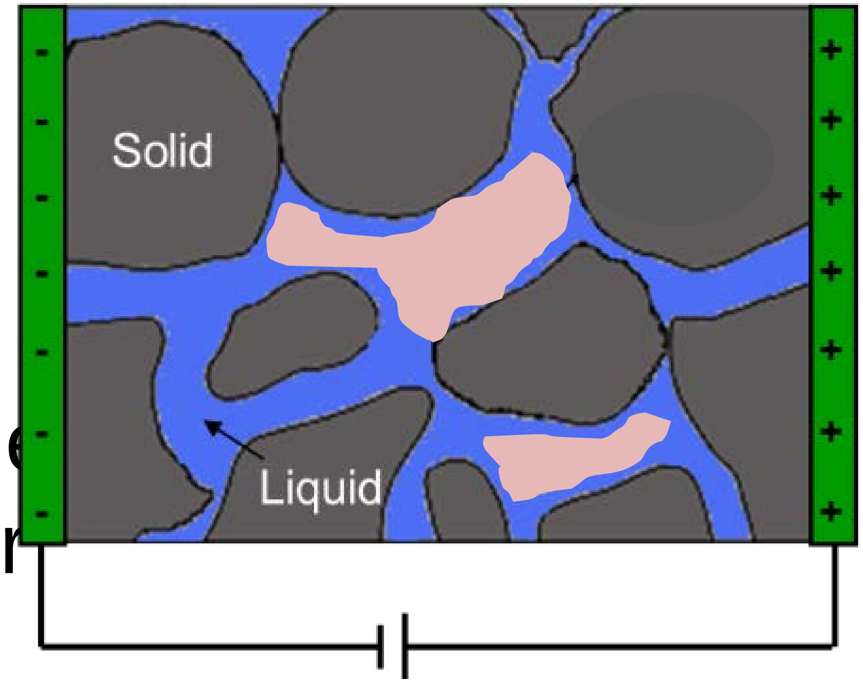
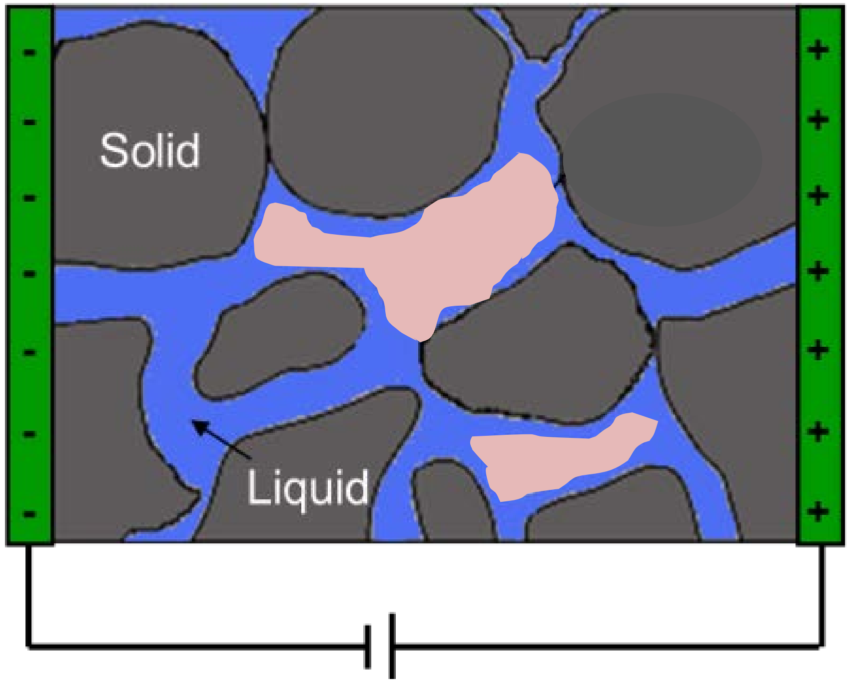
- Fast (seconds to minutes)
- Low cost ($2-2500 dollars)
- Portable (put it in your pocket)



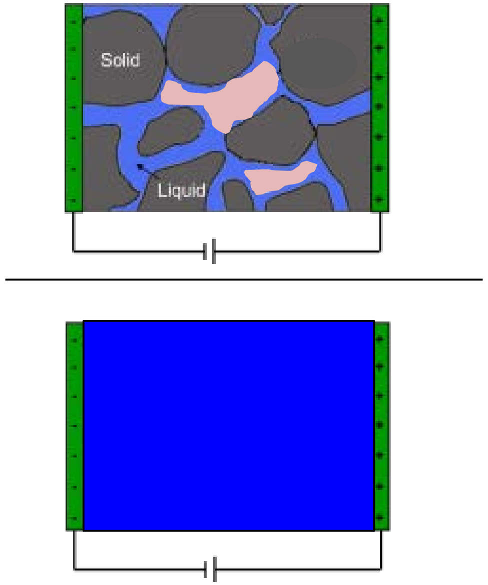
- However resistivity is not a fundame
measurement and we can do better

Resistivity as a Test, F Factor Spec

- Related to pore volume (ϕ)
- Related to pore connectivity (β)

