

Concrete Resistivity for Concrete Production

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Objectives of the Session

- Understand the role of electrical methods in performance-based standards and codes
- Learn about ongoing research and future developments in condition assessment

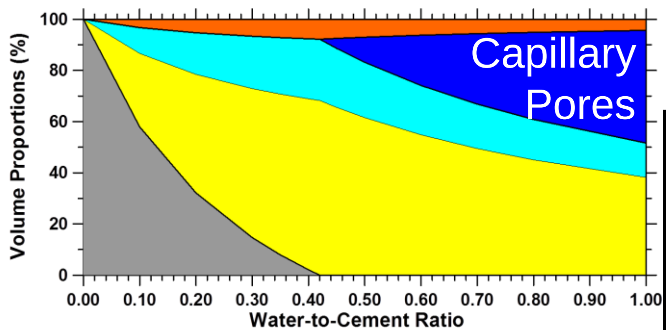
- Our group has used electrical properties to assess drying, property development, strength, freezing, fibers.. Our recent focus however is on standardization and relation to service life prediction

Tests that Relate to Durability

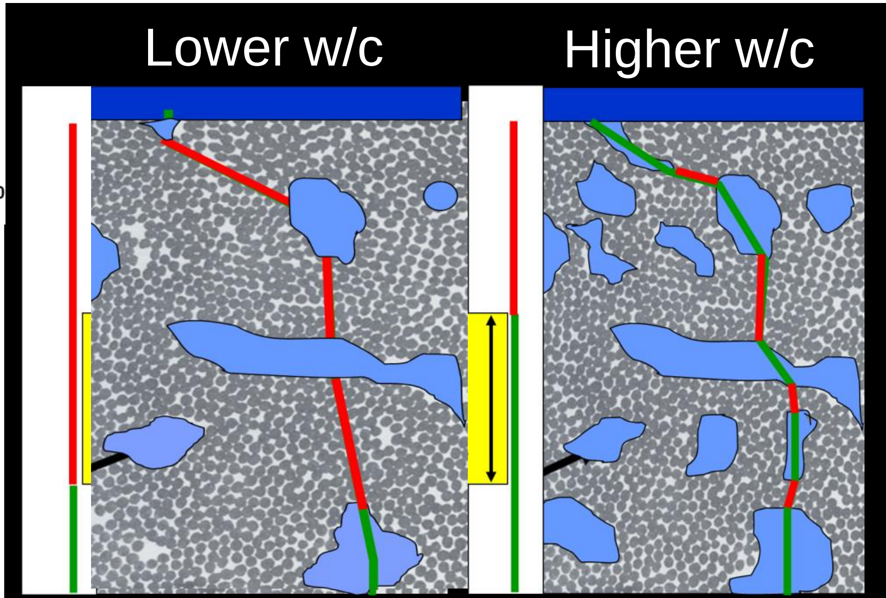
- Much like Indiana we seem to be on the impossible search for the "holy grail"
- We want a test for transport (or durability) that is fast, accurate, inexpensive easy to interpret but it also needs to be scientifically valid
- We think that electrical measurements can be a significant part of this approach

Transport in Large Pores

- Transport occurs mainly in capillary pores, there is some transport in the gel pores however we are generally worried about
- Capillary pores are large and connected

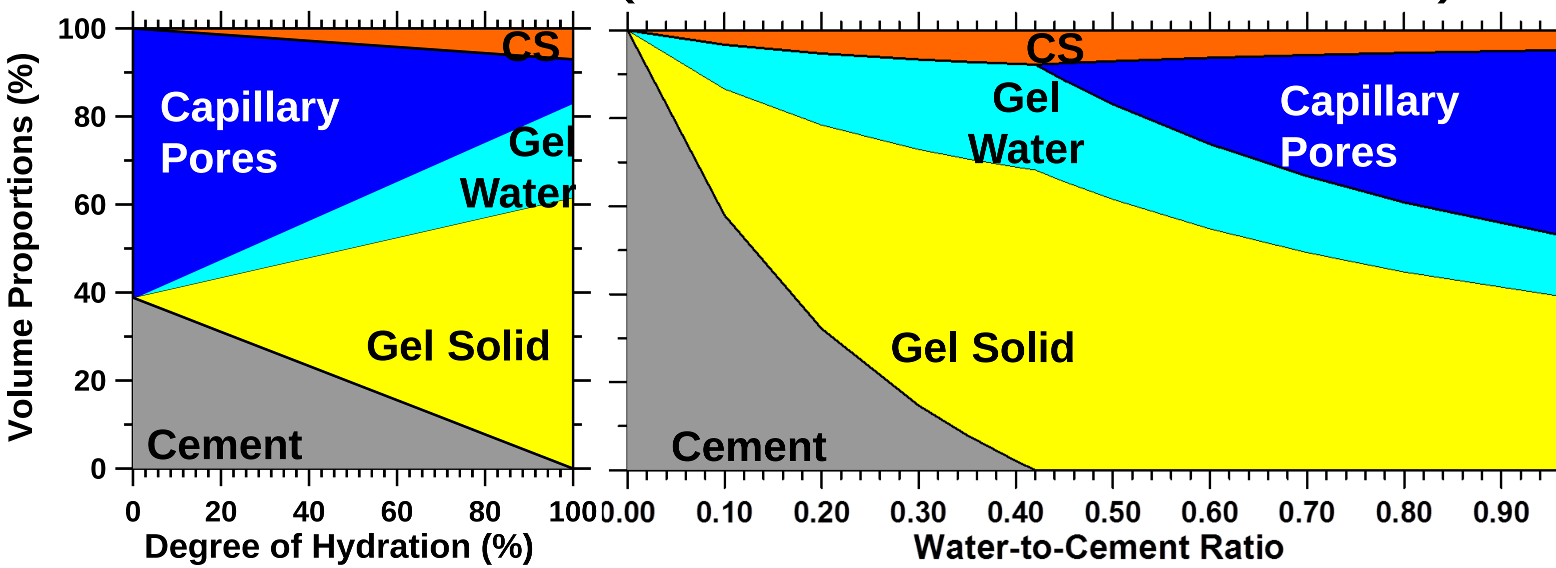


Assumes 100% Hydration



Start with Some Basic Concepts

- The paste portion of concrete can be described using a model by Brownyard and Powers Bul. 29 (T.C. Hansen, O. Jensen)



- Porosity is determined by degree of hydration (time, temp, moisture), the water to cement ratio, and the volume of paste

