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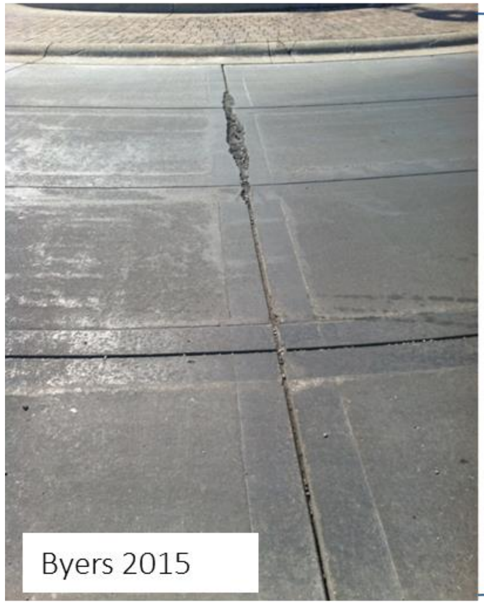
COLLEGE OF ENGINEERING | School of Civil and Construction Engineering

A Roadmap for Test Methods, Innovative Materials, Models and Specifications for Concrete Durability Performance

Jason Weiss, Edwards Distinguished Professor, Oregon State University

Durability Issues Abound


Byers 2015


Byers 2015


Taylor 2013


Taylor 2013


Weiss 2008


Weiss 2005

Current Concrete Durability Specifications

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- Based on empirical observation
- Based largely 4 component systems) which are rapidly becoming out dated
- Many times concrete is falling apart
- Concrete is not the dinosaur, our specifications however ……

- AASHTO currently considering performance based alternatives (PP-84) – I was asked to examine durability

Concrete Mixture Design to Reduce Corrosion

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- Think Tony Saprano

- The pores in concrete that are of the greatest concern are large and connected

Concrete Mixture Design to Reduce Corrosion

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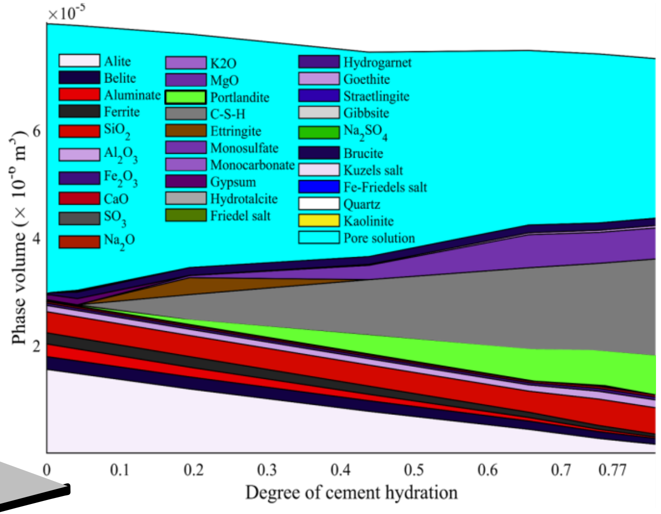
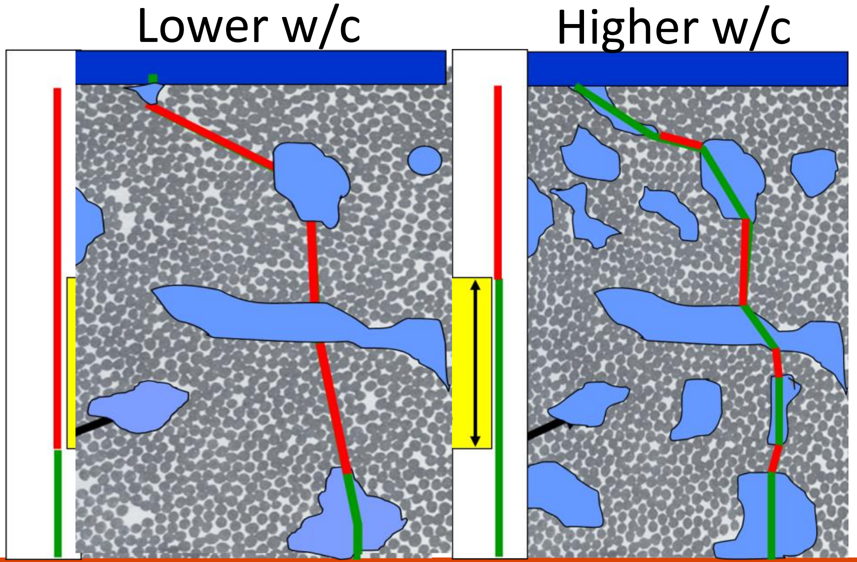
- Transport mainly in capillary pores
- Capillary pores - large and connected
- Predictions exist (Here GEMS, PB)





Four Step Approach

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Assess Performance w/ Standard Tests

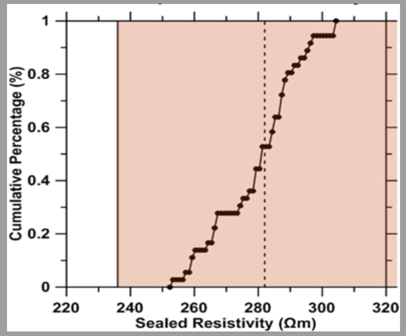
Tests should be:
- easy to perform
- economical
- repeatable

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

Example of a Performance Specification (AASHTO PP84)

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- Suppose we want 75 yr before we repair damage due to corrosion (INDOT)

Example of a Performance Specification (AASHTO PP84)

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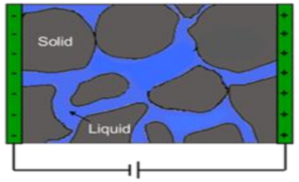
Time to Critical Chloride Concentration For Reinforcement Corrosion

Step 1:
Measure Electrical Resistivity
ρ

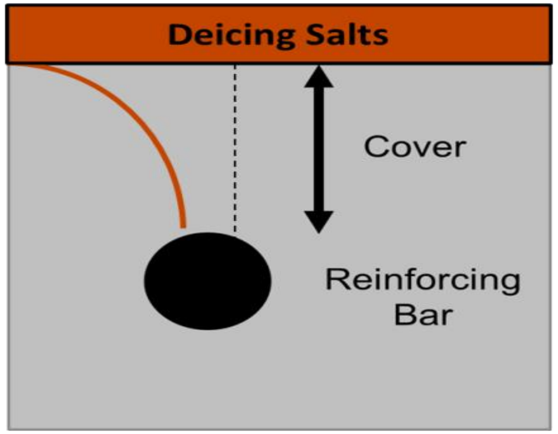
Step 2:
Resistivity to Formation Factor
$F = \frac{\rho}{\rho_O}$

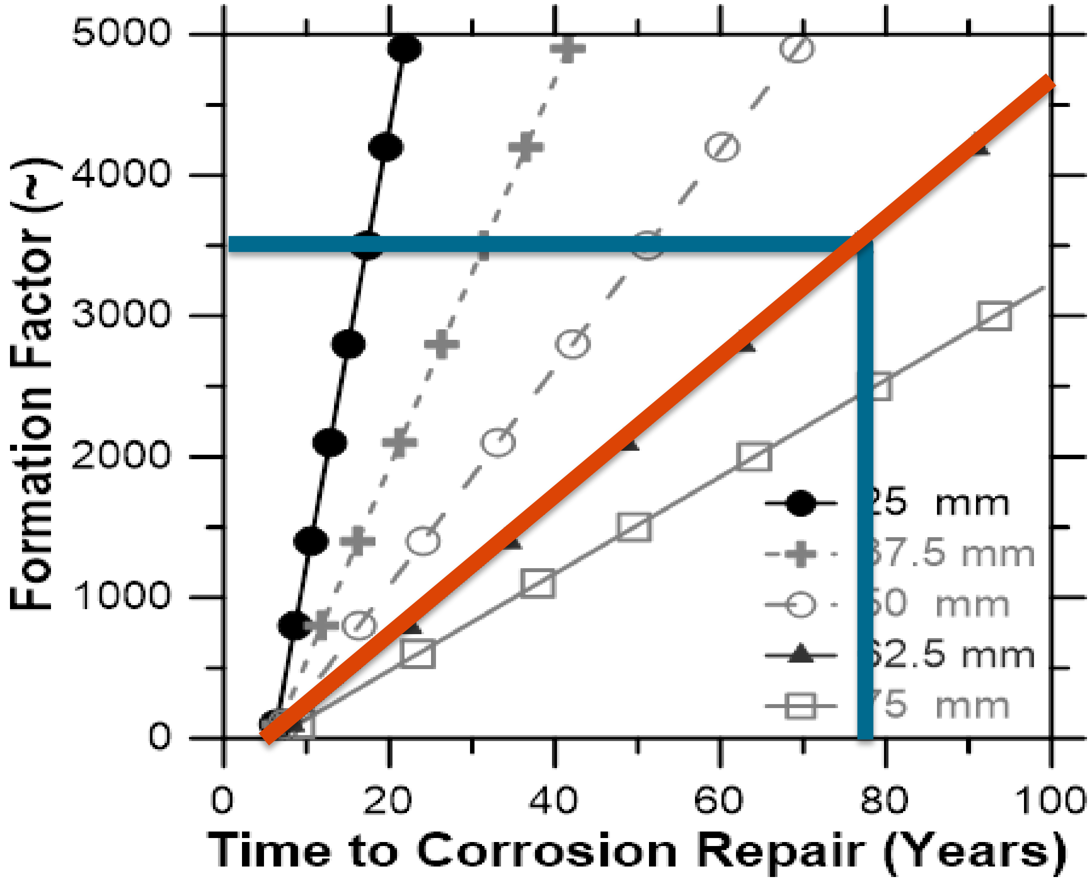
Step 3:
$$\frac{C_x - C_o}{C_s - C_o} = erfc\left[\frac{x\sqrt{F}}{2\sqrt{D_o t}}\right]$$

Step 4:
For a given exposure, predict the time to reach a limit state of chloride content at the rebar



$$F = \frac{\rho}{\rho_O}$$





Example of a Performance Specification (AASHTO PP84)

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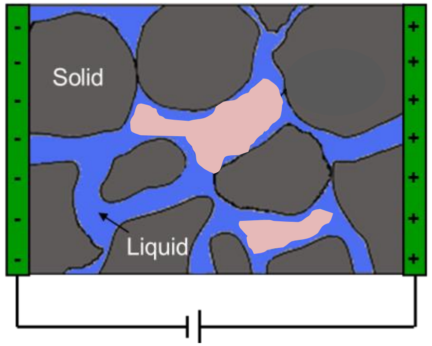
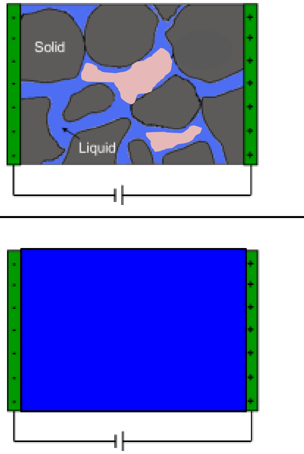
- Suppose we want 75 yr before we repair damage due to corrosion (INDOT)

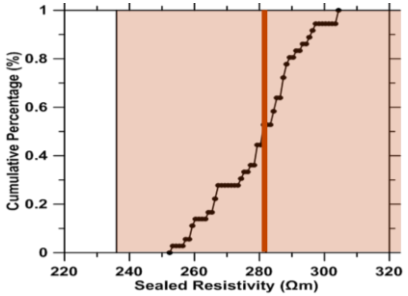
- 75 year F_{SPEC} = 3600
- Pore soln ρ_o 0.079 Ω m