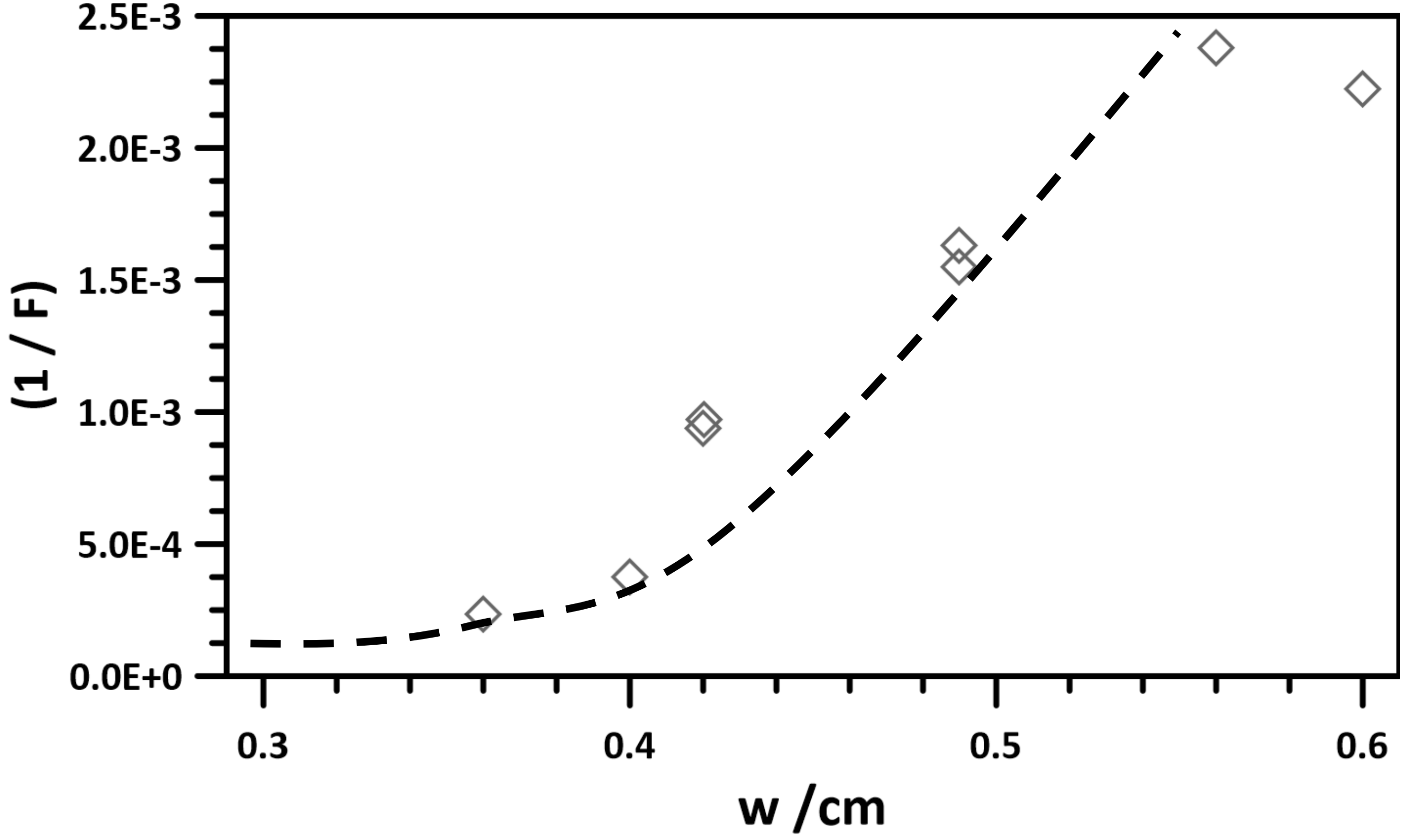


$$F = \frac{\rho}{\rho_o} = \frac{1}{\phi\beta} =$$



What is the Formation Factor

- Measure of the pore structure of concrete
- 1/F is related to fluid permeability
- Can be related to fluid sorption as well
- Can be related to diffusion