Basic Electrical Results

Introduction

Testing Basics

Geometry

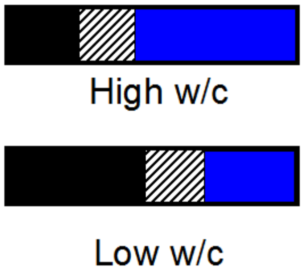
Pore Solution

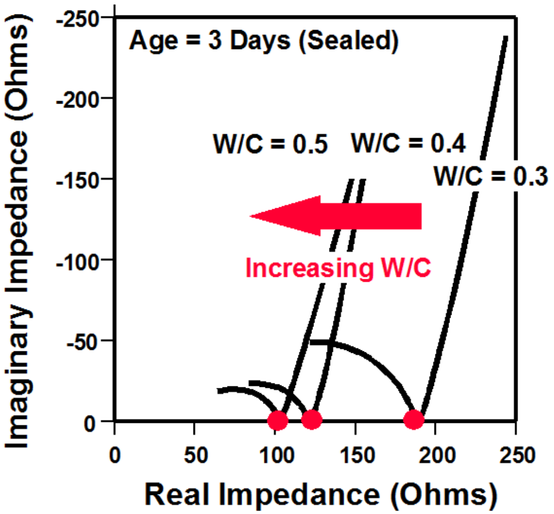
Variability

Curing
Saturation
Test Temperature
Alkali Leaching

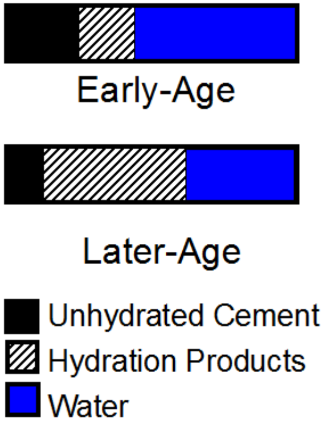
Factors
Acc. Curing

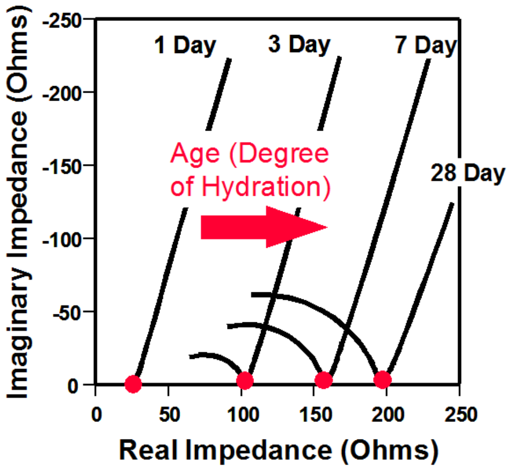
- Varying w/c – Changing fluid volume



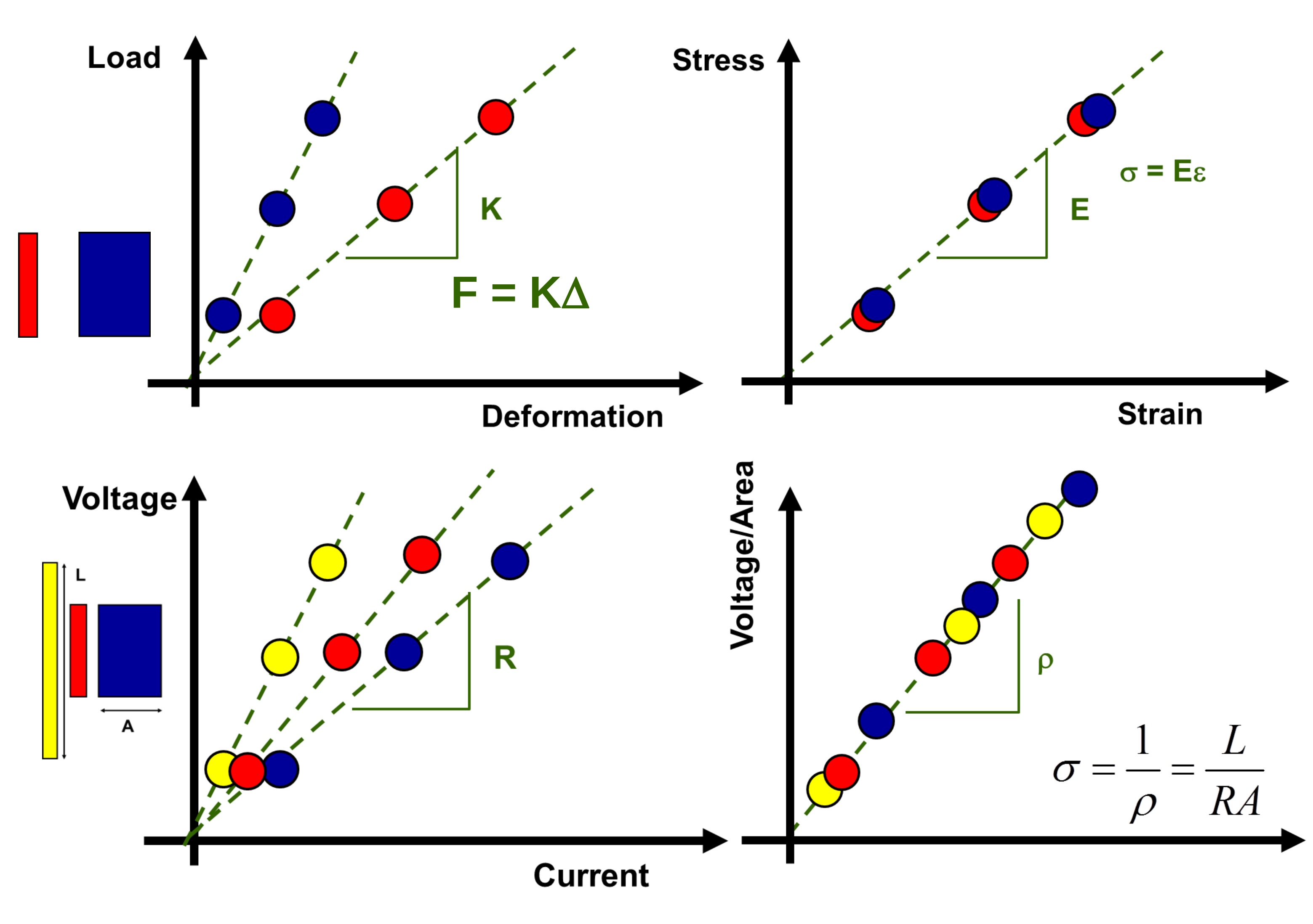


- Varying (DOH) – Changing fluid volume





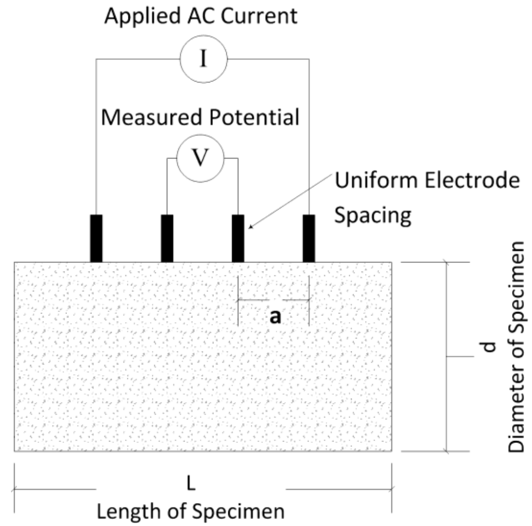
Results Should be Independent of Geometry or Test Configuration



