Electrical Methods to Characterize and Monitor Concrete

ACI Fall 2013 Convention
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Jason Weiss is a Professor of Civil Engineering and Director of the Pankow Materials Laboratory at Purdue University. He earned a B.A.E. from the Pennsylvania State University and a MS and PhD from Northwestern University in 1999. He is actively involved in research on cement and concrete materials specifically focused on early age property development, cracking, transport in concrete, and concrete durability. Dr. Weiss has taught courses in civil engineering materials, concrete materials, service life, repair and non-destructive testing. His primary research interests are in the area of early age shrinkage cracking and mitigation as well as service life sensing and prediction. Dr. Weiss is a member of the American Concrete Institute (Past Chair of ACI 123), American Society of Civil Engineers, RILEM (Bureau Member, Past TAC member, TC CCD chair), Transportation Research Board (AFN 040 Chair), and American Society for Testing and Materials. He is editor in chief of the RILEM Materials and Structures Journal in 2012 and is an associate editor of the ASCE journal of Civil Engineering Materials and is a member of the editorial board of cement and concrete research. Dr. Weiss has authored over 200 publications with over 95 peer-reviewed journal articles. He is recipient of the NSF Career Award, the RILEM L'Hermite Medal, the ACI W. P. Moore, ACI Young Member, and ACI Wason Awards, the ESCSI Erskine Award, the TRB Burgraff and Mather Awards for outstanding research and publications, and the ASCE Huber Award. He is a fellow of ACI and is also the recipient of the Wansik, Munson, Buck, and Burke awards for outstanding teaching/advising in the school of civil engineering, has received the Potter award for outstanding teaching in the college of engineering, and has been inducted into the Purdue Teaching Academy.

Concrete Resistivity for Concrete Production

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Hockema Professor & Director of the Pankow Materials Laboratory

Objectives of the Session

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

- 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

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- 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

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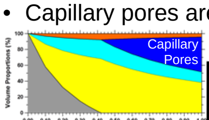
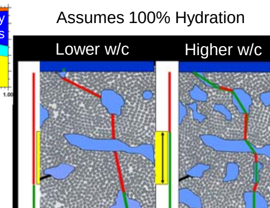
- Transport occurs mainly in capillary pores, there is some transport in the gel pores however we are generally worried about
- Capillary pores are large and connected



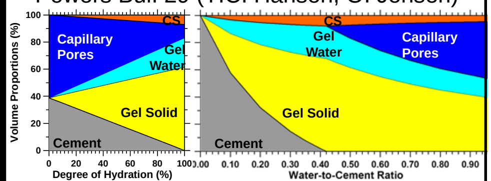
Assumes 100% Hydration



Start with Some Basic Concepts

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

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

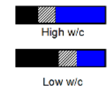


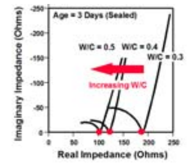
- Porosity is determined by degree of hydration (time, temp, moisture), the water to cement ratio, and the volume of paste

Basic Electrical Results

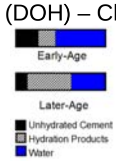
Introduction · Testing Basics · Geometry · Pore Solution · Variability · Curing · Saturation · Test Temperature · Alkali Leaching · Factors · Acc. Curing

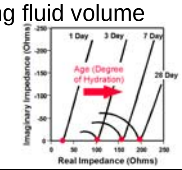
- Varying w/c – Changing fluid volume





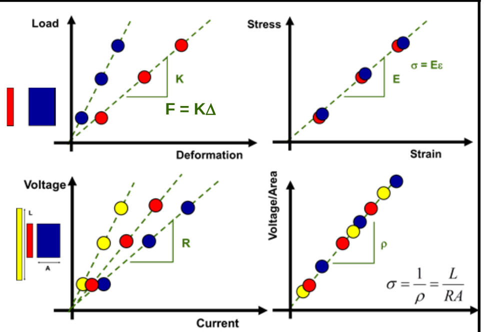
- Varying (DOH) – Changing fluid volume





Results Should be Independent of Geometry or Test Configuration

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



Geometry Factor $\rho = R \cdot k$

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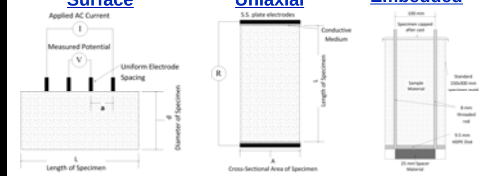
Surface **Uniaxial** **Embedded**