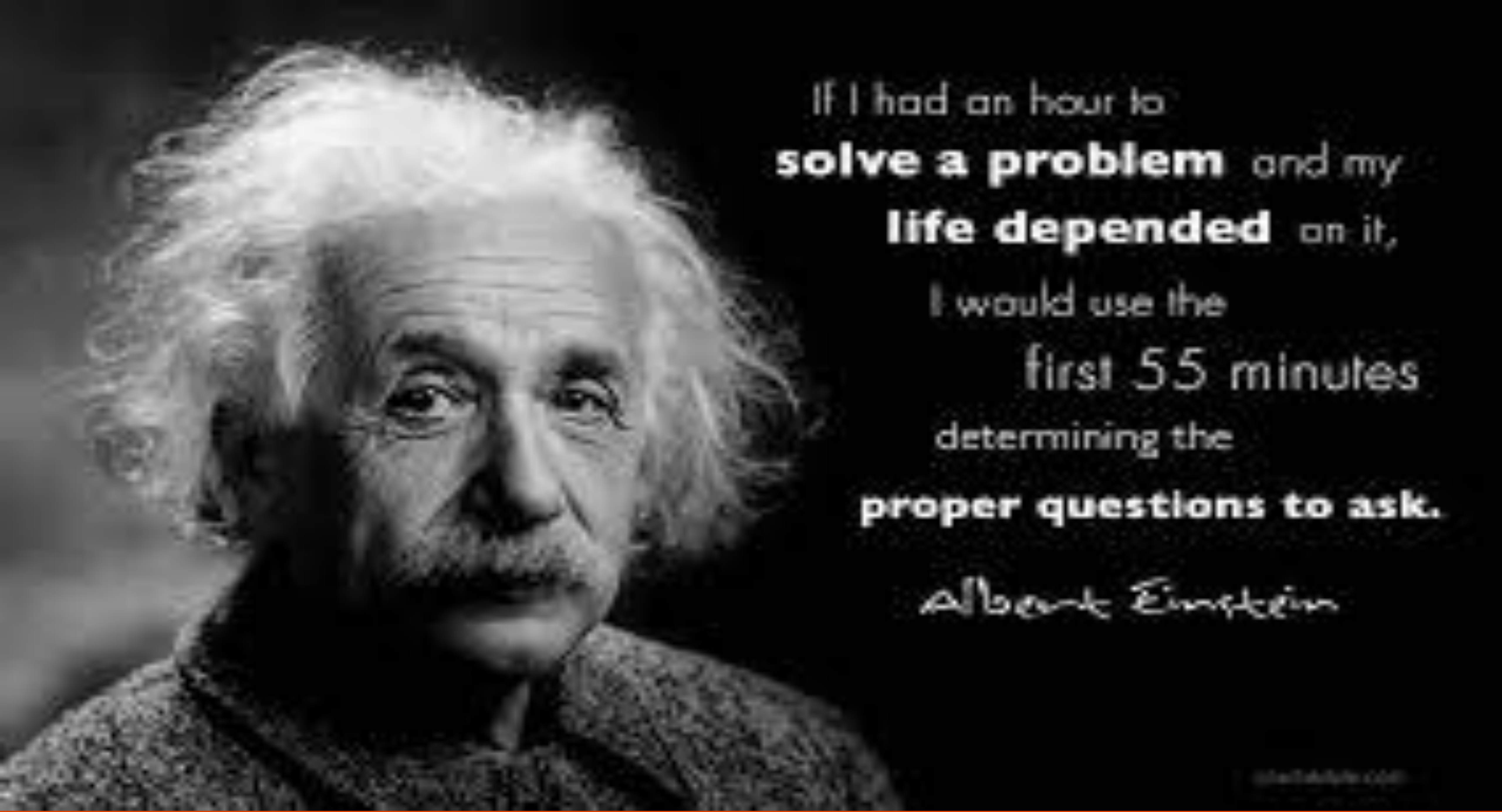
$$F = \frac{\rho}{\rho_o} = \frac{1}{\phi\beta} =$$



- Resistivity, ρ All Values greater than 236 Ω m



Barrett et al. 2015


If I had an hour to
solve a problem and my
life depended on it,
I would use the
first 55 minutes
determining the
proper questions to ask.
Albert Einstein

What is the Problem

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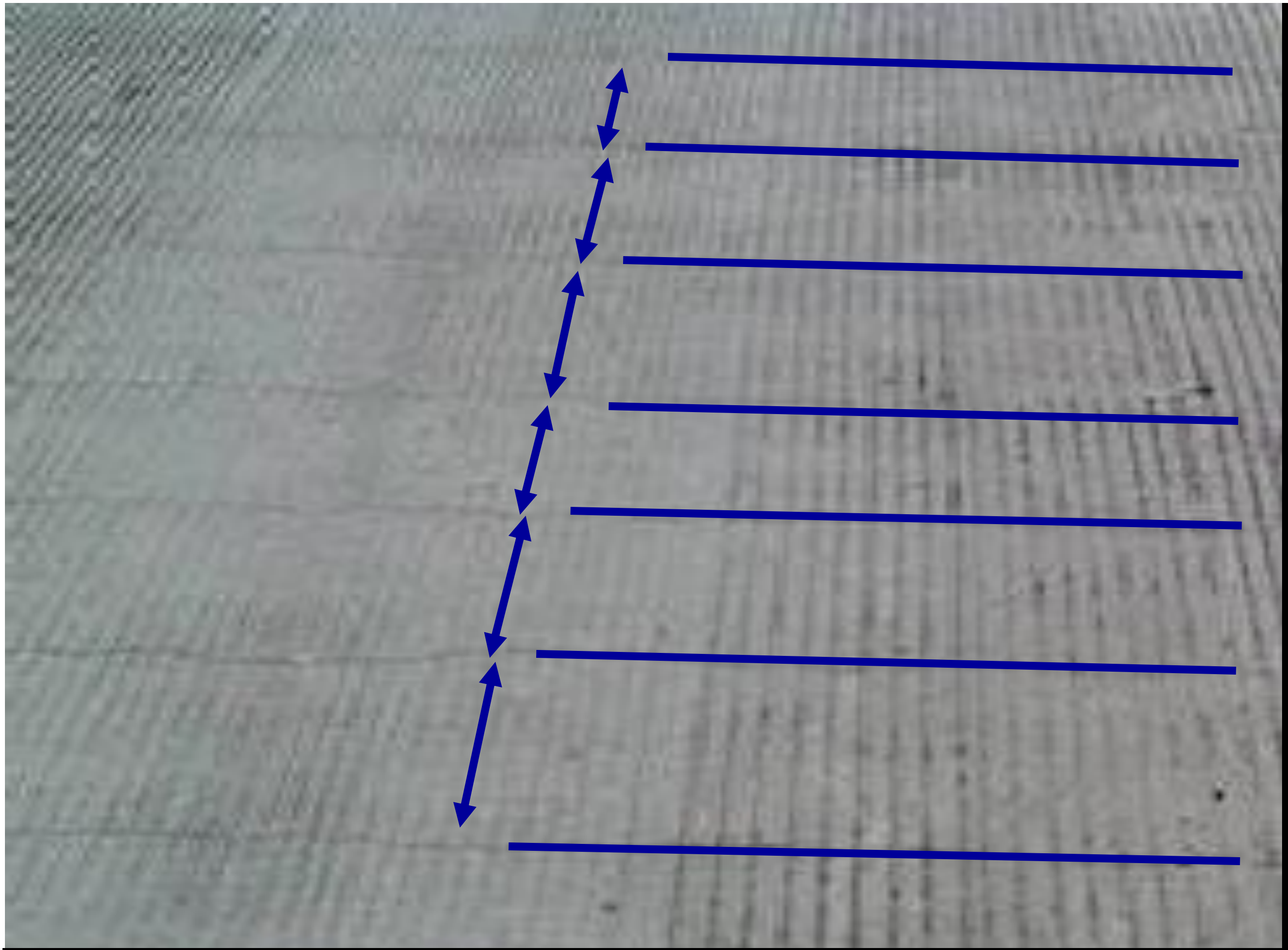
- Transverse cracking in 100,000+ bridges
- 62% of DOT's consider cracking as a problem (28% did not know)
- Cracks shorten service life, increase maintenance cost, and accelerate corrosion
- Common Response – Use Higher Strength



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

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

High Strength Concrete

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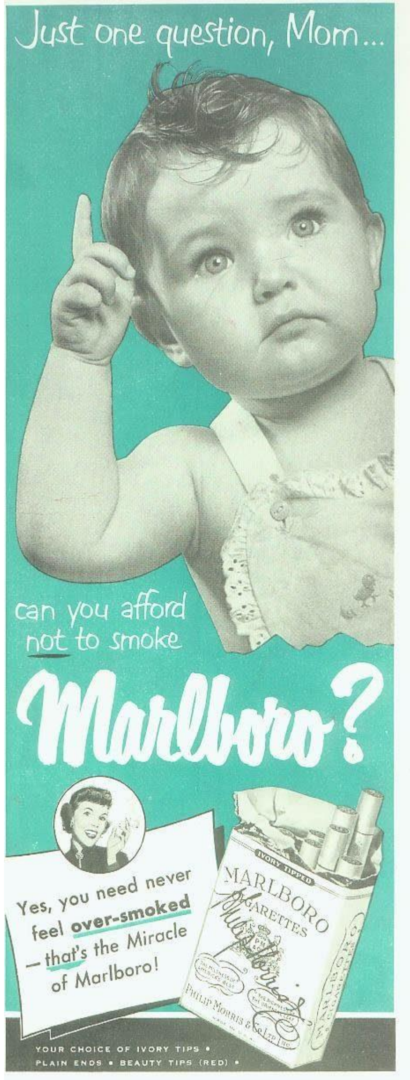
- Higher Strength
- Higher Stiffness
- Low Permeability
- Low Shrinkage
- Low Creep
- Freeze-Thaw Resistance
- Abrasion Resistance
- Toughness



http://thecitydesk.net

High Strength Concrete

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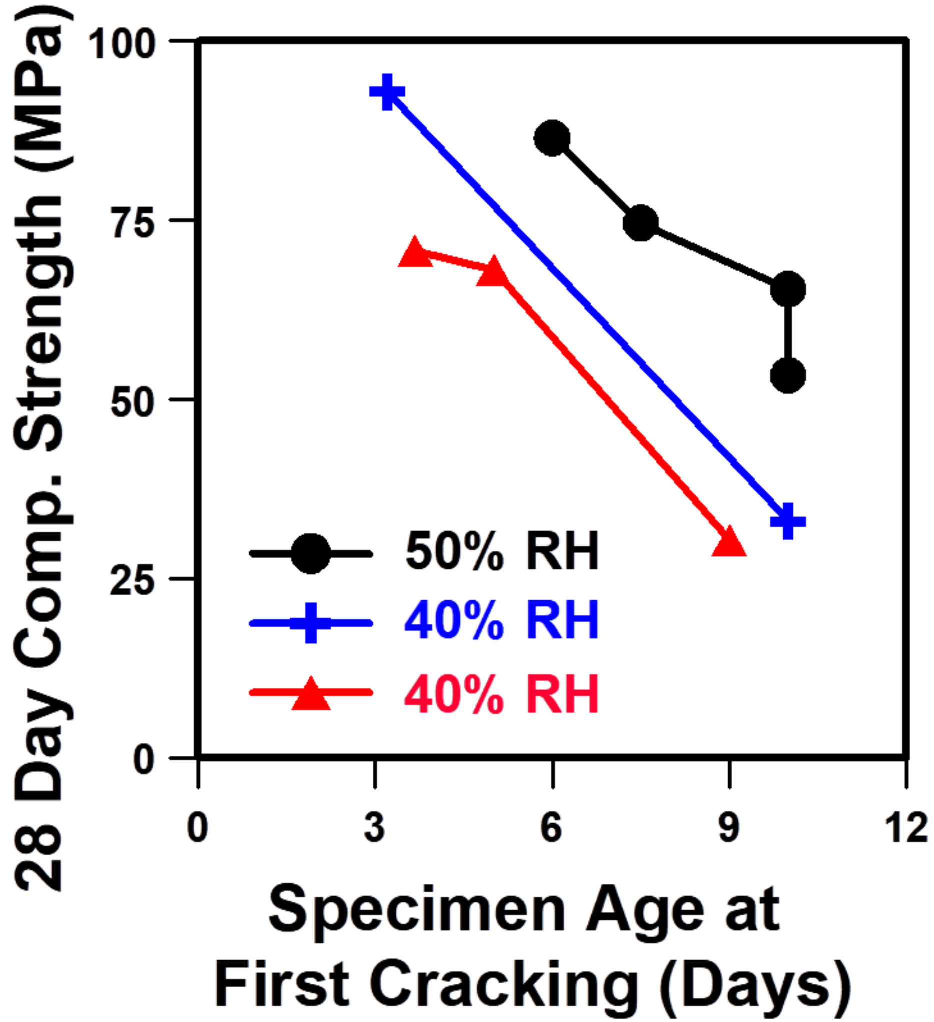
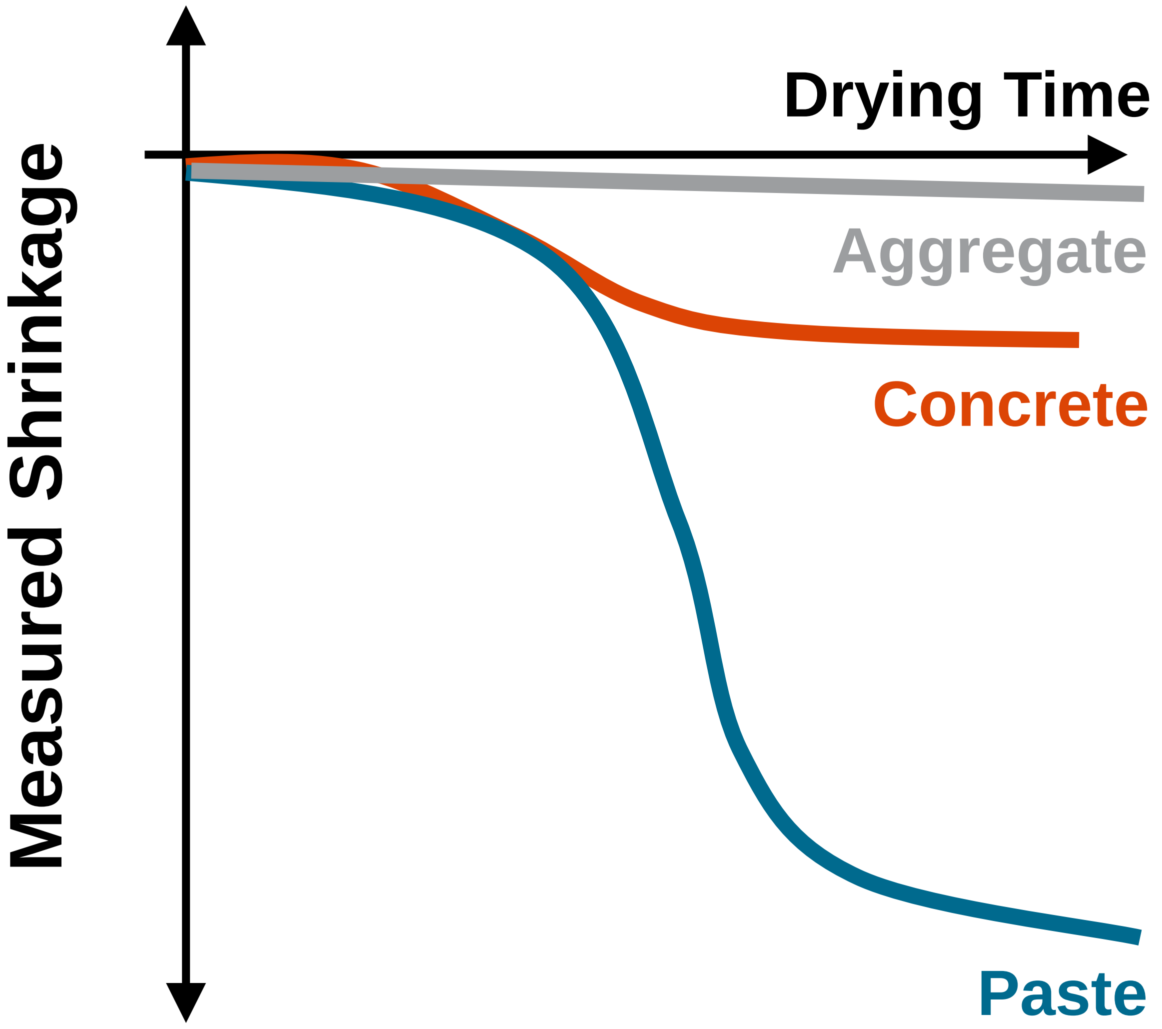