Geometry Factor

$$\rho = R \cdot k$$

Surface

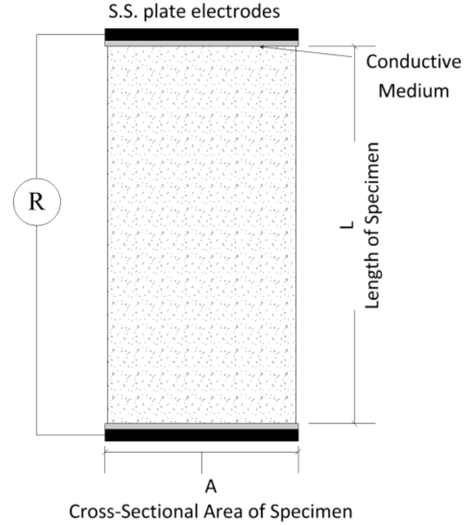


$$\hat{k}_1 = 2\pi a$$

$$\hat{k}_2 = 1.09 - \frac{0.527}{d/a^{1}} + \frac{7.34}{d/a^{2}}$$

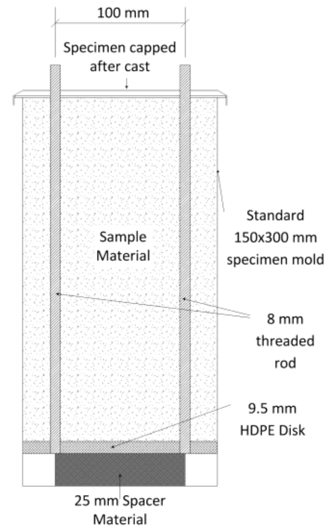
$$k_{surface} = \frac{\hat{k}_1}{\hat{k}_2}$$

Uniaxial



$$k_{uniaxial} = \frac{A}{L}$$

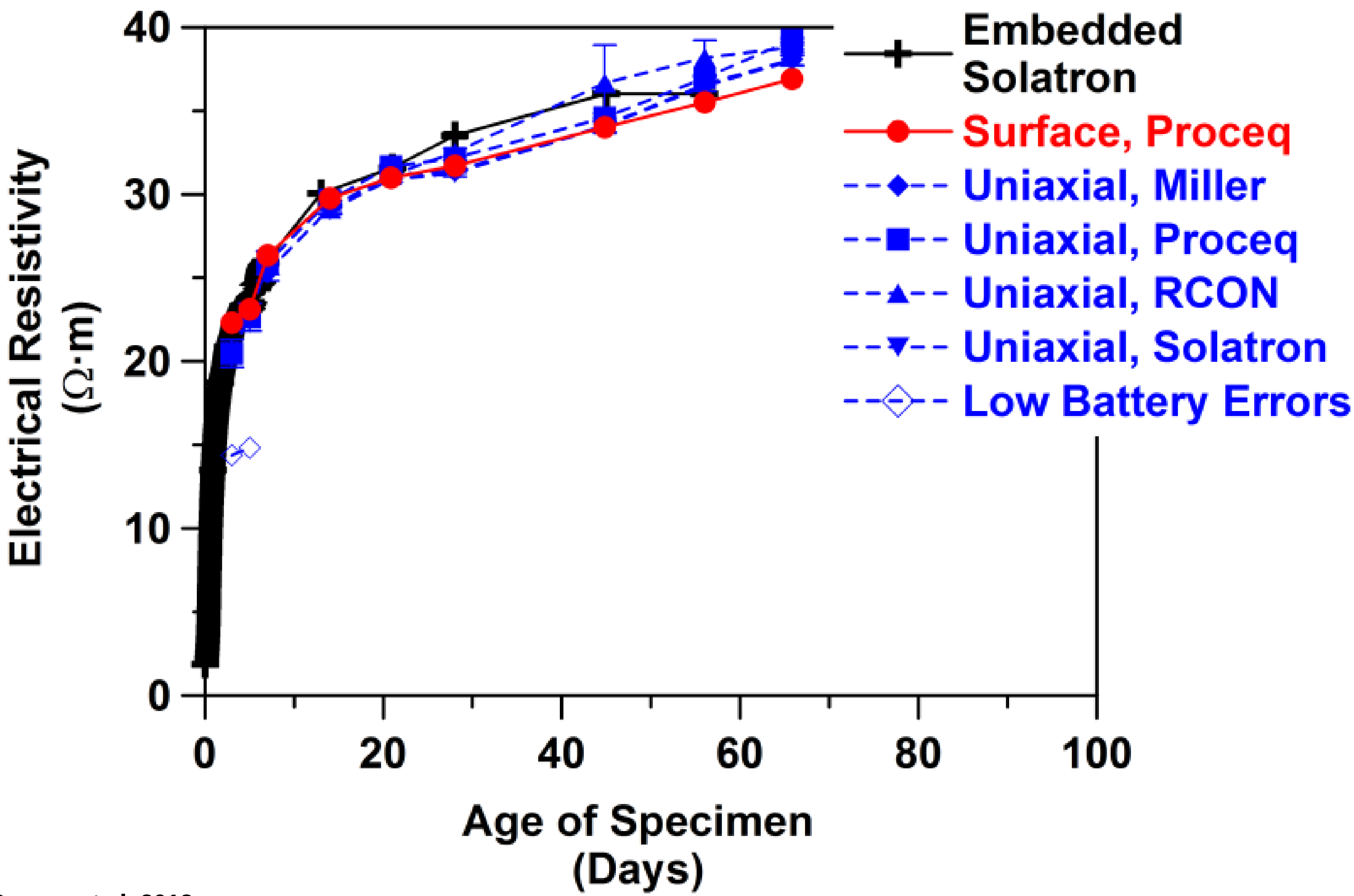
Embedded



$k_{embedded}$ determined experimentally

Morris et al., 1996

Comparison of Different Geometries



Spragg et al. 2012

A Few Items to Start With

Introduction
Testing Basics
Geometry
Pore Solution
Variability
Curing
Saturation
Test Temperature
Alkali Leaching
Factors
Acc. Curing

- Using resistivity, while I prefer conductivity, tests in practice that have discussion in ρ

$$\rho = \frac{1}{\sigma}$$

- Assume the only conductive phase is the fluid and the resistivity of the concrete is the product of resistivity of solution and the formation factor (inverse porosity and connectivity) (solutions exist for other conductive phases Weiss et al.)