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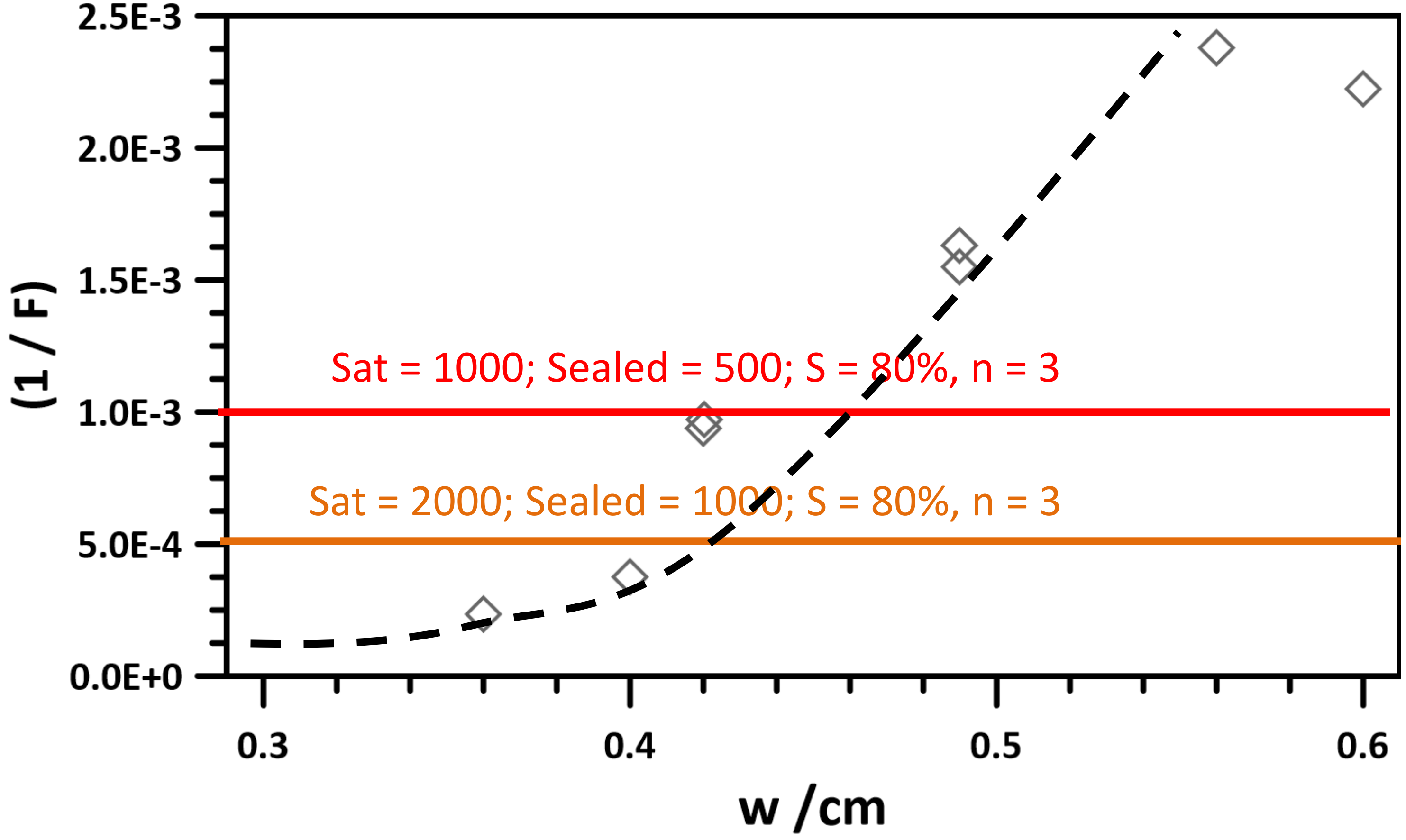
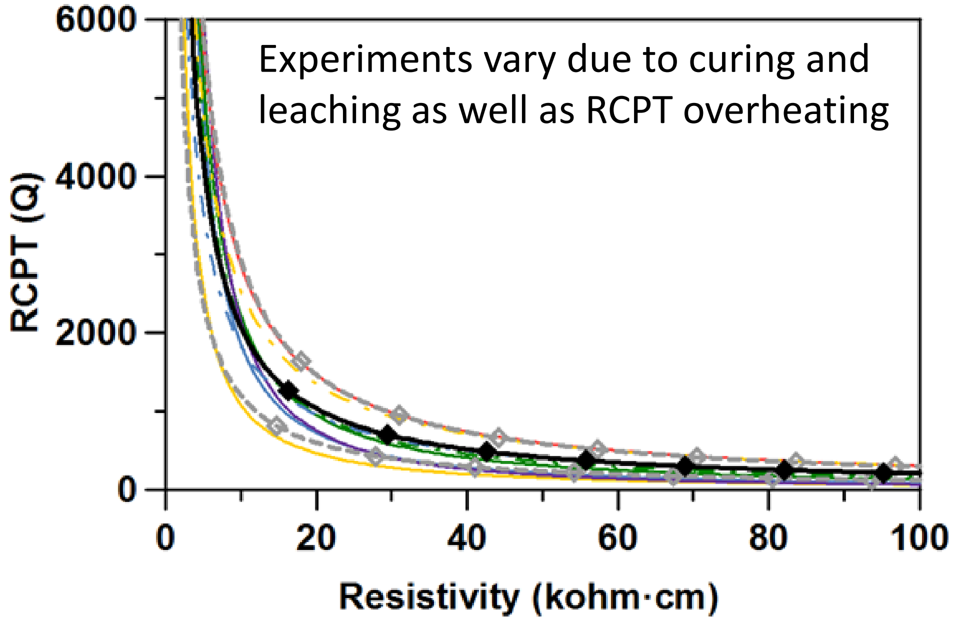


Resistivity and RCPT

- We can fundamentally relate RCPT and resistivity

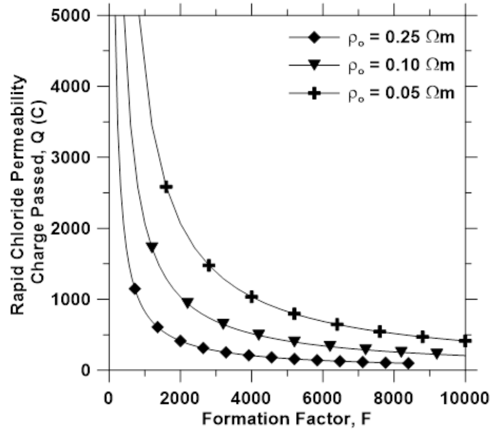
$$Q = \int_{0\,hr}^{6\,hr} I\,dt = \int_{0\,hr}^{6\,hr} \frac{V}{R}\,dt = \int_{0\,hr}^{6\,hr} \frac{V}{\rho}\frac{A}{L}\,dt$$

$$Q = V\,\frac{A}{L}\,t\,\frac{1}{\rho} = 60V\,\frac{8107\,mm^2}{50.8\,mm}\,21{,}600\,s\,\frac{1}{\rho} = \frac{206{,}830\,V\,m\,s}{\rho}$$