Weiss et al. 1999

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



Volume of Paste is One Approach – V_{Paste}

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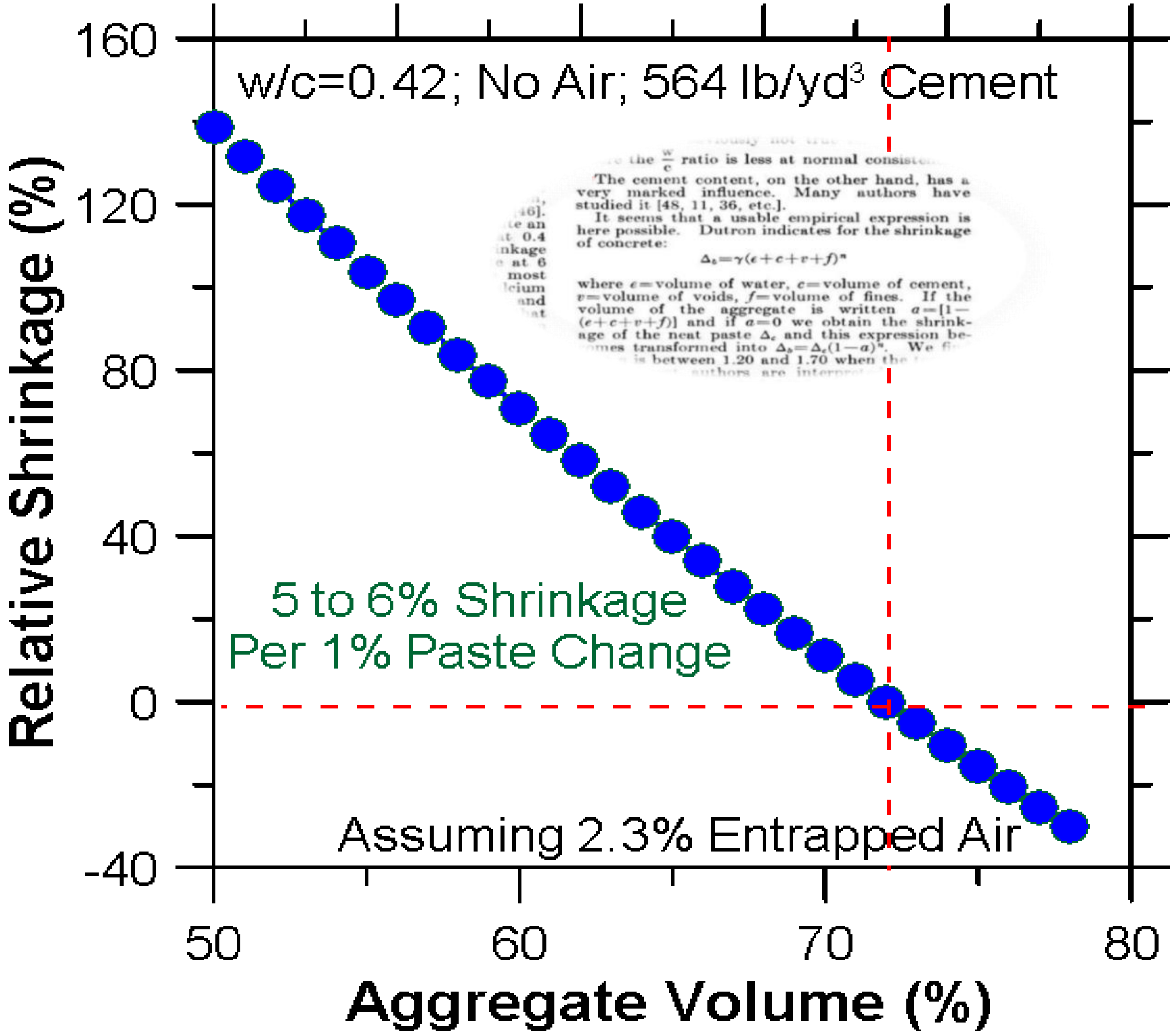
- Dutron (1956) shares data
- L'Hermite (1960 no influence of the w/c) (We can shown this is due to PSD)
- Pickett ('65) and others work on eqn

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

- SRA, IC change this approach doable)



Stress Development

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Initial Specimen

Shrinkage Effect

Restraint Effect

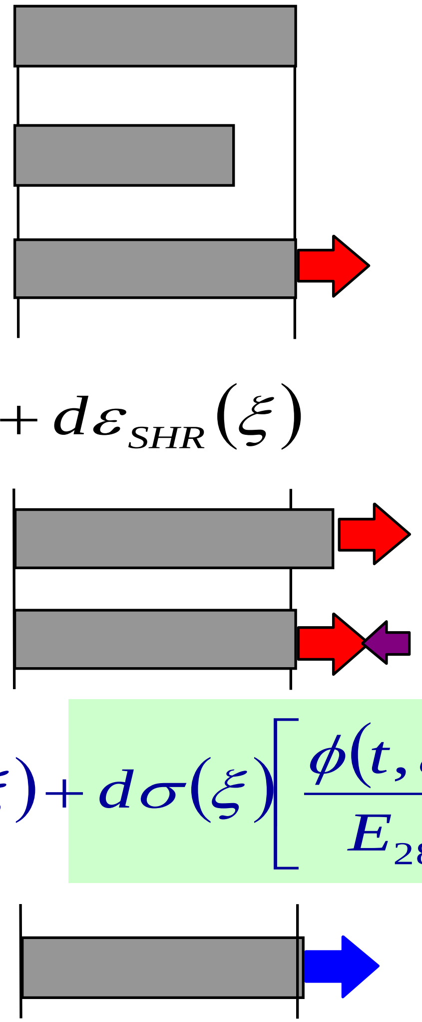
$$d\varepsilon(t,\xi) = \frac{d\sigma(\xi)}{E_\sigma(\xi)} + d\varepsilon_{SHR}(\xi)$$