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

Determining Pore Solution

Introduction

Testing Basics

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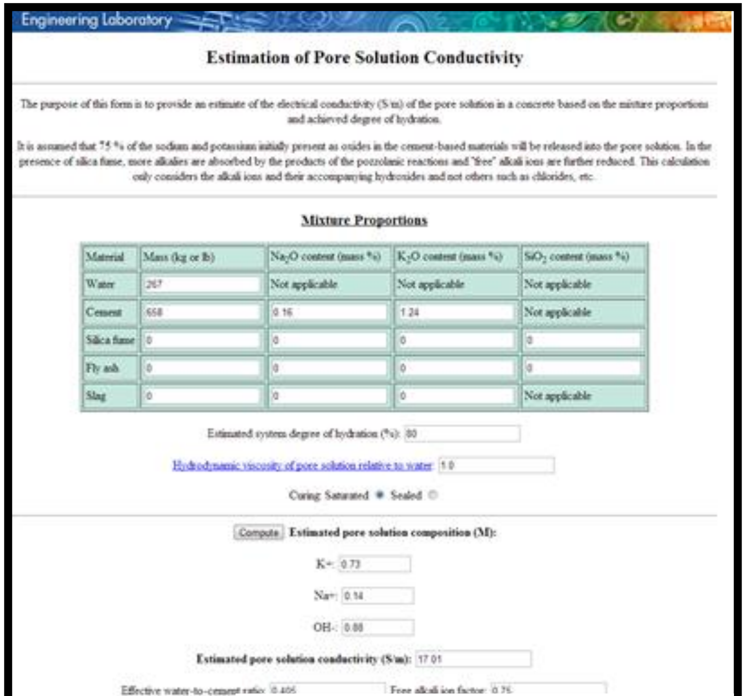
- Extraction
- Theoretical (Website)
- Embedded Sensor



Engineering Laboratory

Estimation of Pore Solution Conductivity

The purpose of this form is to provide an estimate of the electrical conductivity (S/m) of the pore solution in a concrete based on the mixture proportions and achieved degree of hydration.

It is assumed that 75 % of the sodium and potassium initially present as oxides in the cement-based materials will be released into the pore solution. In the presence of silica fume, more alkalies are absorbed by the products of the pozzolanic reactions and "free" alkali ions are further reduced. This calculation only considers the alkali ions and their accompanying hydroxides and not others such as chlorides, etc.

Mixture Proportions

Material	Mass (kg or lb)	Na_2O content (mass %)	K_2O content (mass %)	SiO_2 content (mass %)
Water	267	Not applicable	Not applicable	Not applicable
Cement	668	0.16	1.24	Not applicable
Silica fume	0	0	0	0
Fly ash	0	0	0	0
Slag	0	0	0	Not applicable

Estimated system degree of hydration (%): 80

Hydrodynamic viscosity of pore solution relative to water: 1.0

Curing: Saturated ● Sealed ○

Compute **Estimated pore solution composition (M):**

K+: 0.73

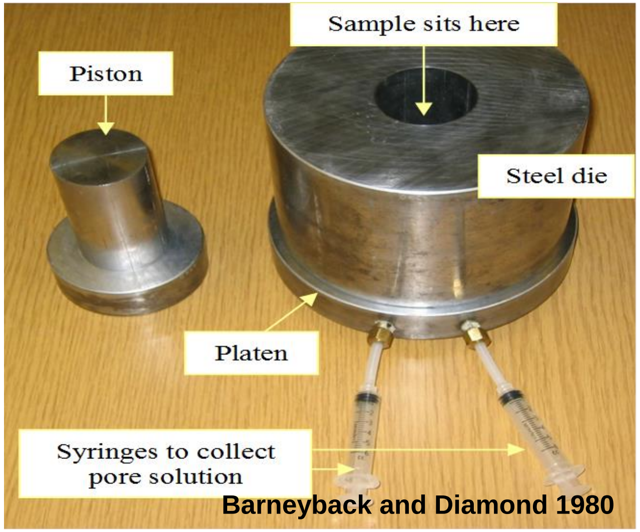
Na+: 0.14

OH-: 0.88

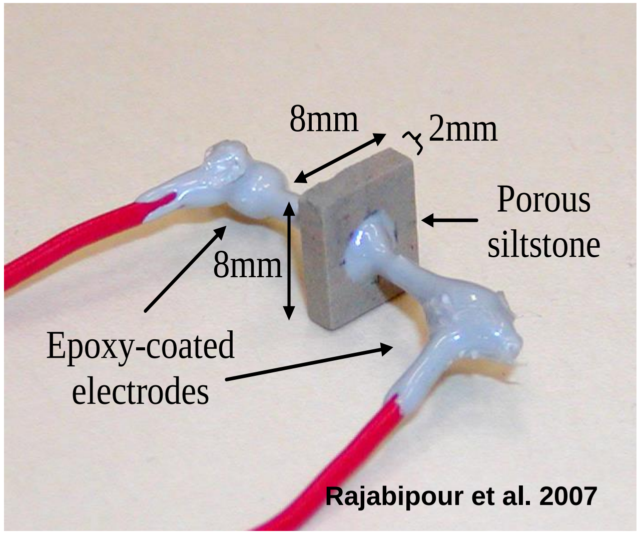
Estimated pore solution conductivity (S/m): 17.01

Effective water-to-cement ratio: 0.405 Free alkali ion factor: 0.75

concrete.nist.gov/poresolncalc.html



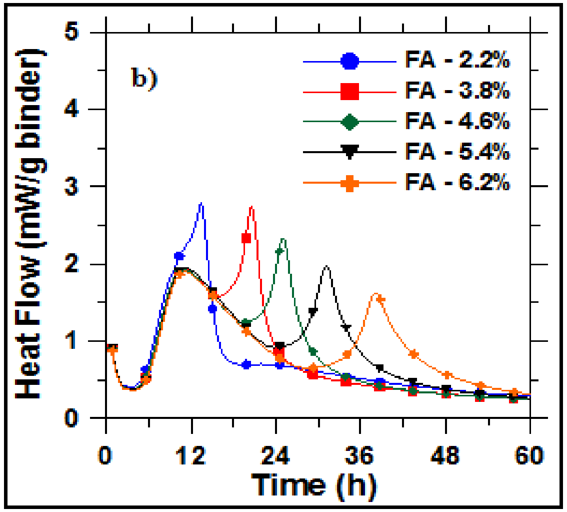
Barneyback and Diamond 1980

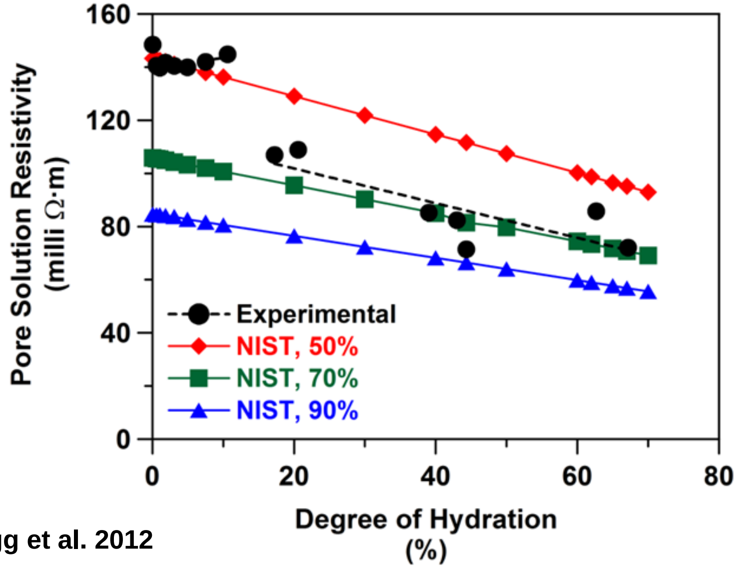


Rajabipour et al. 2007

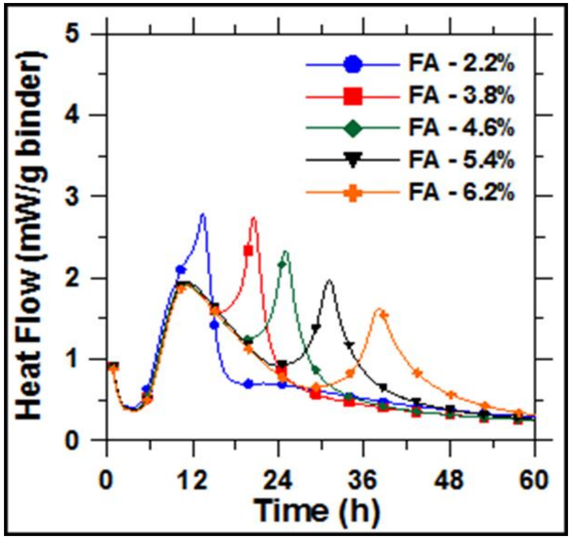
Comment on Pore Solutions

- After sulfate depletion accurately predicted
- ‘linear’ with DOH
- Primary interest in the field applications