- This is written as F-Factor which shows errors in RCPT if p soln is not known

$$Q = V\,\frac{A}{L}\,t\,\frac{1}{\rho_0}\frac{1}{F} = 60V\,\frac{8107\,mm^2}{50.8\,mm}\,21{,}600\,s\,\frac{1}{\rho_o}\frac{1}{F} = \frac{206{,}830\,V\,m\,s}{\rho_o}\,\frac{1}{F}$$



Weiss et al. 2016

F Factor and Absorption

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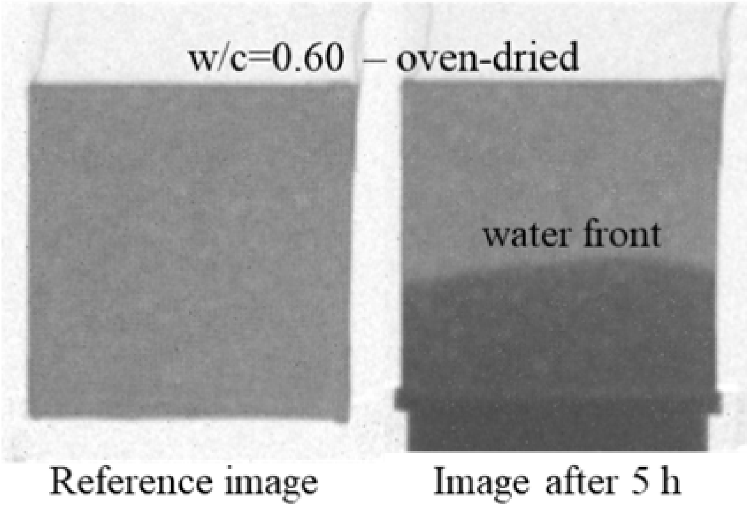
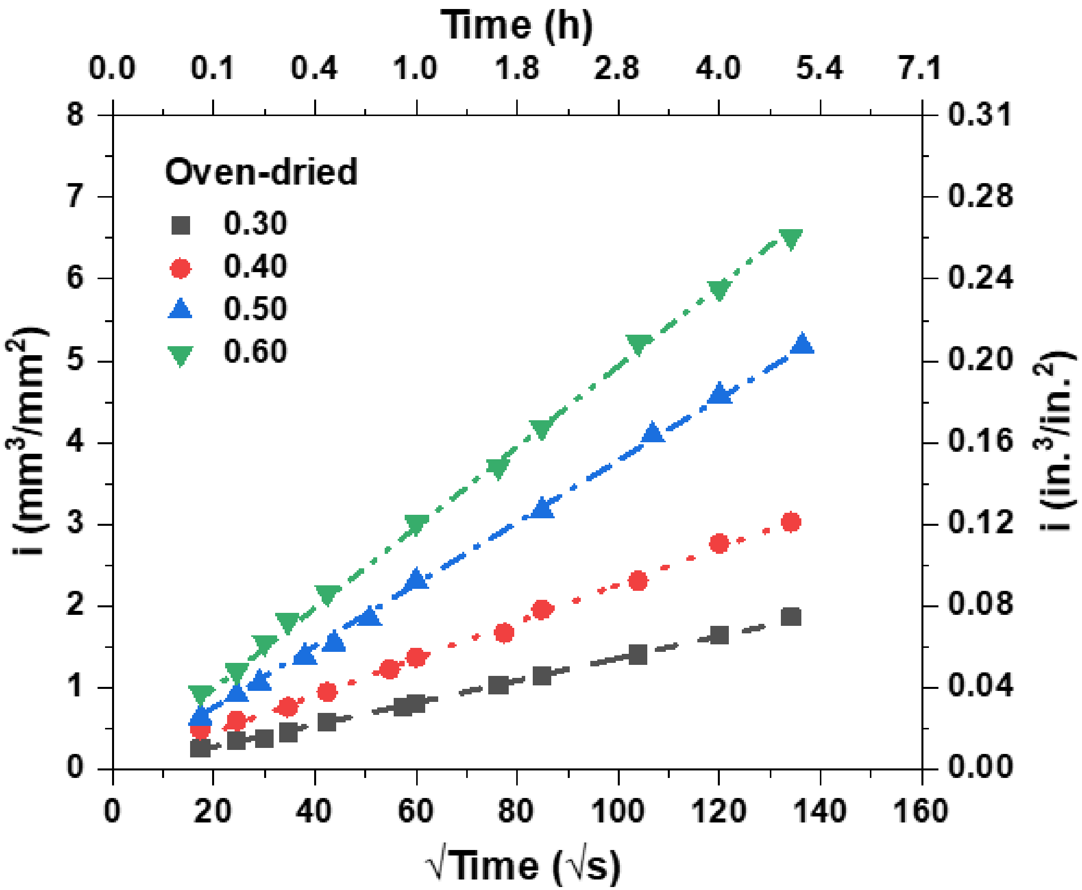
- One advantage of the Formation Factor is that it can be related to other transport properties directly.
- In a recently submitted paper we demonstrate that the mass of absorbed water (M) is related to ($F^{-0.5}$)
- Derived from first principles