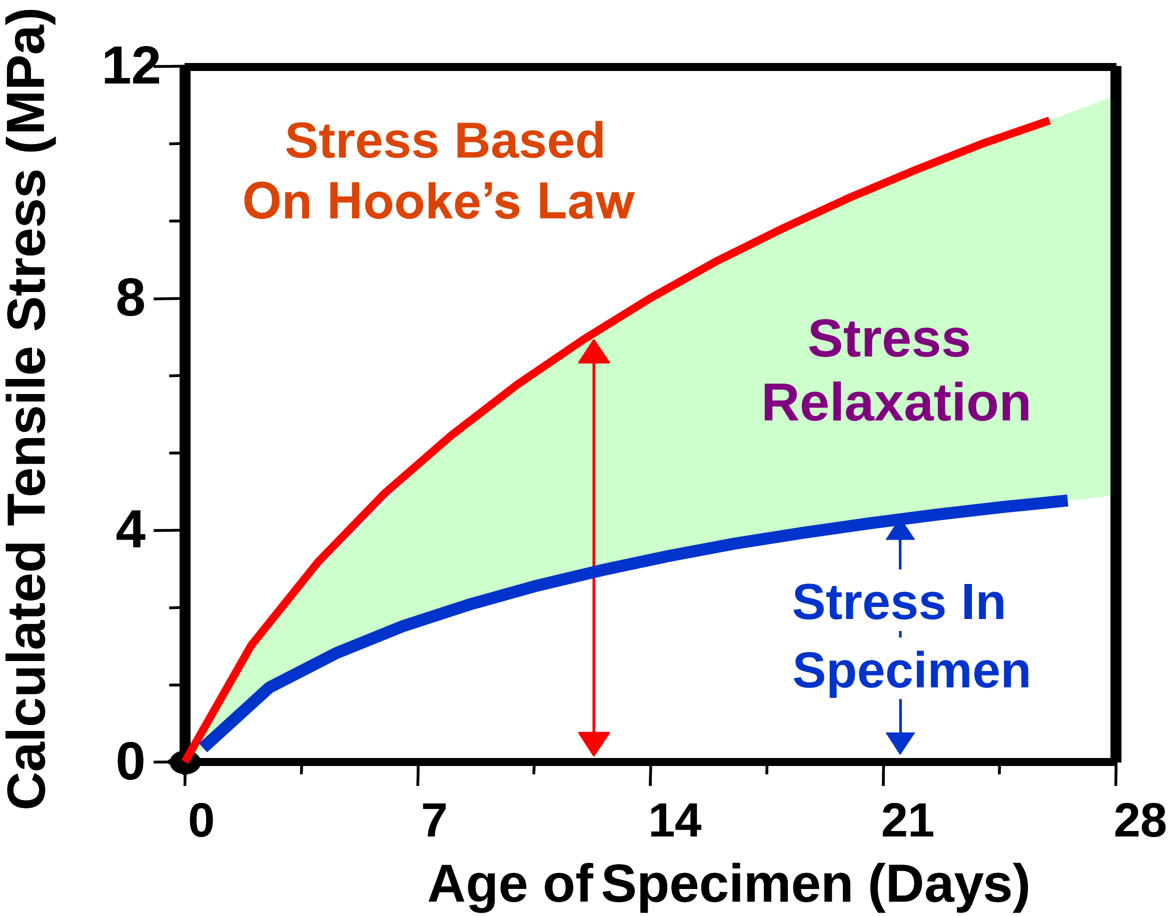
Creep/Cracking Effect

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





Probability of Cracking

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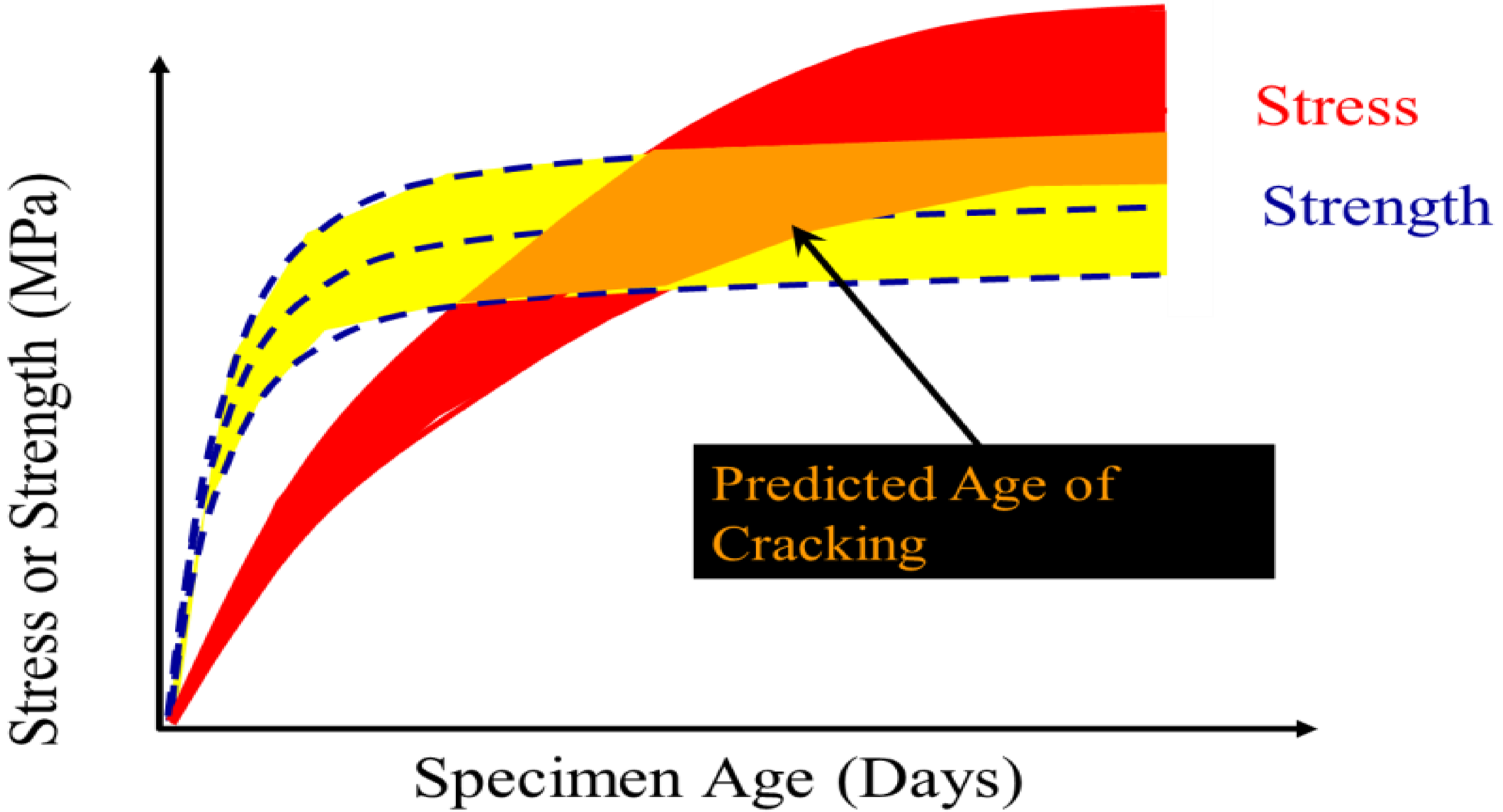

Stress Development

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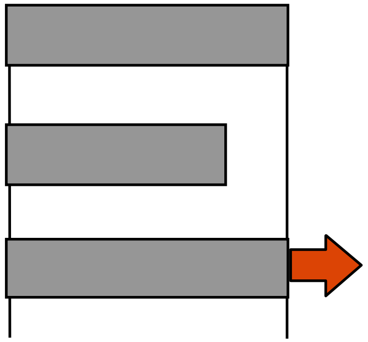
Initial Specimen

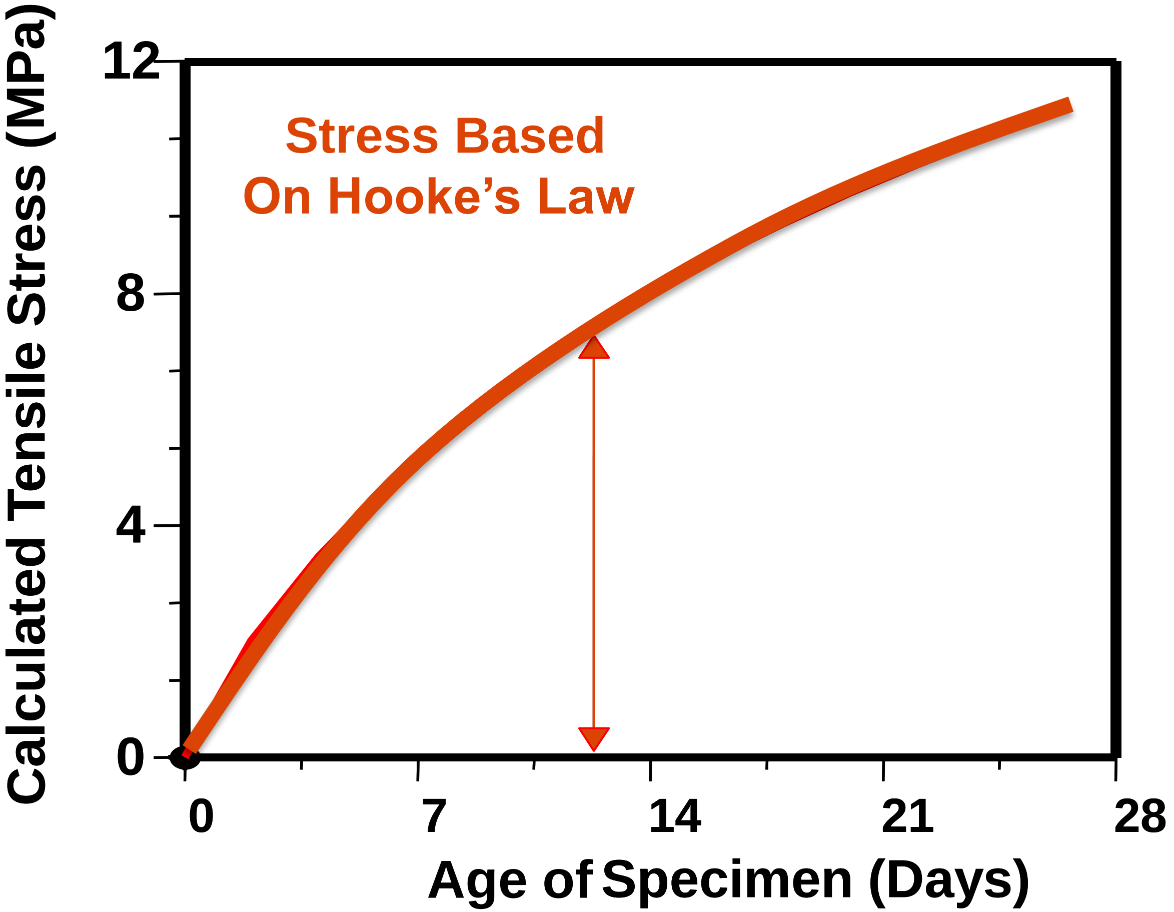
Shrinkage Effect

Restraint Effect



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

Increase in Stiffness is More Likely to Crack



Considering Variability in Shrinkage Cracking

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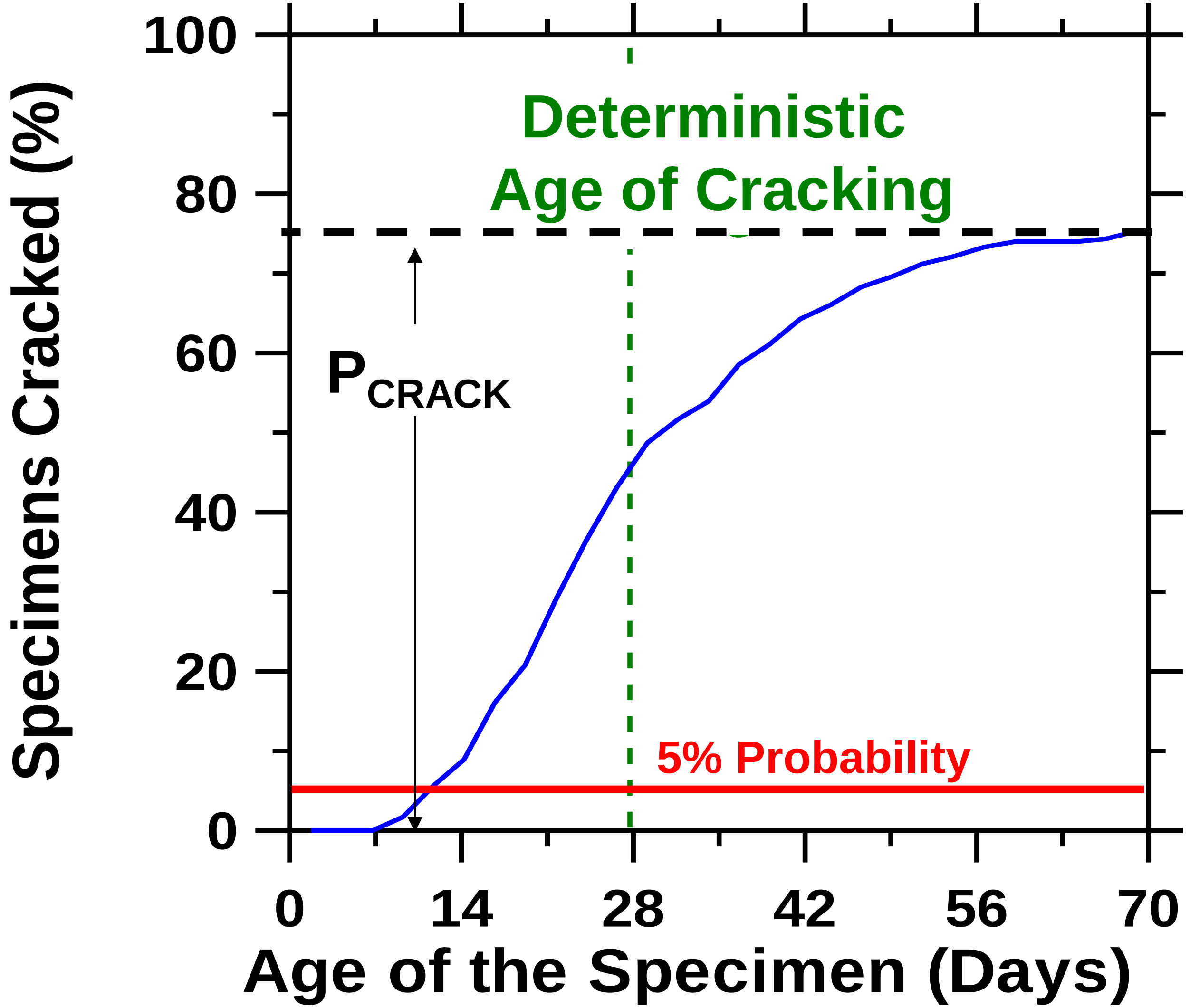
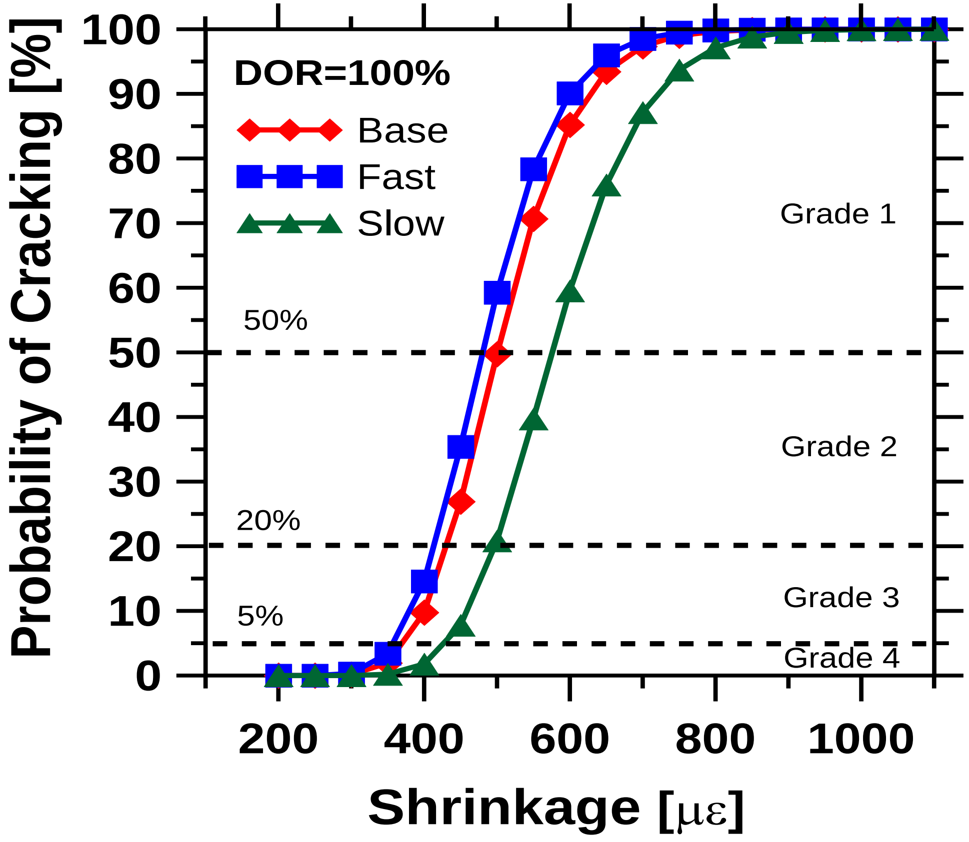
- Plotted the percentage of specimens cracked by a specific age
- Results of 10,000 simulations
- Can quantify risk or total probability