Spragg et al. 2012

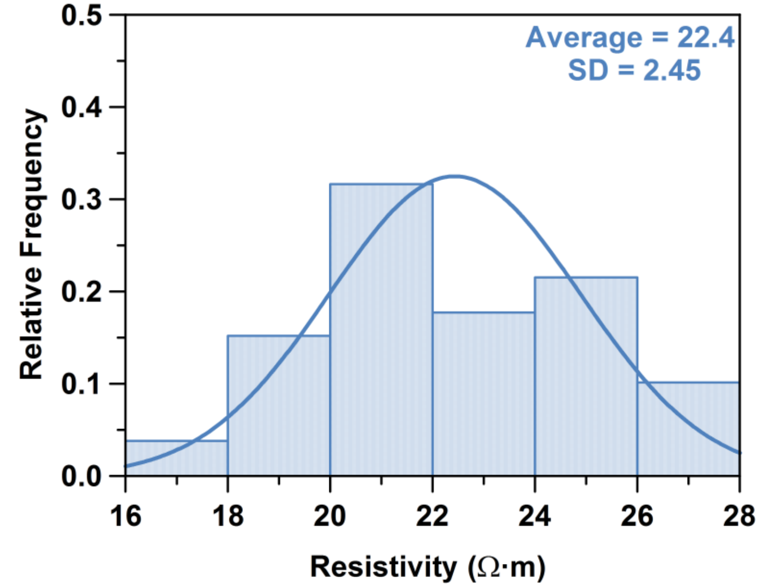


De La Varga et al. 2012

Components of Variation

$$\sigma_{total} = \sqrt{\sigma^2_{machine} + \sigma^2_{operator} + \sigma^2_{material} + \sigma^2_{production} + \sigma^2_{curing}}$$

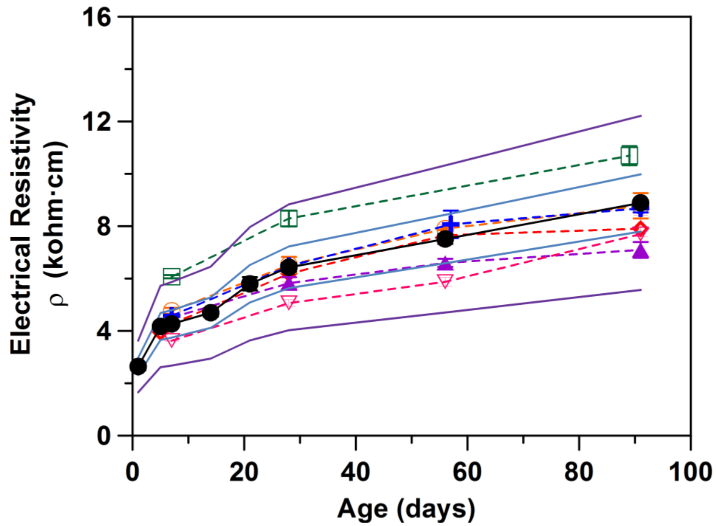
- Machine/Operator/Material
  - Traditionally estimated in a single lab as
  - 3-4% (Purdue, LaDOT)
- Production
  - Important when used as a QC/QA tool
  - Dependent on contractor quality
  - 10% is a typical value

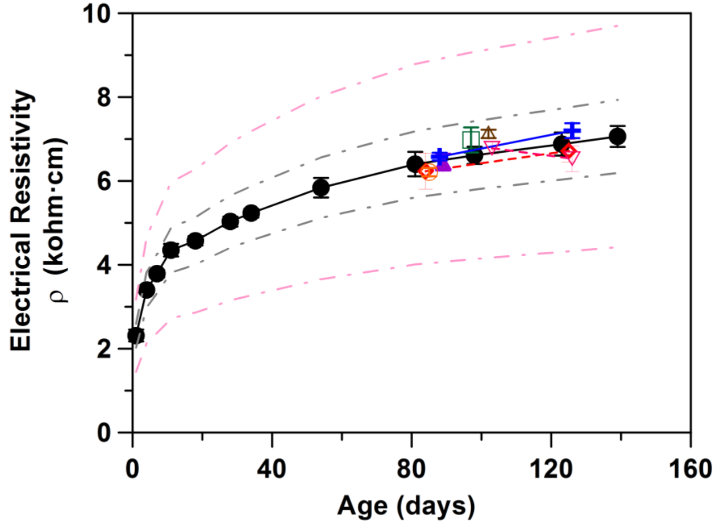


- Data shown is from a central mix plant with one mixture run frequently, low variation

AASHTO Round Robin

- AASHTO RR (12)
- Within-lab: 4.36%
  - Machine/Operator/ Material
- Multi-lab: 13.22%
  - Machine/Operator/ Material and curing
  - Believed Curing Variation: 12.5%
- State Variation Shown (top young, bottom old samples)





Incorporating Aspects of Curing

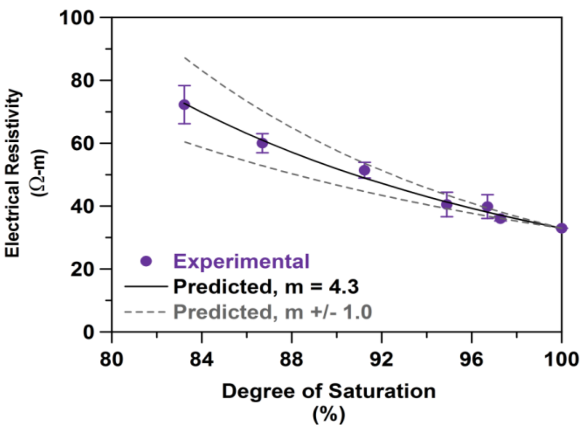
- Spragg developed a program to investigate factors that could influence curing (not discussing temp or RH here that change DOH)