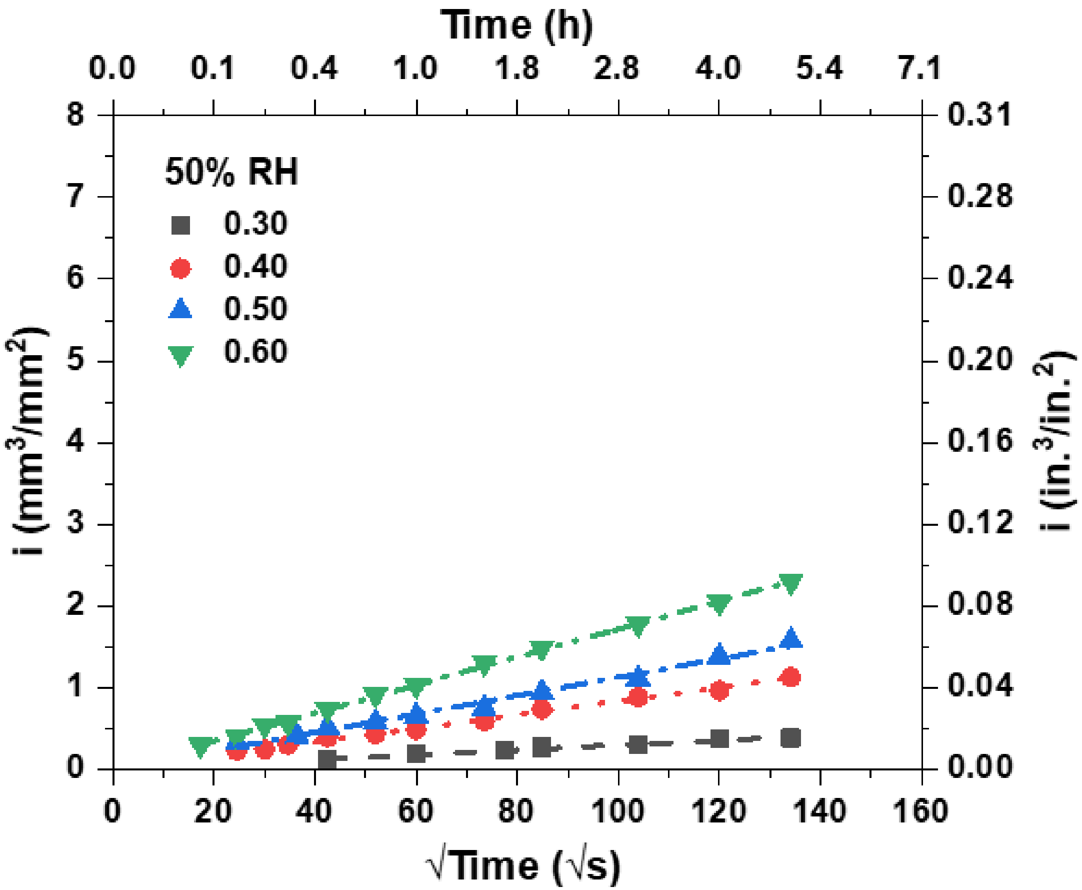
$$M(t) = \frac{A\rho R_i}{2}\sqrt{\frac{\varepsilon P_{cap}}{\mu}}\sqrt{\frac{1}{F}}\sqrt{t}$$



Moradllo et al. submitted

Absorption





Moradllo et al. submitted

Typical Results

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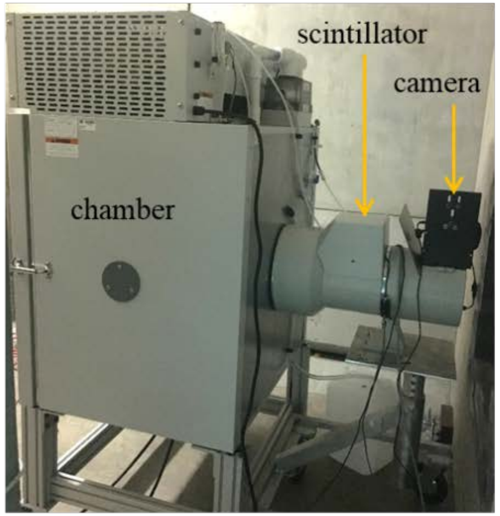
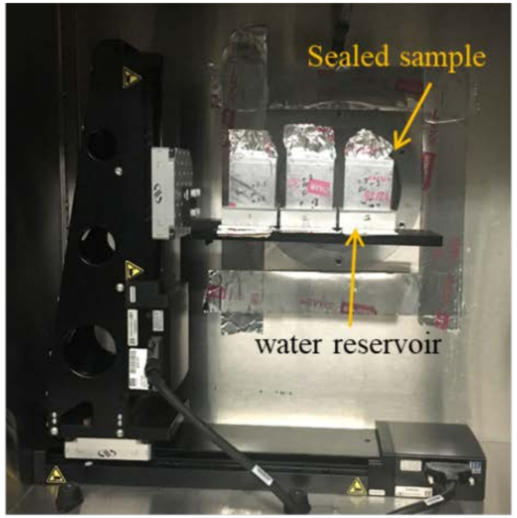
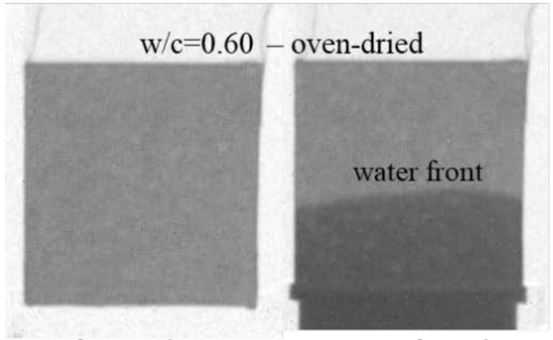


(a) Chamber with scintillator at the back
Neutron beam is parallel to the scintillator