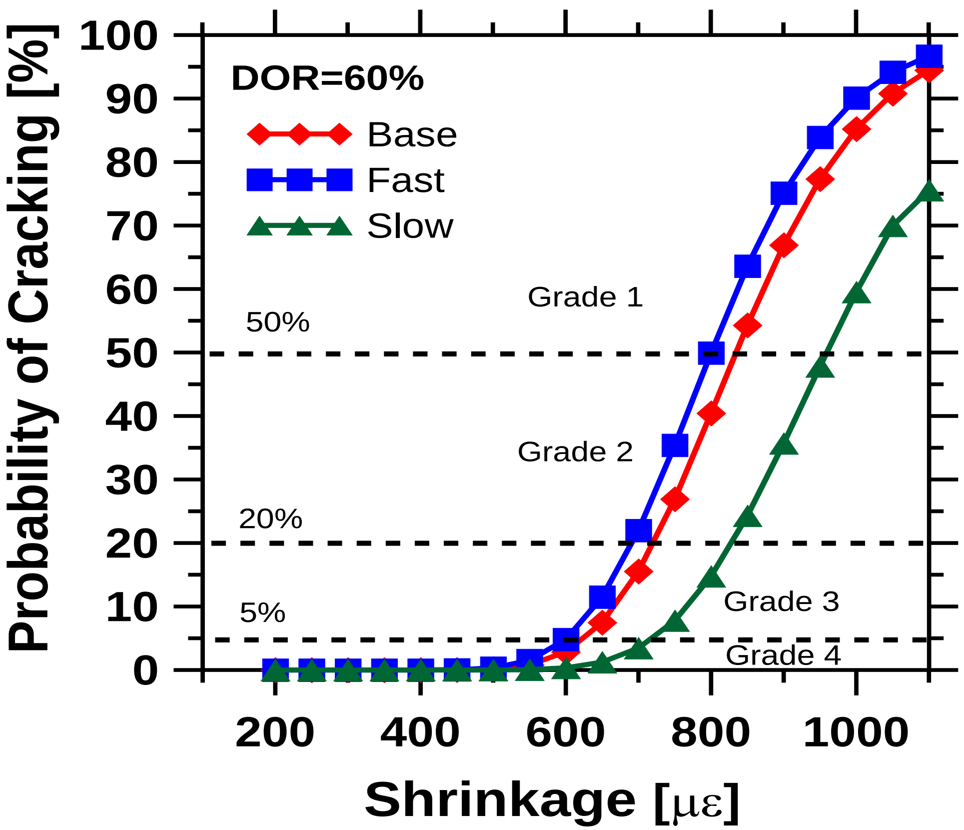


Radlinska al. 2006

Probability Based Shrinkage Specification

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





Radlinska al. 2006

Examine the Problem from Fundamentals

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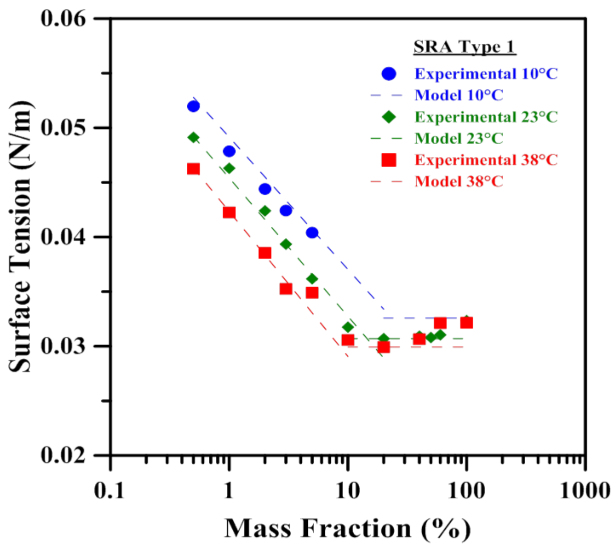
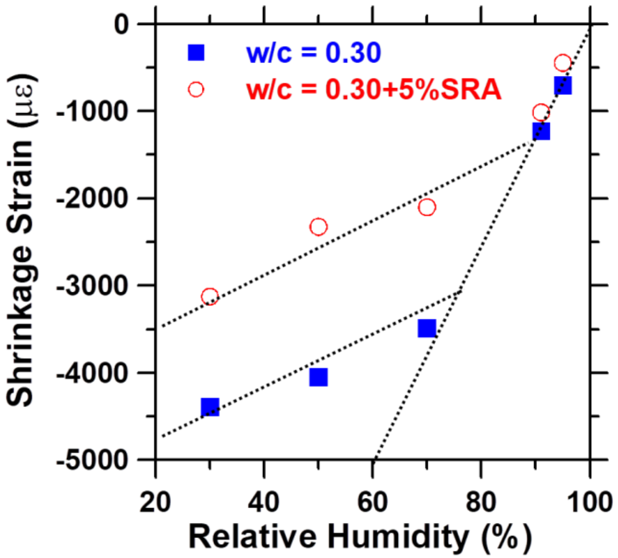
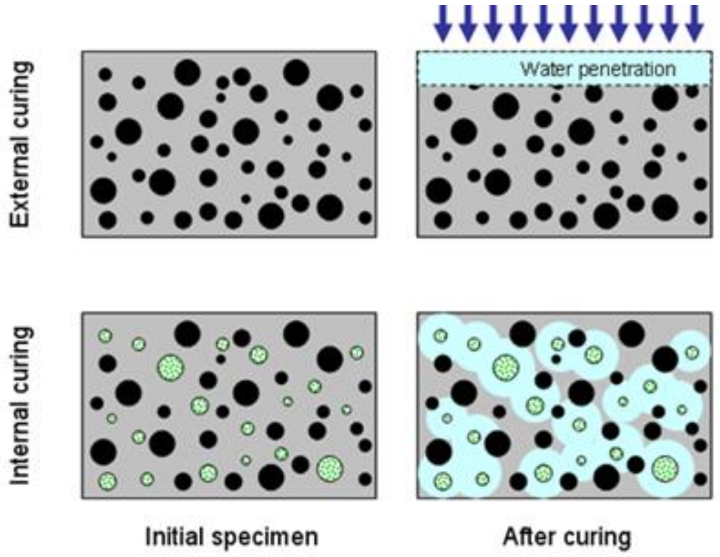
- Shrinkage Occurs Due to Capillary Stress

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

- To reduce stress one can reduce the surface tension of the fluid (reduce γ) or increase the radius of the meniscus (or emptying pore radius, r)







IC Applications

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- INDOT, IL Tollway, NYDOT Decks
- 2010, 2013 INDOT Decks – No/Minimal Cracking
- To Date 100 decks

Concern on Durability of Concrete Joints

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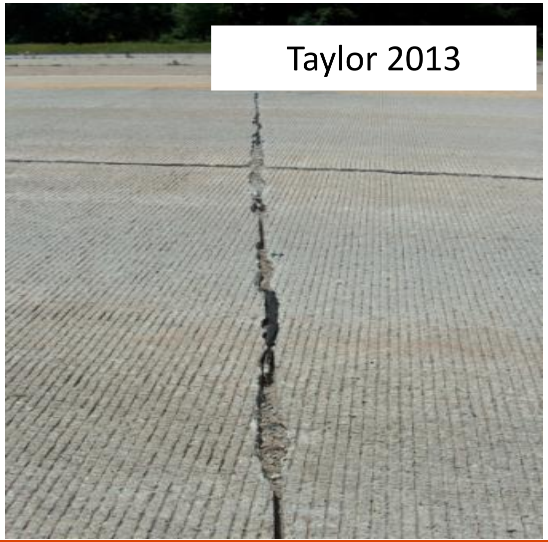
- Majority of concrete pavement performs well; however joints are failing/need repair
- A problem for an other-wise healthy pavement
- The cost is approximately $1 million dollar per mile


Taylor 2013


Weiss 2005


Taylor 2013


Weiss 2008


Weiss 2005

Our research began to look at this differently

Zones of High Fluid Saturation

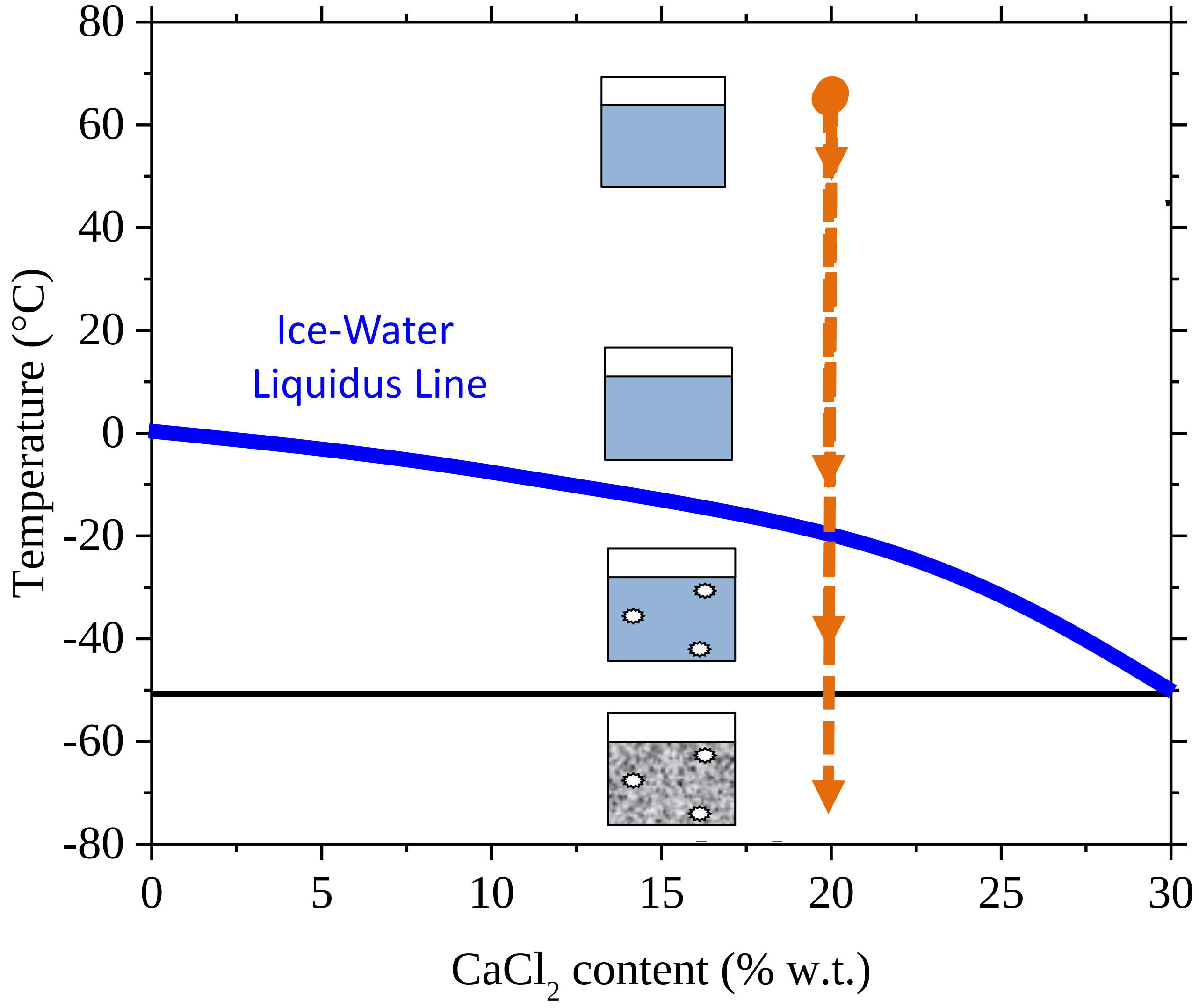
- Geometry
- Fluid Sits
- Fluid is not Water