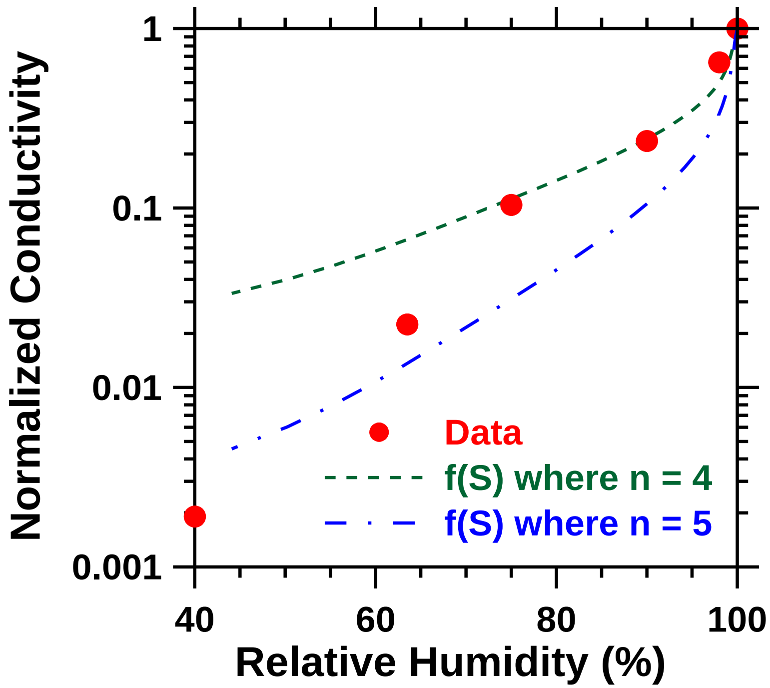
$$\boldsymbol{\rho = \rho_o^* \cdot F \cdot f(S) \cdot f\left(T_{Testing}\right) \cdot f(Leach)}$$

- ρ is the resistivity at an equivalent age $t_{equivalent}$
- ρ_o^*: pore solution resistivity at saturation
- $f(S)$ saturation function
- $f(T_{testing})$ testing temperature correction
- $f(Leach)$ leaching function

Saturation

- Weiss et al. (2012) approach accounted for loss of fluid, concentration of ions, and change in path, expression combines these
- $f(S) = S^m$
  - $m \approx 3 - 5$





$$\rho = \rho_o^* \cdot F \cdot f(S) \cdot f(T_{Testing}) \cdot f(Leach) \; at \; t_{equivalent}$$

Testing Temperature

Introduction

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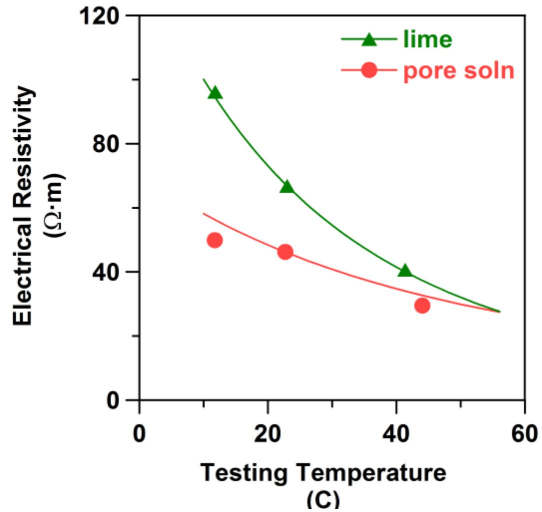
Acc. Curing

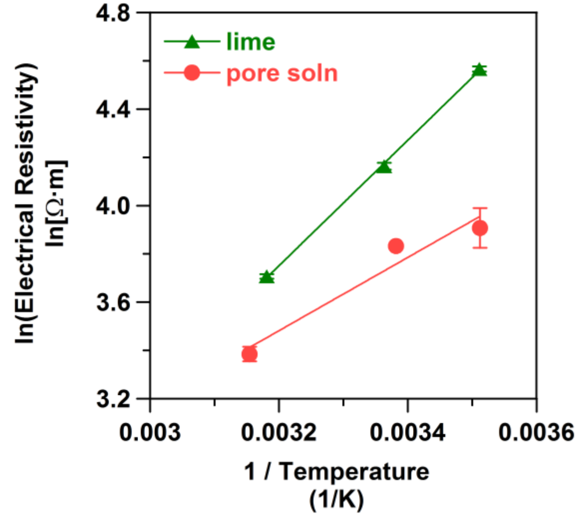
- Activation Energy of Conduction (test temp)

  Rajabipour et al. 2007, Sant et al.2007

$$\frac{\rho_{T_{ref}}}{\rho} = exp\left[\frac{E_{a-con}}{R}\left(\frac{1}{T} - \frac{1}{T_o}\right)\right]$$

- In the past we noticed differences between
- Varied the solutions
  - Pore Solution: 9-12 kJ/mol
  - Bulk Sample: 20-25 kJ/mol

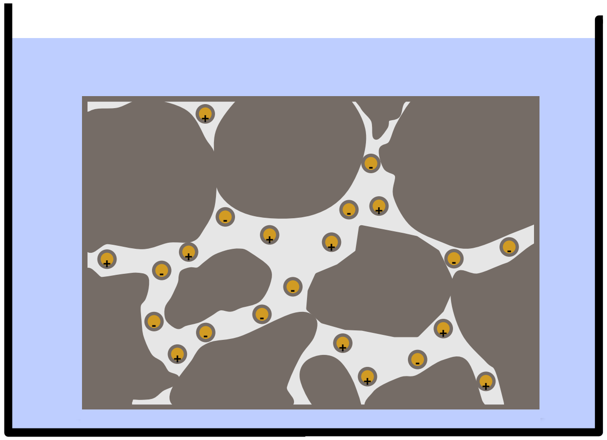


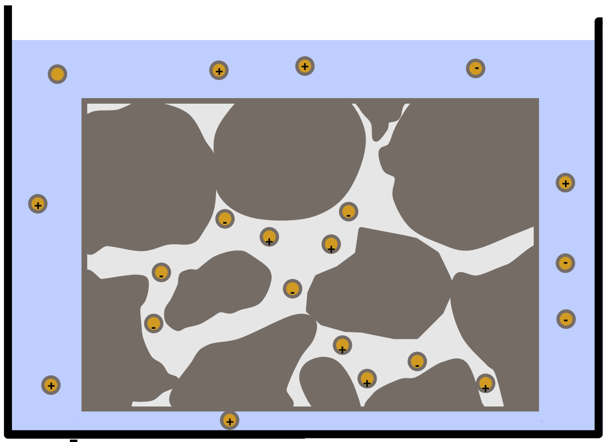


$$\rho = \rho_o^* \cdot F \cdot f(S) \cdot f\left(T_{Testing}\right) \cdot f(Leach)\ at\ t_{equivalent}$$