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

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

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

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

$k_{embedded}$ determined experimentally

Morris et al., 1996

Comparison of Different Geometries

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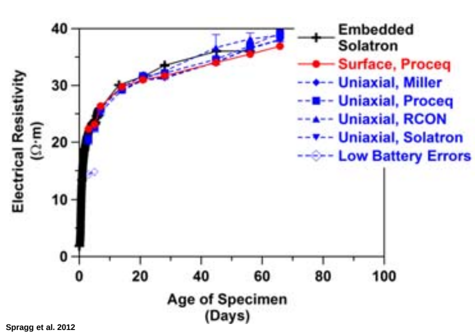

Spragg et al. 2012

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

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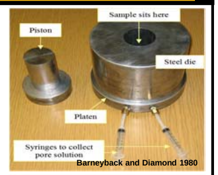
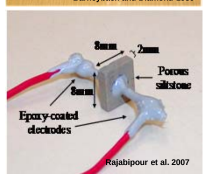
- Extraction
- Theoretical (Website)
- Embedded Sensor





Comment on Pore Solutions

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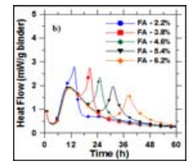
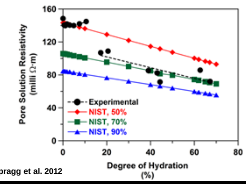
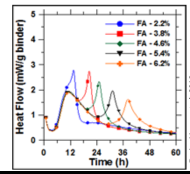
- After sulfate depletion accurately predicted
- 'linear' with DOH
- Primary interest in the field applications







Components of Variation

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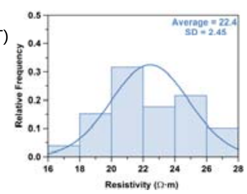
$$\sigma_{total} = \sqrt{\sigma^2_{machine} + \sigma^2_{operator} + \sigma^2_{material} + \sigma^2_{production} + \sigma^2_{curing}}$$

- 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

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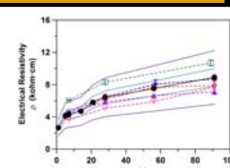
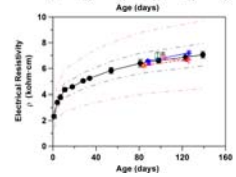
- AASHTO RR (12)
- Within-lab: 4.36%
  - Machine/Operator/ Material
- Multi-lab: 13.22%
  - Machine/Operator/ Material and curing
  - Believed Curing Variation: 12.5%
- State Variation Shown (top young, bottom old samples)





Incorporating Aspects of Curing

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

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

- 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

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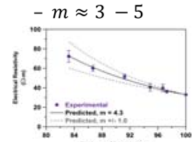
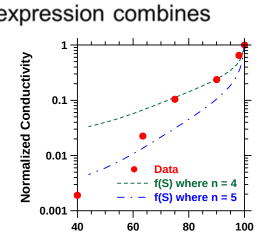
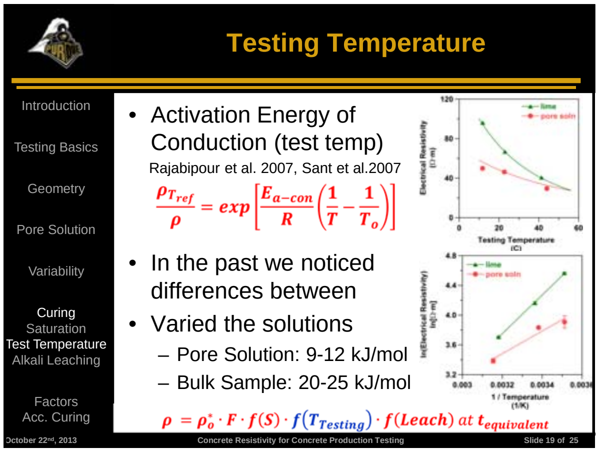
- Weiss et al. (2012) approach accounted for loss of fluid, concentration of ions, and change in path, expression combines these
- $f(S) = S^m$
  - $m \approx 3 - 5$