Zones of Chemical Attack

- ‘New’ Salts
- ‘New’ Reactions
- ‘New’ Problem

Classic $CaCl_2$ – H_2O Phase Diagram

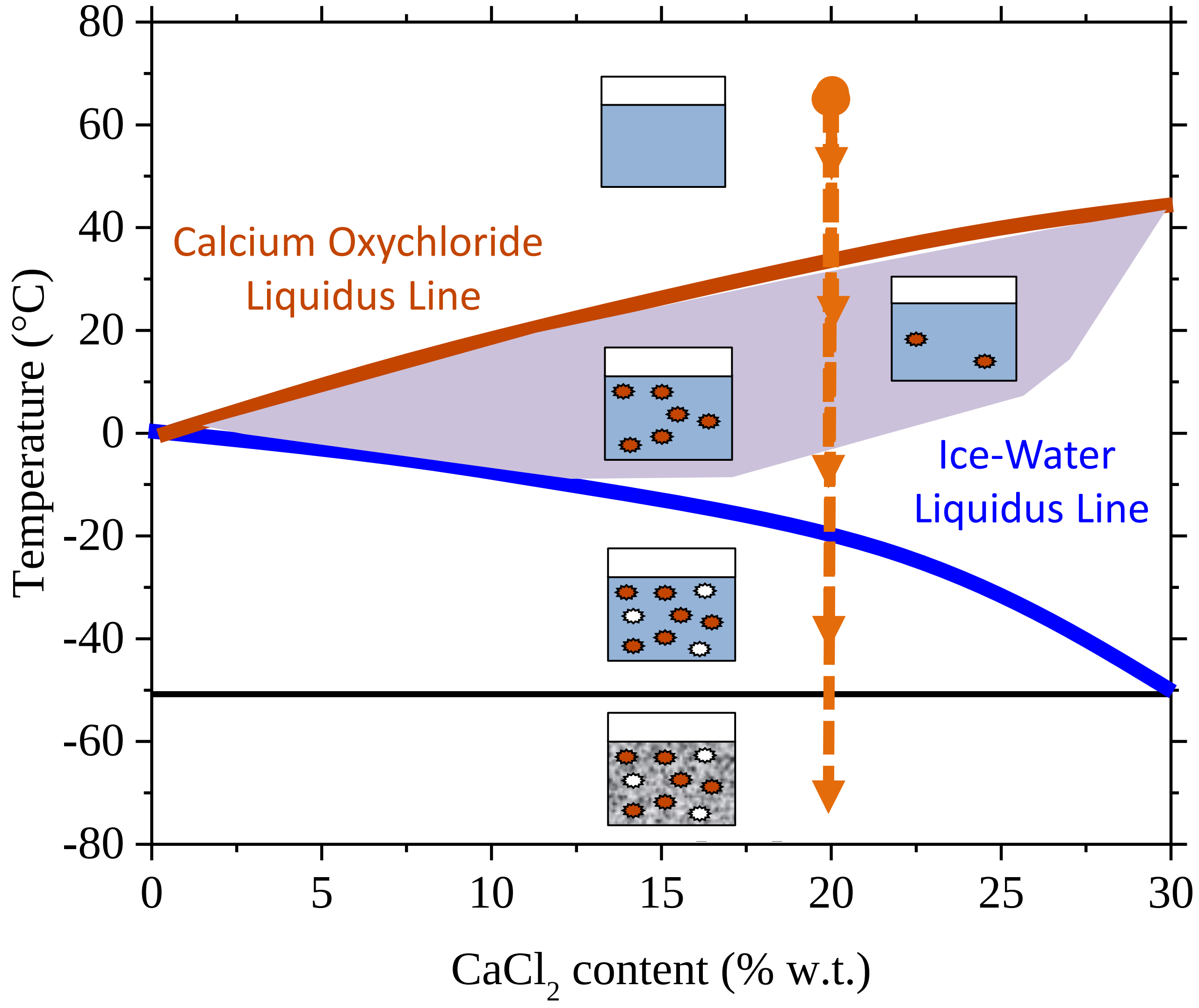
- We likely are not spending a lot of time thinking about the $CaCl_2$ phase diagram
- However this diagram is being used by many SHA as they prepare for deicing and anti-icing operations
- Many prefer $CaCl_2$ due to its lower melting temperature



$CaCl_2$ – H_2O – $Ca(OH)_2$ Phase Isopleth

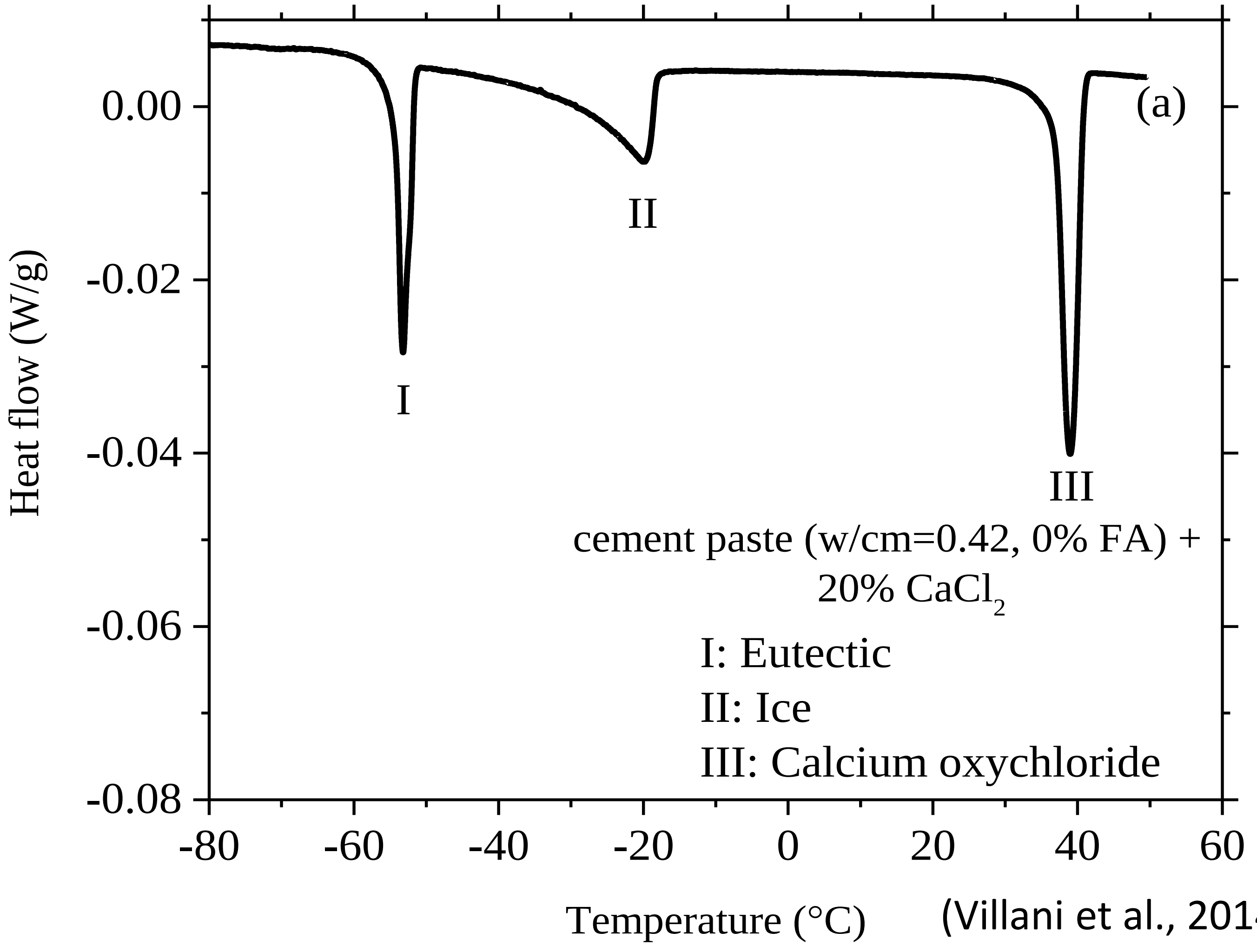
- Unfortunately however when we are working with cementitous systems we need to also consider the calcium hydroxide
- CaOxy is traced out and exhibits a 303% vol change

$$3Ca(OH)_2 + CaCl_2 + 12H_2O \rightarrow CaCl_2 \cdot 3Ca(OH)_2 \cdot 12H_2O$$



A Test to Quantify CaOxy (LTDSC)

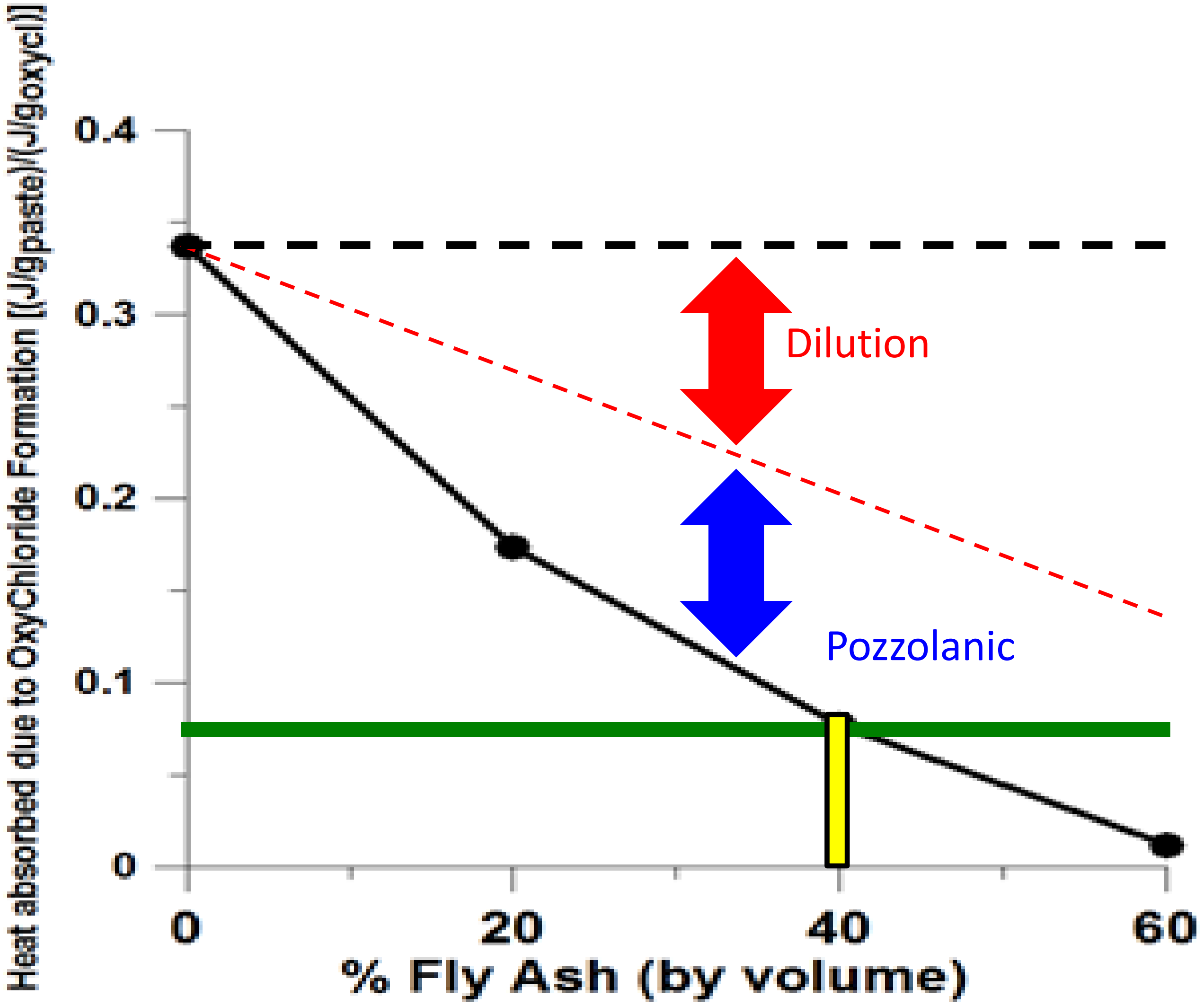
- Low Temperature – Differential Scanning Calorimeter (LT-DSC)
- Temperature is decreased from 50 ^{o}C to -80 ^{o}C, the sample is then re-heated
- Uses powder with $CaCl_2$
- Notice heat flow peaks at various phase formations