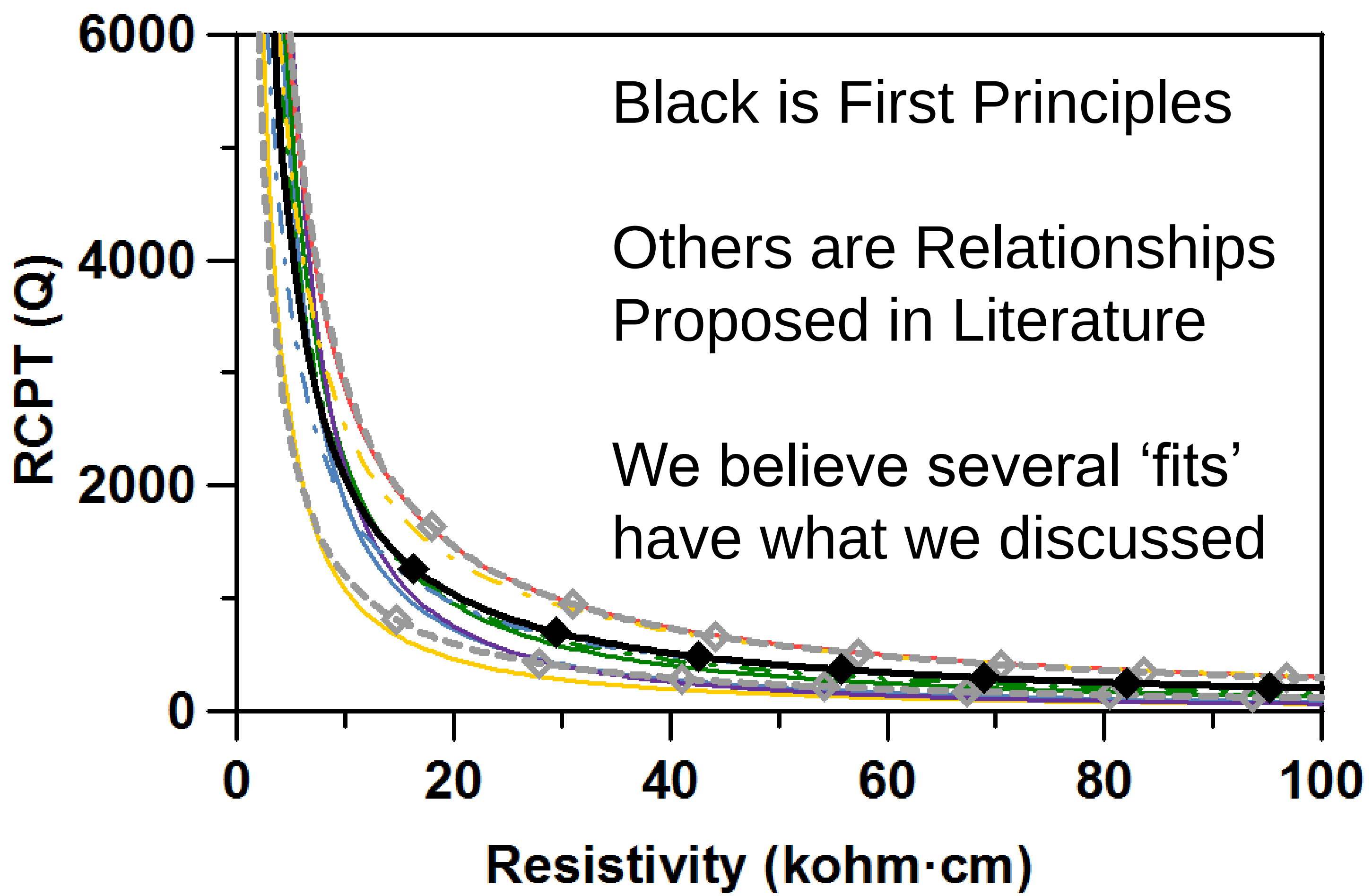
Leaching During Storage

- Many people think of CH leaching
- However we are worried about alkali leaching
- Cement pore solution
  - OH^-, K^+, Na^+
  - $\rho \approx$ 40–100 m ohm·m
- Standard Solution
  - $CaOH_2$ (CH)
  - $\rho \approx$ 1000 milli ohm·m
- Measured storage solution