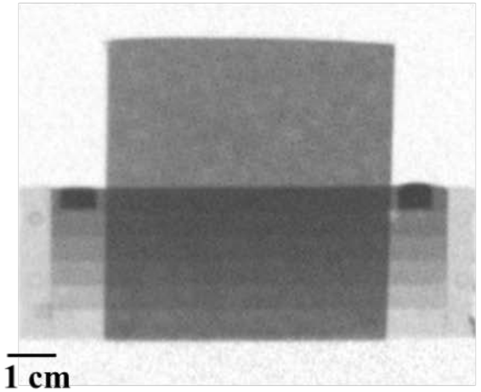
(b) Translating stage inside the chamber



Reference image   Image after 5 h

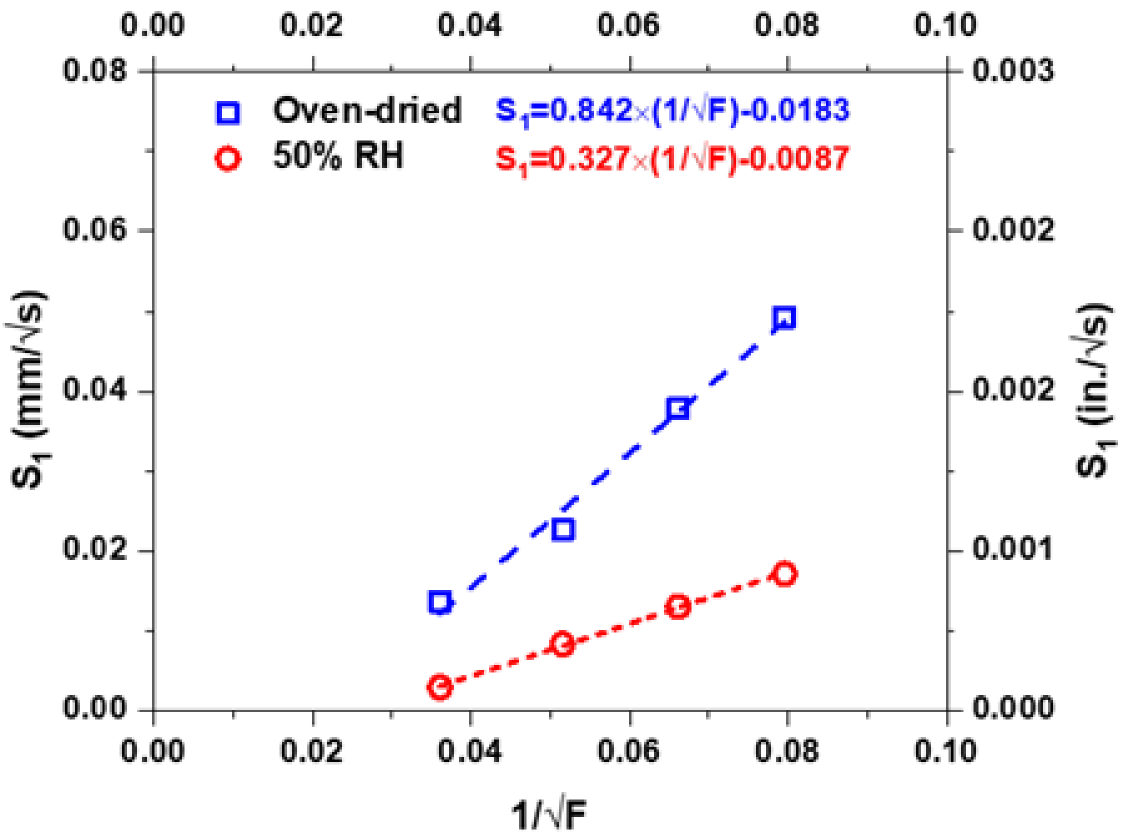
2 cm

(c) Raw images from camera



1 cm

(d) Water-filled stepped cells to measure water attenuation coefficient – thickness: 1-5 mm



Moradllo et al. submitted

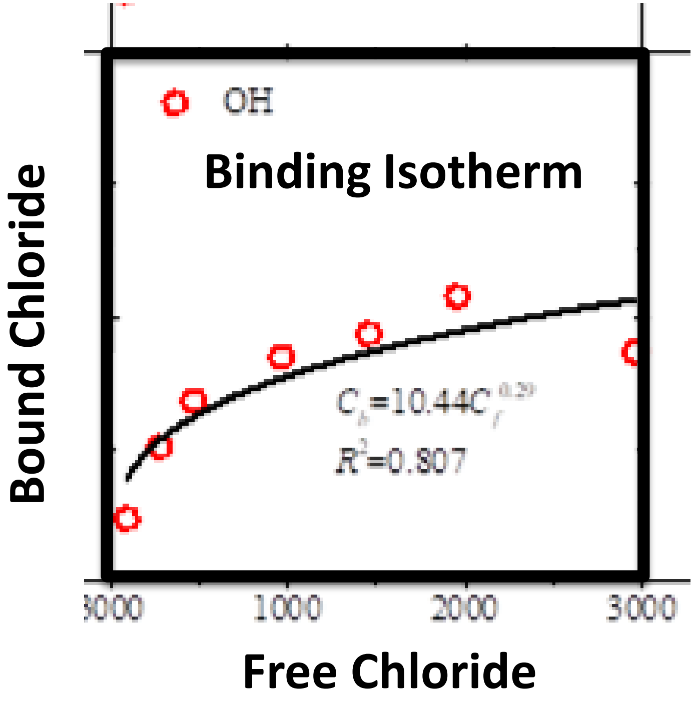
F Factor and $D_{Apparent}$

- Frequent criticism of F-Factor - it doesn't include binding
- While this is true (neither does any electrical measure) it can be shown that F Factor can easily be combined with a binding isotherm to predict performance
- Nernst Plank

$$J_i = -\frac{D^o}{F}(S_l)\left[\text{grad}c_i + c_i\text{grad}(\ln\gamma_i) + \frac{z_iF}{RT}c_i\text{grad}\psi\right]$$