(Villani et al., 2014)

Designing Mixtures

- Effect of Dilution (Less CH)
- Effect of Reaction (Less CH)
- Limiting Factor
- Mixture Design



Monical et al. 2016

Our research began to look at this differently

Zones of High Fluid Saturation

- Geometry
- Fluid Sits
- Fluid is not Water

Zones of Chemical Attack

- ‘New’ Salts
- ‘New’ Reactions
- ‘New’ Problem

FT Service Life Model

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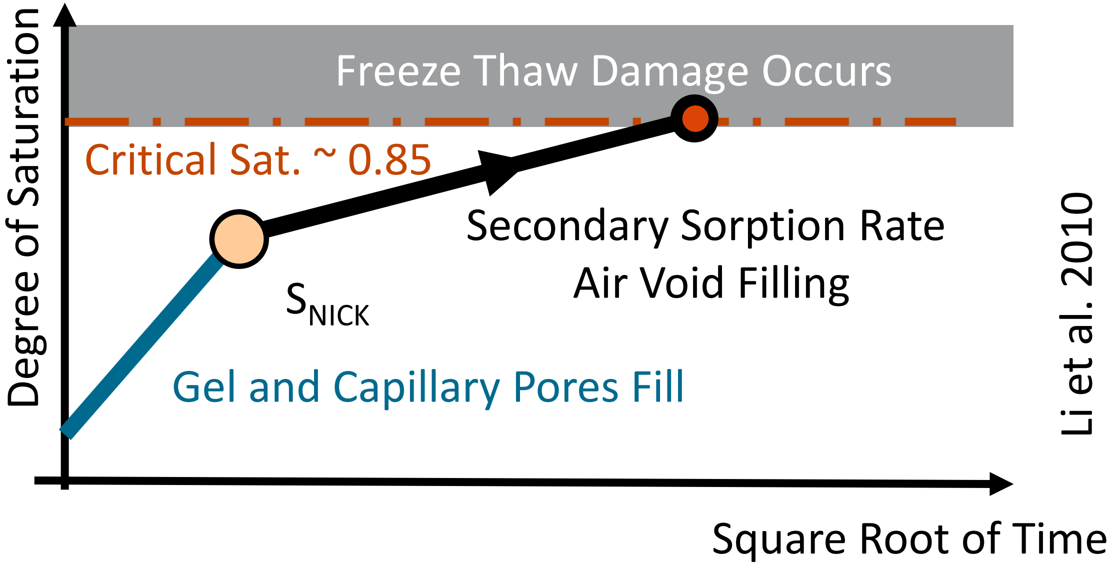
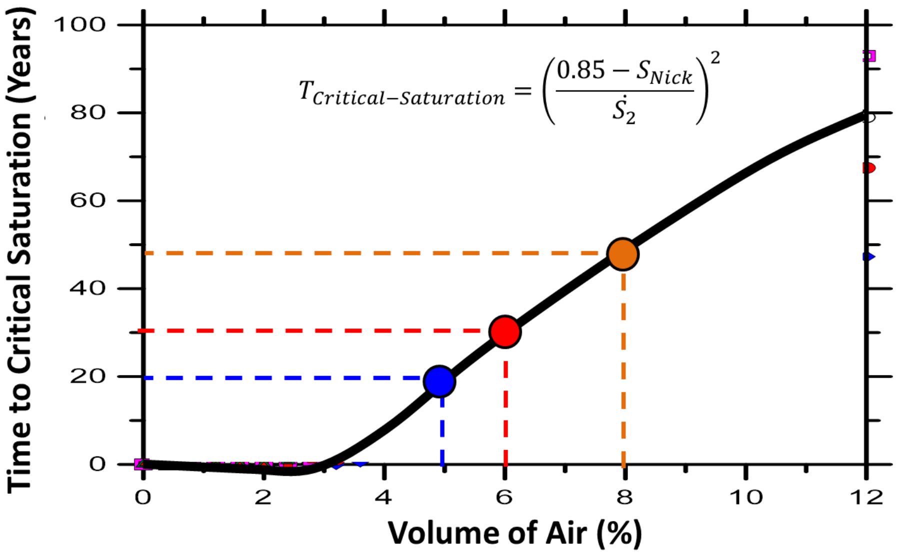
- Simple sorption based model is shown
- Important to recognize that we are not predicting FT damage; rather we are predicting a limit state
- Great framework
- Lets discuss the model inputs (tests that we will measure)



Li et al. 2010



Weiss et al. 2014

What About Variability

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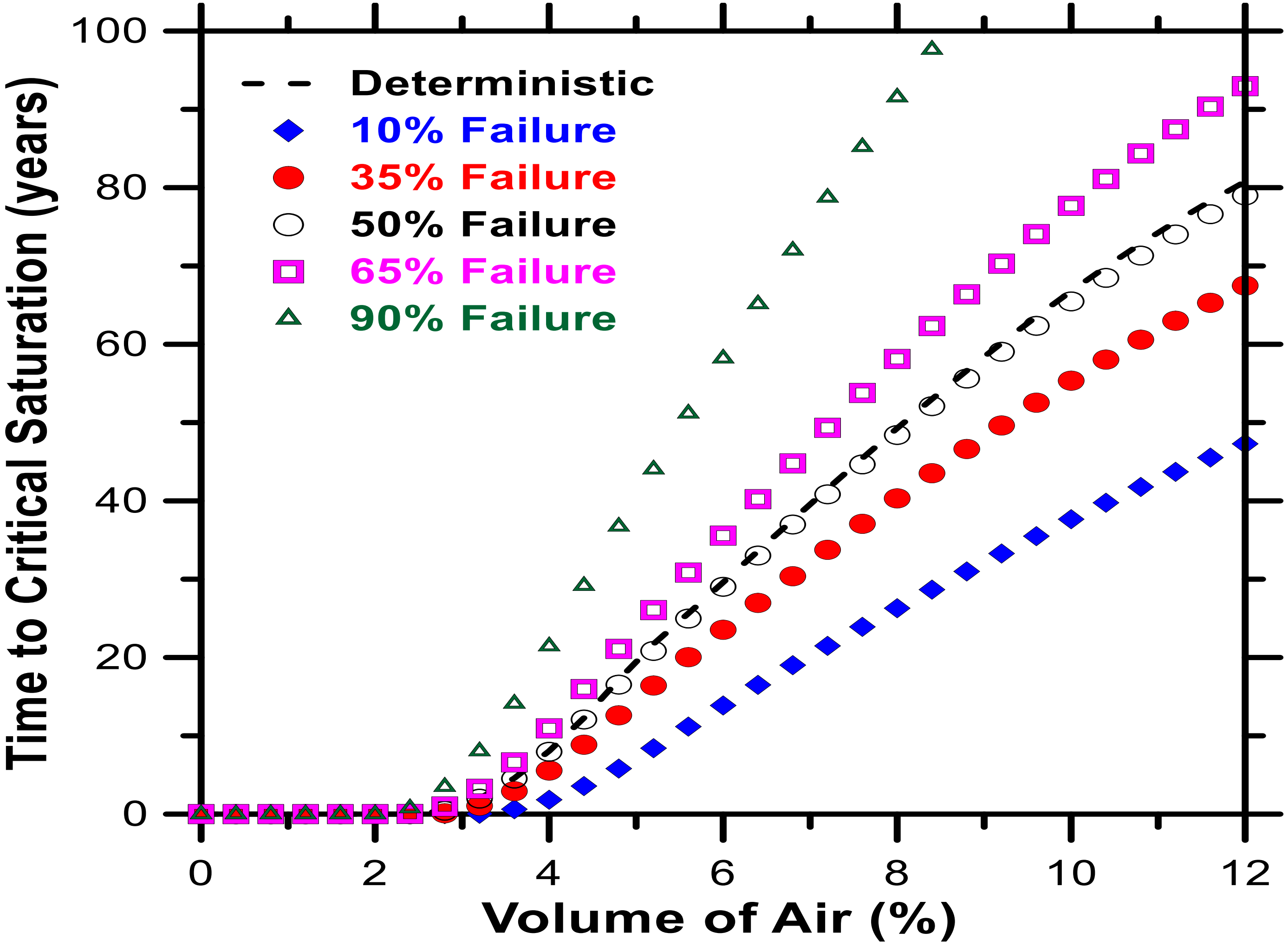
- Design Mixture
  - 0.42 w/c
  - 6% Air
  - 564 lb cement
  - Fine Aggregate
- Lets Assume Variations
  - w/c 5% (0.38 to 0.46)
  - Air 15% (4.2 to 7.8)



Calculated from the ARA PRS Project

What About Variability

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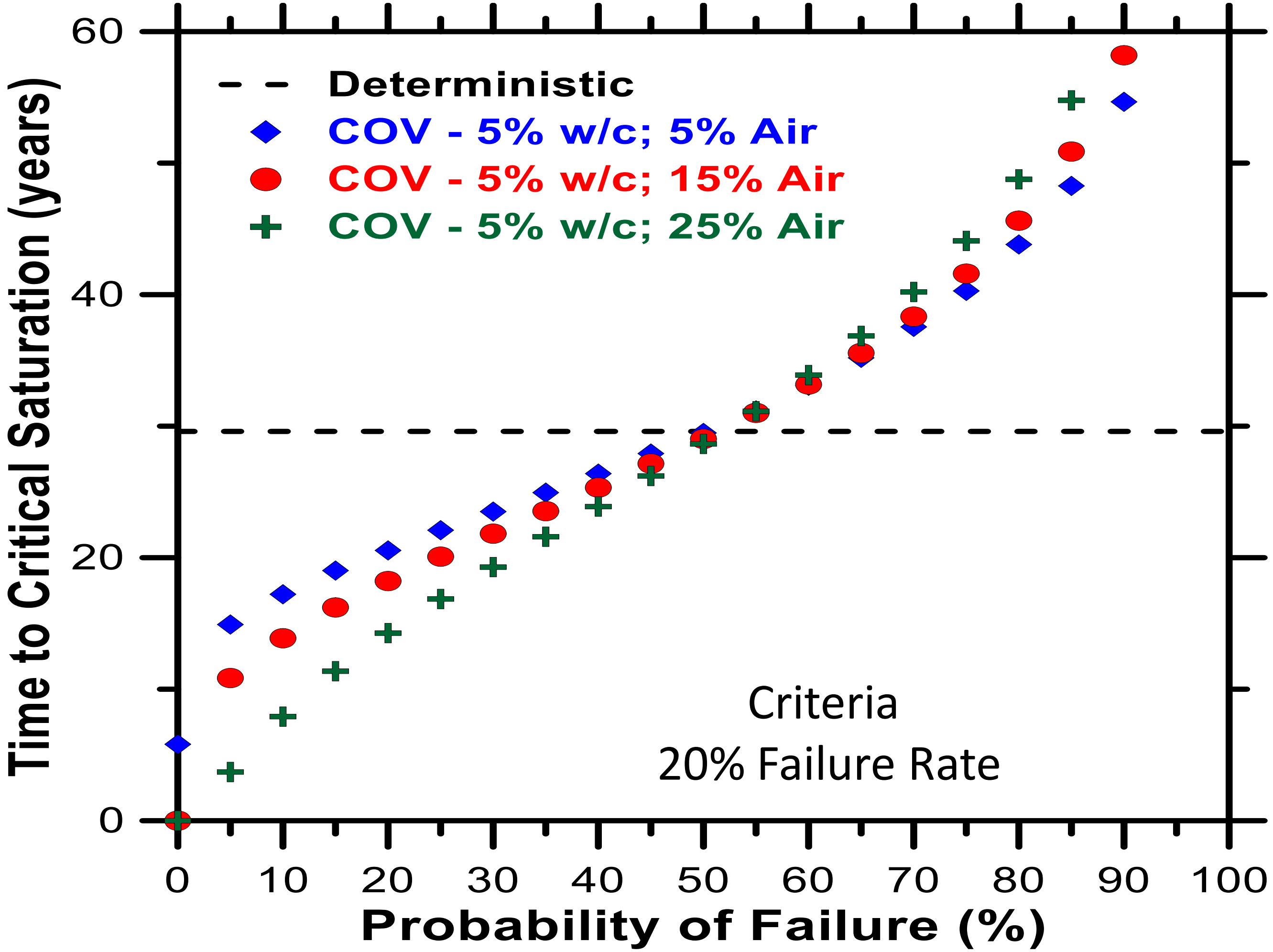
- Design Mixture
  - 0.42 w/c
  - 6% Air
  - 564 lb cement
  - Fine Aggregate
- Assume Variation
  - w/c 5% (0.38 to 0.46)
  - Air 5% (5.4 to 6.6)
  - Air 15% (4.2 to 7.8)
  - Air 25% (3.0 to 9.0)