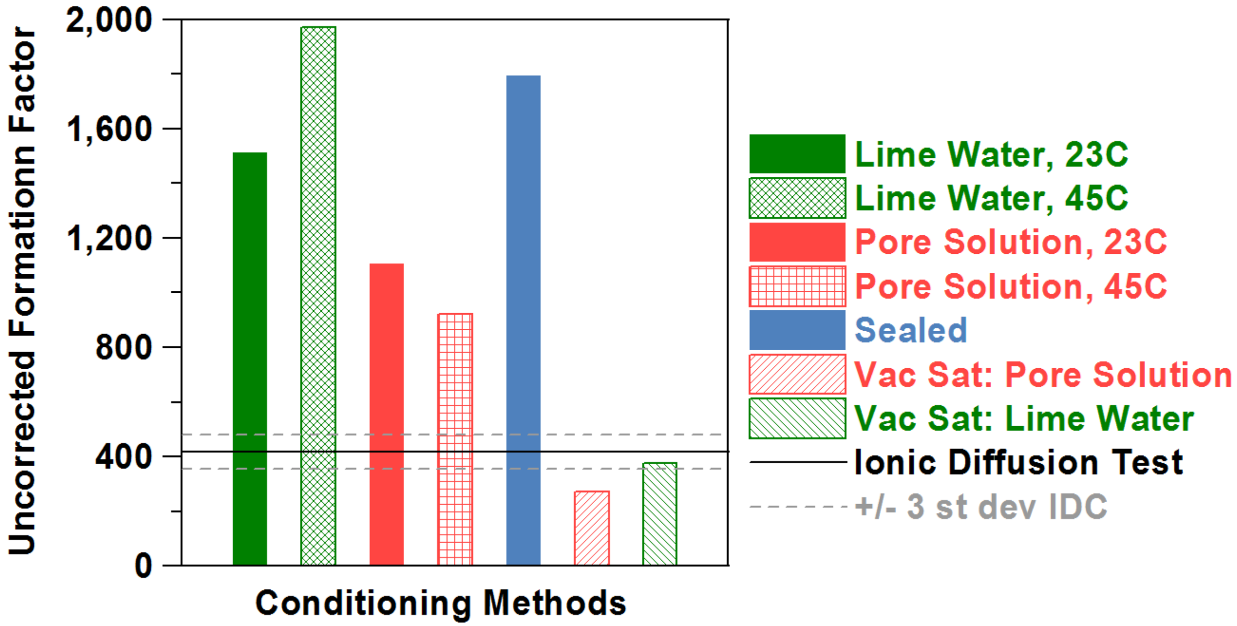
Comparing to Other Tests



Comparing Results With No Correction

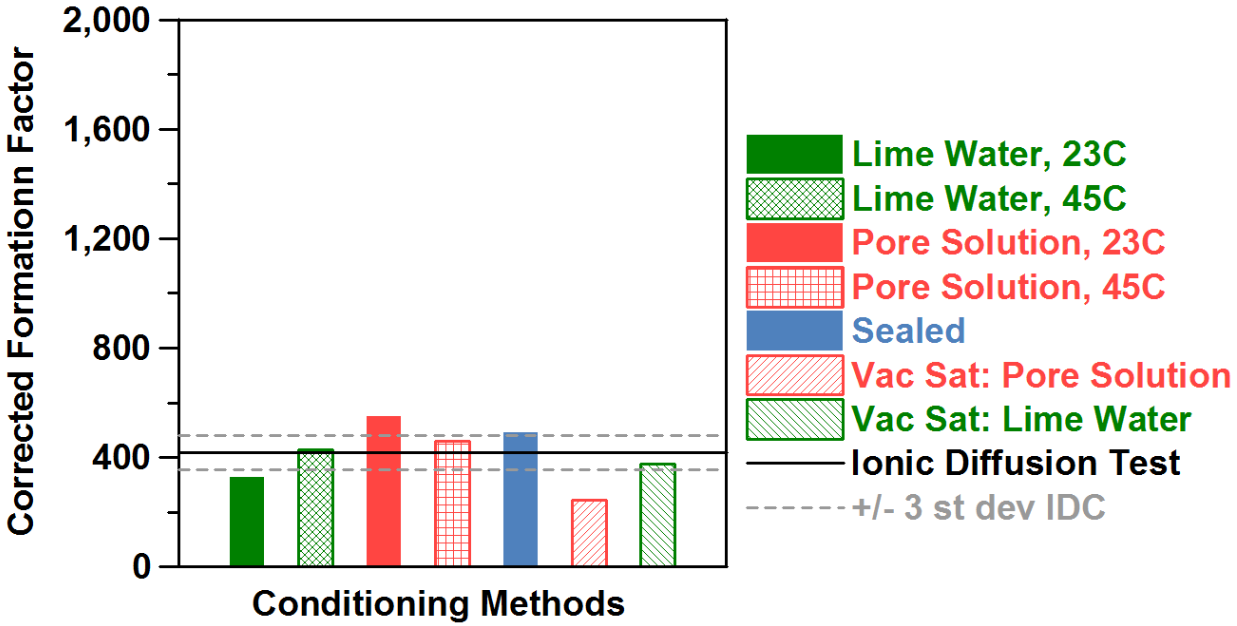
- Introduction
- Testing Basics
- Geometry
- Pore Solution
- Variability
- Curing
- Saturation
- Test Temperature
- Alkali Leaching
- Factors
- Acc. Curing

- $F = 420$
- Only using measurement and pore solution from cement chemistry



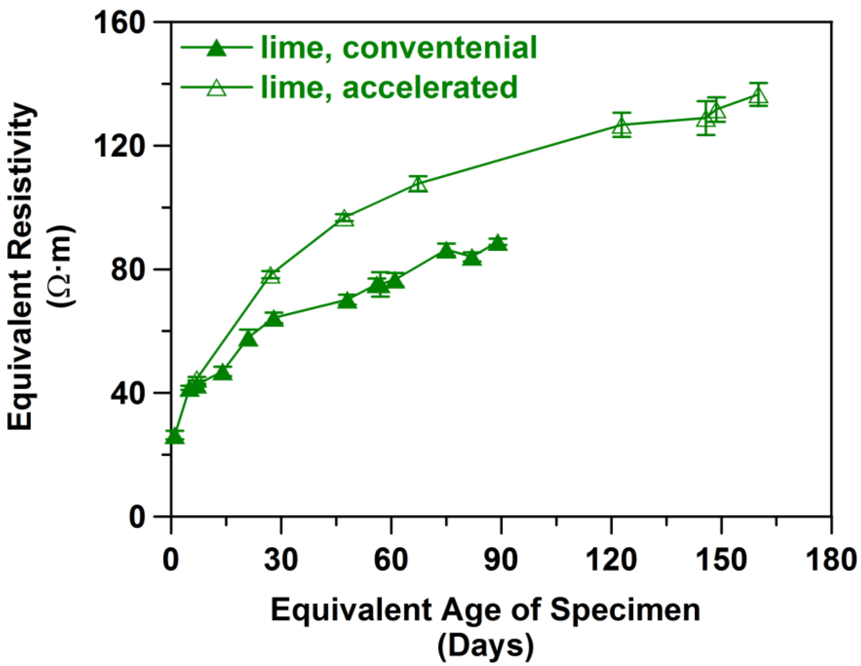
Comparing Results with Corrections

- $F = 420$
- Using corrections discussed here for leaching and saturation



Accelerated Curing Differences Explained with Corrections

- Higher Temperature
  - "Virginia Method/NRMCA" – differences from calendar
  - Lime water
  - 7d@23C, 21d@38C
  - $t_{equivalent}$ of 56 d
  - Accelerated alkali leaching



$$\rho = \rho_o^* \cdot F \cdot f(S) \cdot f(T_{Testing}) \cdot f(Leach) \text{ at } t_{equivalent}$$

Summary

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Factors
Acc. Curing

- Controlling water content and w/c is the first item to control for field testing
- Testing geometry is important and needs to be accounted for (approach shown)
- Variation (test low, curing and storage appears to be part of this)
- Temperature, leaching and saturation all are important when considering sample storage especially for standard tests
- We are looking at 'sealed samples' in a current approach

Applications – Acceptance Phase

Introduction

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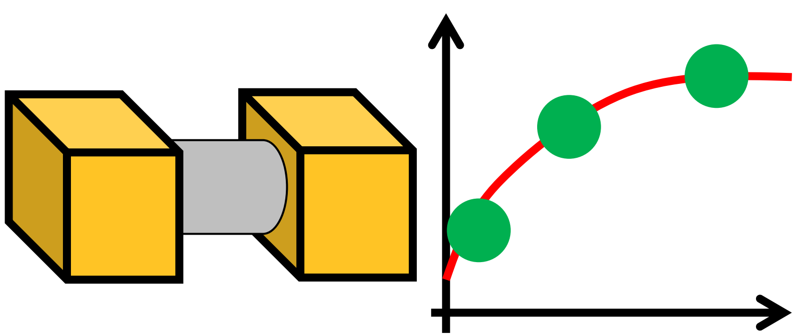
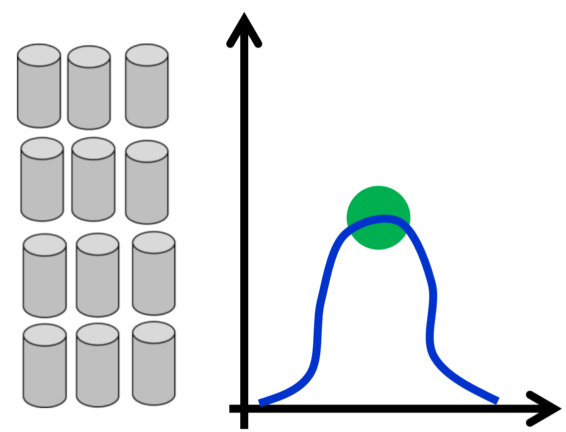
Mixture Acceptance

- Before construction to "qualify mixture"
- Time to corrosion
  - Absolute value of D
- Development of master curve data
  - strength v time
  - resistivity v time



Quality Control

- Measurements during construction
- Test with good repeatability
- Easy tests allow for large sample size, statistical information as well



Applications – Production Phase

Quality Control

- Measurements during construction
- Owner: Is this the same mixture we qualified?
- Producer: Is this the mixture we want to produce?
- Test with good repeatability
- Easy tests allow for large sample size, statistical information as well