- Binding

$$c_b = \alpha \cdot {c_{Cl}}^{\beta}$$



Chloride Diffusion

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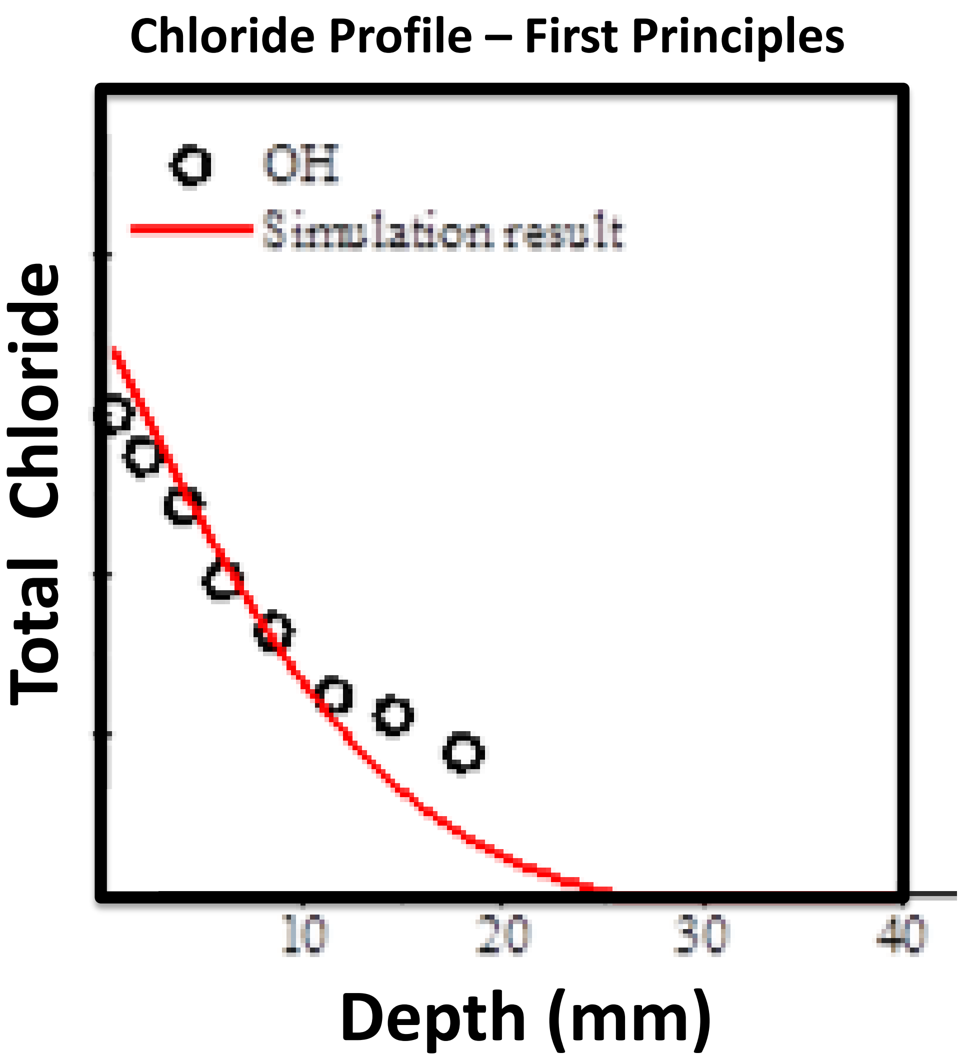
- Here we see that combining the F-Factor and binding is very powerful
- This does a good job at predicting chloride ingress
- This is much faster than ASTM 1556
- Further binding is a qualification test and F is a QC/QA test



National PFS Underway

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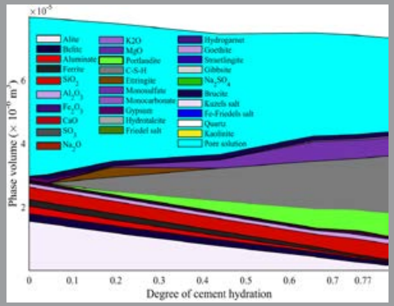
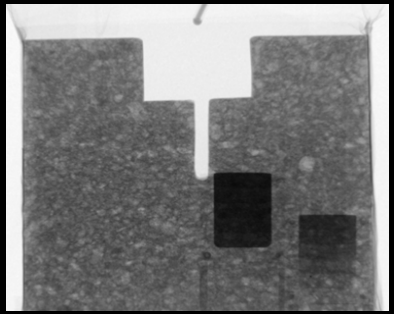
Unify Transport Tests and F

Goal:
complete theoretical framework to enable F-factor to replace existing transport tests first principles



GEMS & Reactive Transport

Goal:
Use computational models to simplify and complement field testing



Water Transport & Implications

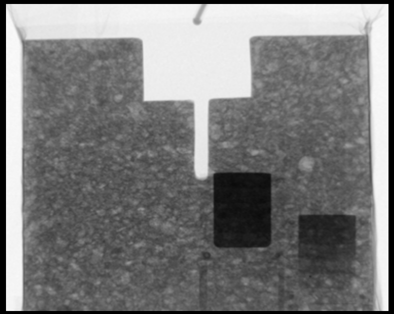
Goal:
Use quantitative neutron radiography to better understand moisture content and movement