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


Testing Temperature
Introduction
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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
$\rho = \rho_o^* \cdot F \cdot f(S) \cdot f(T_{Testing}) \cdot f(Leach)$ at $t_{equivalent}$
Testing Temperature (C)
1 / Temperature (1/K)
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Concrete Resistivity for Concrete Production Testing
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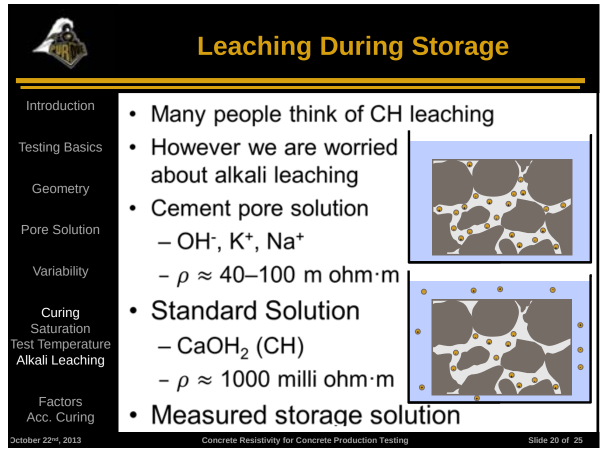
Leaching During Storage
Introduction
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Many people think of CH leaching
However we are worried about alkali leaching
Cement pore solution
– OH^-, K^+, Na^+
– $\rho \approx$ 40–100 m ohm·m
Standard Solution
– $CaOH_2$ (CH)
– $\rho \approx$ 1000 milli ohm·m
Measured storage solution
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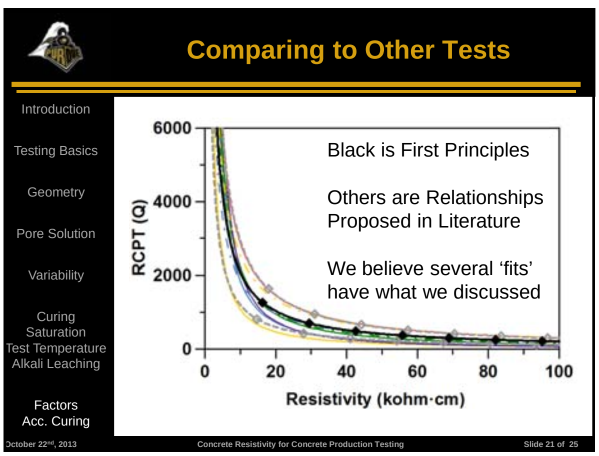
Comparing to Other Tests
Introduction
Testing Basics
Geometry
Pore Solution
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Black is First Principles
Others are Relationships Proposed in Literature
We believe several 'fits' have what we discussed
RCPT (Q)
Resistivity (kohm·cm)
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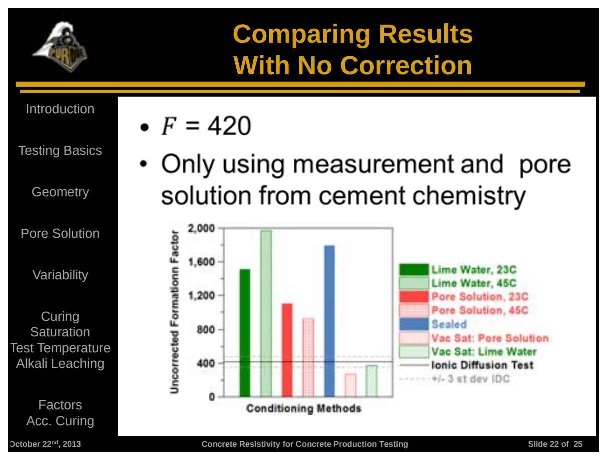
Comparing Results With No Correction
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F = 420
Only using measurement and pore solution from cement chemistry
Uncorrected Formationn Factor