Calculated from the ARA PRS Project

Model Correlations

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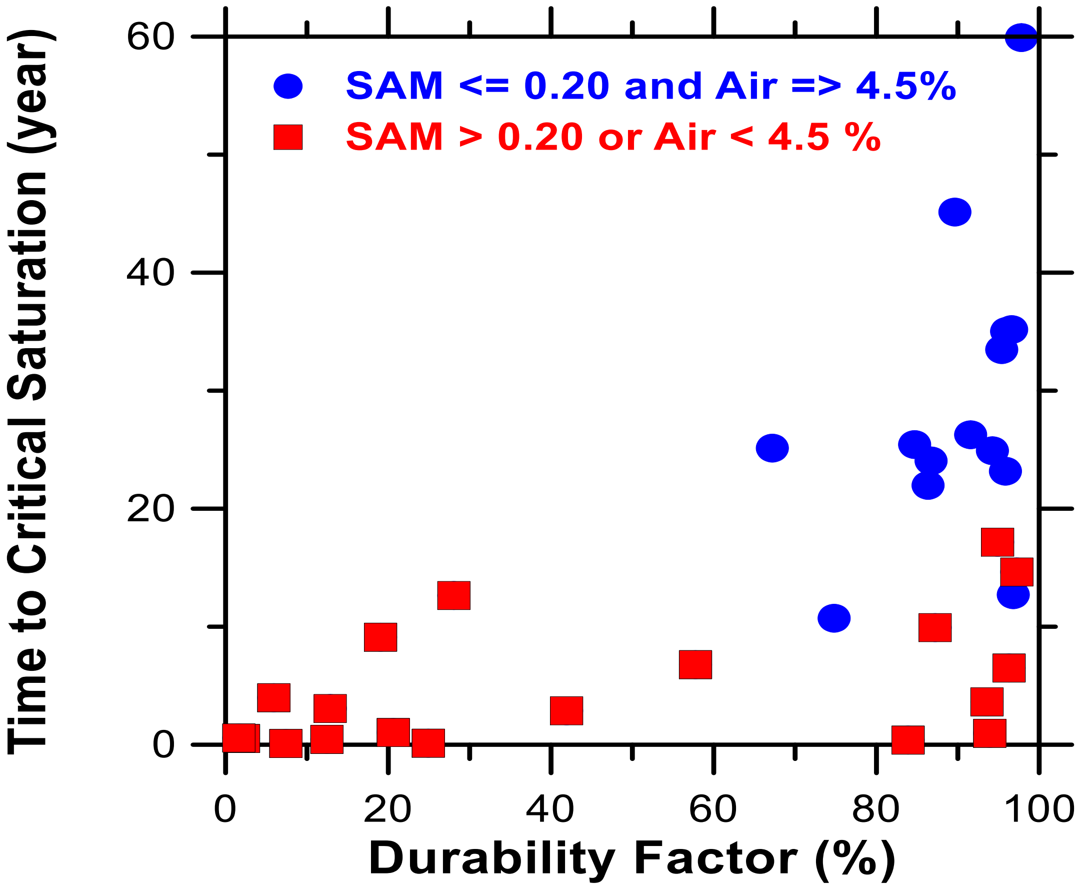

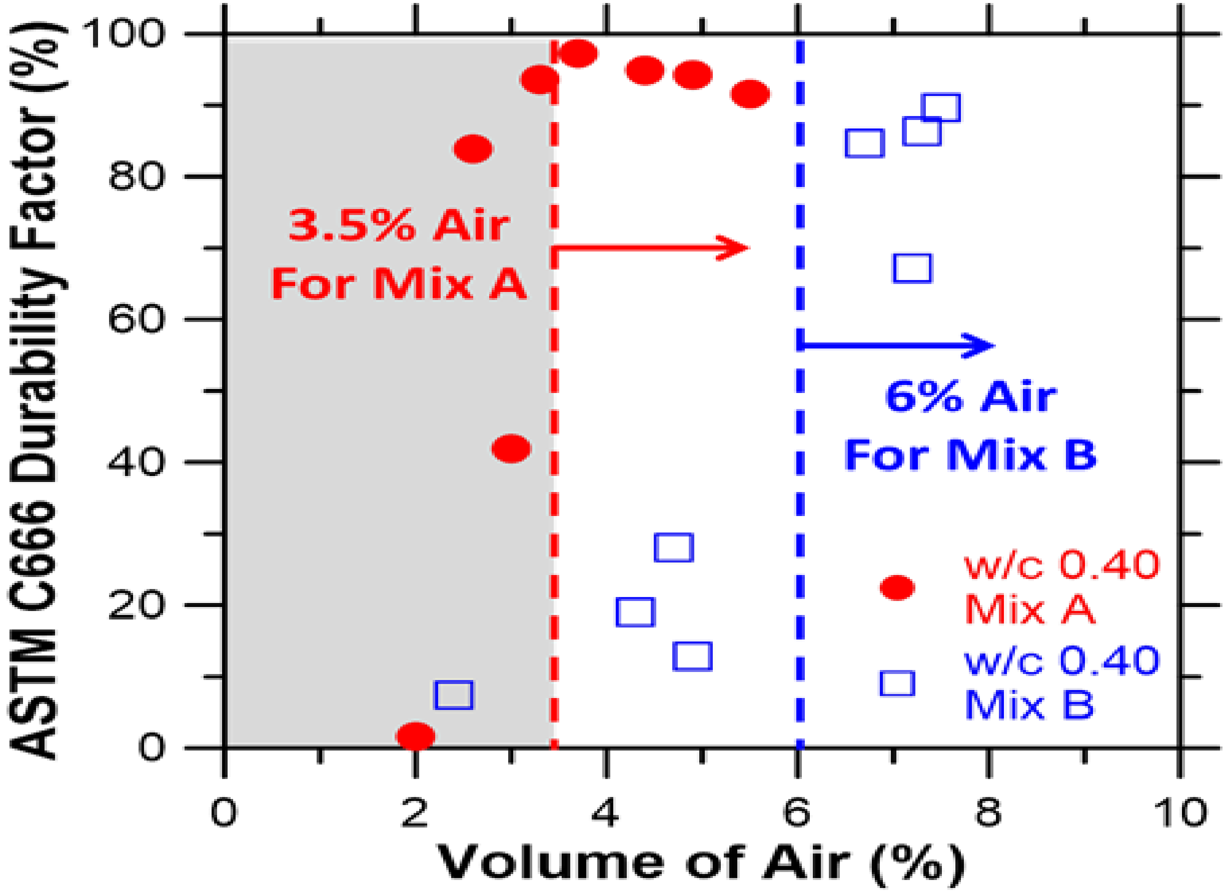

Four Step Approach

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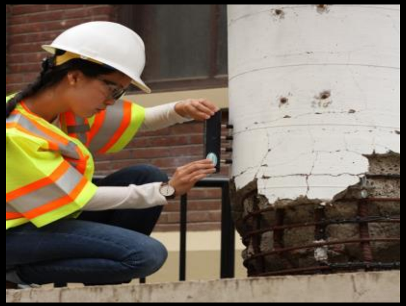

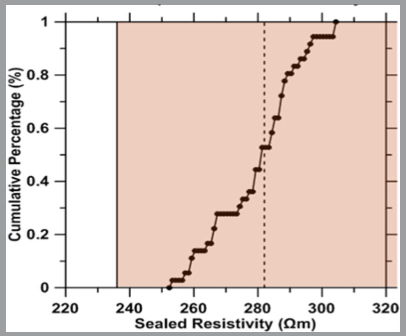

1. Assess Performance w/ Standard Tests
2. Convert Test Results to Fundamental Properties
3. Relate Properties w/ Exposure Conditions
4. Establish Performance Grade and Measure

- Shrinkage Cracking/Probability of Cracking
- Formation Factor and Corrosion
- Freeze-Thaw Saturation Model
- Salt Damage in Pavements

Barde et al. 2007

Summary

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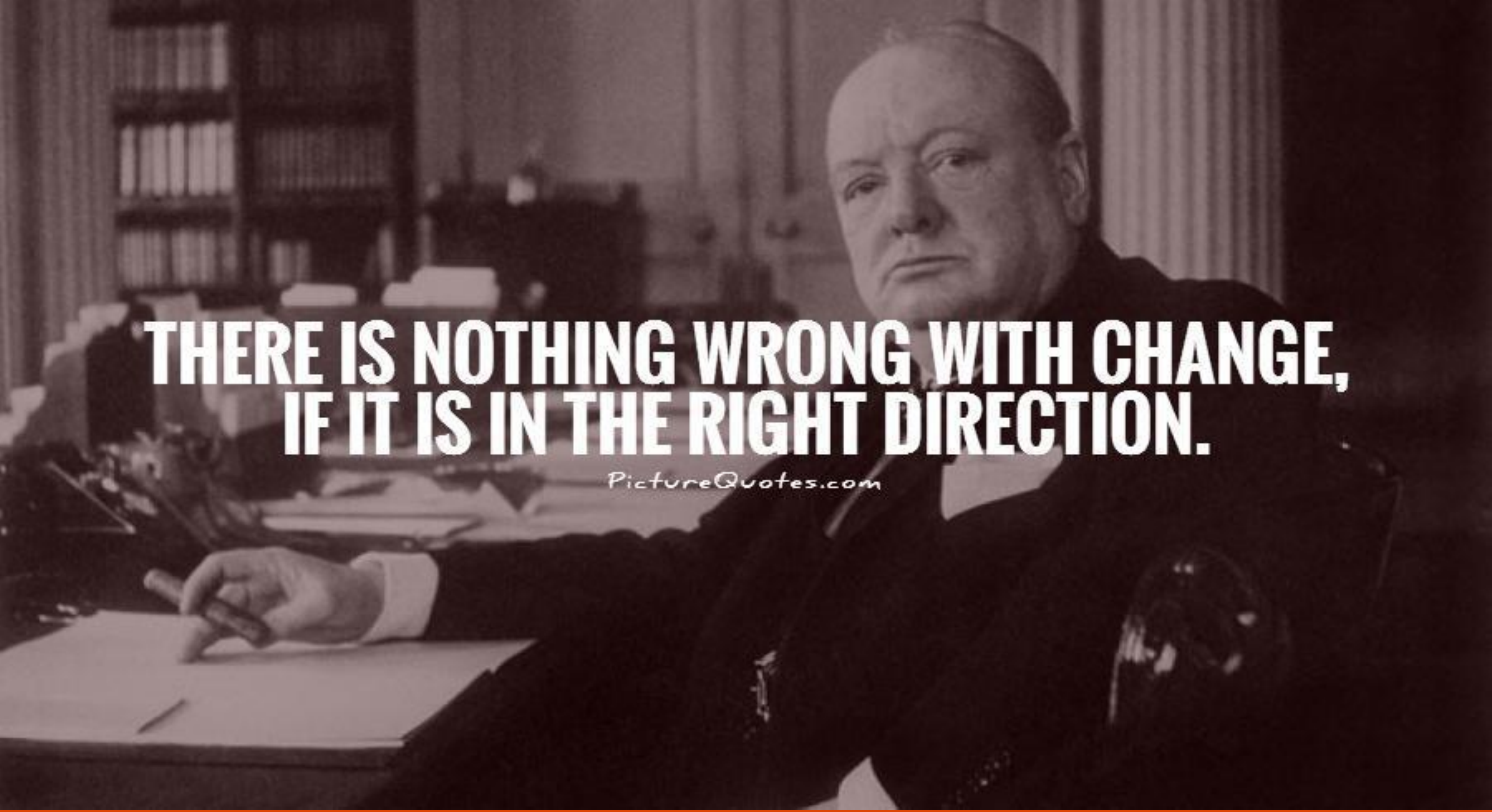
Name				
Damage Mechanism	Transport/Corrosion	Random Cracking	Freeze-Thaw	Salt Damage
	Formation Factor	Crack Probability	Critical Saturation	Calcium Oxychloride
Test Method	Resistivity	Ring Testing	Sorption/Sat	LTDSC
Correction	F-Factor	Probability	Degree of Sat.	Damage Model
Model	GEMS	Stress Develop.	Critical Saturation	GEMS
Material	HPC, VMA	Vol Paste, SRA, IC	Air, HPC, new FT	SCM, carb., topical
Implementation	Evaluation, Spec	Limited	Discussion	Limited

Weiss et al. 2016


THERE IS NOTHING WRONG WITH CHANGE,
IF IT IS IN THE RIGHT DIRECTION.
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