Rapid Test for Water Content

Goal:
Use test methods to measure water content before placemeent

Weiss et al. 2016

Water Transport



Curing and its Implications

Goal:
Use quantitative neutron radiography to better understand curing

- Instead of using individual coefficients, use a single hydration product

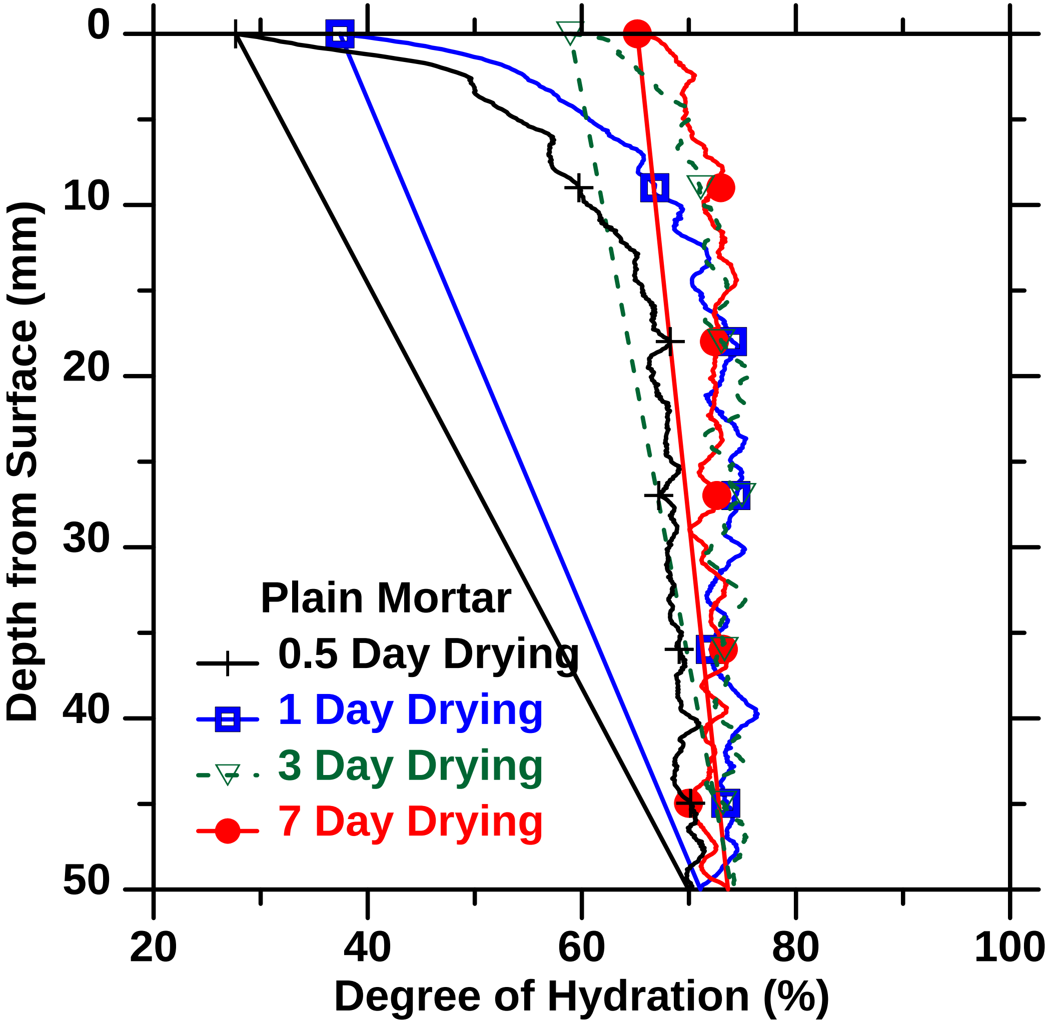
$$\ln\left(\frac{I_T}{I_O}\right) = -\left(\mu_A V_A + \mu_C V_{C-Original} + \mu_W V_{W-Hydration\ Products}\right) x_S$$

- This enables the volume of hydration products to be determined

$$V_{W-Hydration\ Products} = -\left(\frac{1}{\mu_W}\right)\left(\frac{\ln\left(\frac{I_T}{I_O}\right)}{x_S} - \mu_A V_A - \mu_C V_{C-Original}\right)$$

Typical Results – Duration of Curing

- DOH increased 24% in the top 5 mm of plain samples by extending the wet burlap duration from 1 to 3 days.
- Sealed plain samples had 3.2% greater hydration at the core than the samples exposed to drying at 1 day



Khanzadeh et al. submitted

Rapid Water Content

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Rapid Test for Water Content

Goal:
Use test methods to measure water content before placement

- Working on a test method that can be used for fresh concrete
- Very comfortable with it in the lab, additional work is needed to make sure it is robust and ready for the field
- At the current time we know that temperature corrections are very important as well as the role of ionic species which we are working on

Poursaee et al. 2010, Isgor et al. 2014

Main Thoughts – Are We Ready ?

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- Water to cement ratio (w/c)
  - Historically – w/c is specified (pore volume and connectivity)
  - Performance – The formation factor can measure transport
  - w/c to resistivity to F Factor
- Air content
  - Historically – A table was created based on empirical performance
  - Performance – New tests exist, new predictive methods exist for saturation and salt and we can begin to link these together
- Shrinkage methods are ready based on models or tests