Conditioning Methods
Lime Water, 23C
Lime Water, 45C
Pore Solution, 23C
Pore Solution, 45C
Sealed
Vac Sat: Pore Solution
Vac Sat: Lime Water
Ionic Diffusion Test
+/- 3 st dev IDC
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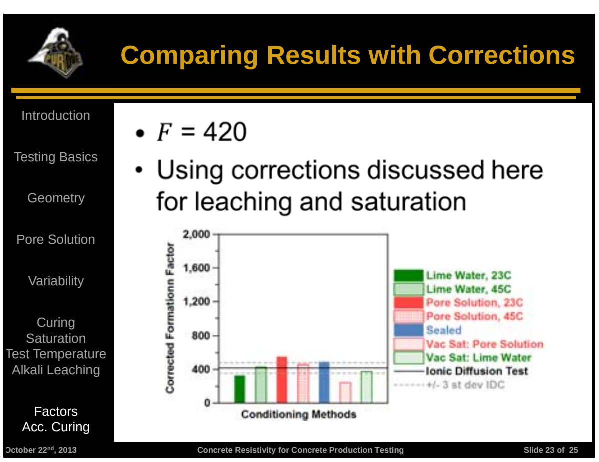
Comparing Results with Corrections
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Factors
Acc. Curing
F = 420
Using corrections discussed here for leaching and saturation
Corrected Formationn Factor
Conditioning Methods
Lime Water, 23C
Lime Water, 45C
Pore Solution, 23C
Pore Solution, 45C
Sealed
Vac Sat: Pore Solution
Vac Sat: Lime Water
Ionic Diffusion Test
+/- 3 st dev IDC
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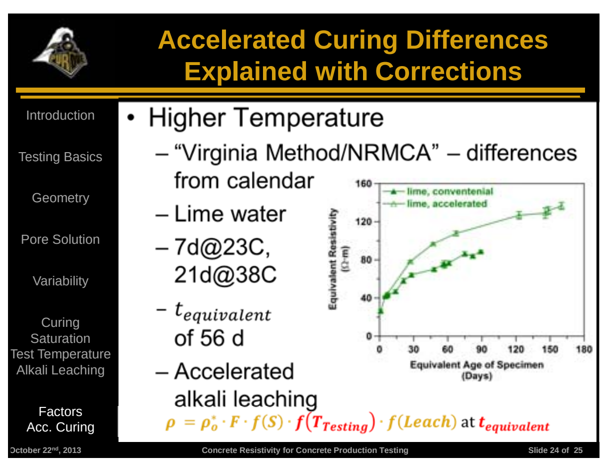
Accelerated Curing Differences Explained with Corrections
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Higher Temperature
– "Virginia Method/NRMCA" – differences from calendar
– Lime water
– 7d@23C, 21d@38C
– $t_{equivalent}$ of 56 d
– Accelerated alkali leaching
lime, conventenial
lime, accelerated
Equivalent Resistivity (Ω·m)
Equivalent Age of Specimen (Days)
$\rho = \rho_o^* \cdot F \cdot f(S) \cdot f(T_{Testing}) \cdot f(Leach)$ at $t_{equivalent}$
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Concrete Resistivity for Concrete Production Testing
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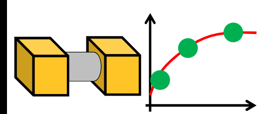
Summary

- 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

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