



American Concrete Institute®
Advancing concrete knowledge

Performance-Based Specifications and Testing Part 1

ACI Spring 2011 Convention
April 3 - 7, Tampa, FL

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ACI Web Sessions

The audio for this web session will begin momentarily and will play in its entirety along with the slides.

However, if you wish to skip to the next speaker, use the scroll bar at left to locate the speaker's first slide (indicated by the icon in the bottom right corner of slides 10 and 35). Click on the thumbnail for the slide to begin the audio for that portion of the presentation.

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ACI is bringing you this Web Session in keeping with its motto of "Advancing Concrete Knowledge." The ideas expressed, however, are those of the speakers and do not necessarily reflect the views of ACI or its committees.

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ACI Web Sessions are recorded at ACI conventions and other concrete industry events. At regular intervals, a new set of presentations can be viewed on ACI's website free of charge.


After one week, the presentations will be temporarily archived on the ACI website or made part of ACI's Online CEU Program, depending on their content.

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ACI Online CEU Program

ACI offers an easy-to-use Online CEU Program for anyone who needs to earn Continuing Education credits.

Once registered, you can download and study reference material. After passing a 10-question exam on the material, you will receive a certificate of completion that you can present to local licensing agencies.



Visit www.concrete.org/education/edu_online_CEU.htm for more information.

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ACI Conventions

ACI conventions provide a forum for networking, learning the latest in concrete technology and practices, renewing old friendships, and making new ones. At each of ACI's two annual conventions, technical and educational committees meet to develop the standards, reports, and other documents necessary to keep abreast of the ever-changing world of concrete technology.

With over 1,300 delegates attending each convention, there is ample opportunity to meet and talk individually with some of the most prominent persons in the field of concrete technology. For more information about ACI conventions, visit www.aciconvention.org.

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Fall 2011 Seminars

These seminars, cosponsored by ACI and the Portland Cement Association (PCA), will cover all the major changes in the new edition of the **318-11 Building Code**.

DATE	LOCATION	DATE	LOCATION
September 13	Chicago, IL	November 3	Charlotte, NC
September 27	Philadelphia, PA	November 8	Boston, MA
September 29	Houston, TX	November 10	Detroit, MI
October 4	Seattle, WA	November 15	Des Moines, IA
October 6	Los Angeles, CA	November 17	Portland, OR
October 11	New York, NY	November 29	Denver, CO
October 13	Minneapolis, MN	December 1	Phoenix, AZ
October 20	Cincinnati, OH	December 6	Atlanta, GA
October 25	New Brunswick, NJ	December 8	Washington, DC
October 27	St. Louis, MO	December 13	Dallas, TX
November 1	Orlando, FL	December 15	San Francisco, CA

For more information, visit [ACI seminars](#).

ACI Web Sessions

This ACI Web Session includes 2 speakers presenting at the ACI spring convention held in Tampa, FL April 3 – 7, 2011. Additional presentations will be made available in future ACI Web Sessions.


Please enjoy the presentations.




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Advancing concrete knowledge

Performance-Based Specifications and Testing Part 1

ACI Spring 2011 Convention
April 3 - 7, Tampa, FL



Alireza Akhavan, Ph.D. Candidate, Civil and Environmental Engineering, Pennsylvania State University. Mr. Akhavan has earned a Master of Science degree in structural engineering and a Bachelor of Science degree in civil engineering from Gilan University. During this time he had worked on the behavior of anchor bolts with nuts in concrete experimentally and numerically and the influence of concrete strength on the anchorage capacity. Currently during his Ph.D. Mr. Akhavan is working on effect of cracking on concrete permeability as a function of crack geometry.




Civil and Environmental Engineering
The Pennsylvania State University

Measuring Water Permeability and Ion Diffusivity of Cracks in Concrete

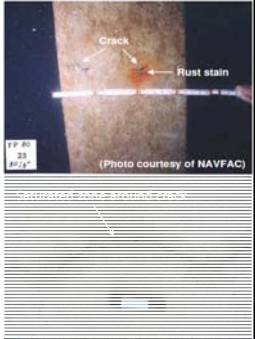
By:
Alireza Akhavan, Farshad Rajabipour

Presented at:
ACI Spring Convention
April, 2011, Tampa, FL



Why are cracks a concern?

- Corrosion (by accelerating transport)
- Leaks (basement walls, nuclear containment vessels, etc.)
- Freeze/thaw (due to enhanced saturation)
- Existing service-life models do not account for cracks



(Photo courtesy of NAVFAC)

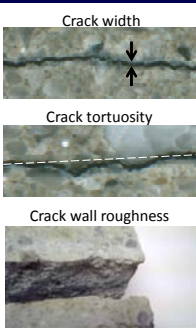
Objective: To quantify Transport Properties as a function of Crack Geometry

Transport Properties

- Saturated Water Permeability
- Saturated Ion Diffusivity

Crack Geometry

- Crack width
- Crack tortuosity
- Crack wall roughness



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Experiments

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Mortar disks cracked by indirect tension
LVDTs used to monitor horizontal displacement



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Electrical impedance spectroscopy (EIS) was used to measure crack diffusivity

- Crack was saturated with synthetic pore solution

$$\sigma_{Composite} = \sigma_{Matrix} \phi_{Matrix} \beta_{Matrix} + \sigma_{Crack} \phi_{Crack} \beta_{Crack}$$

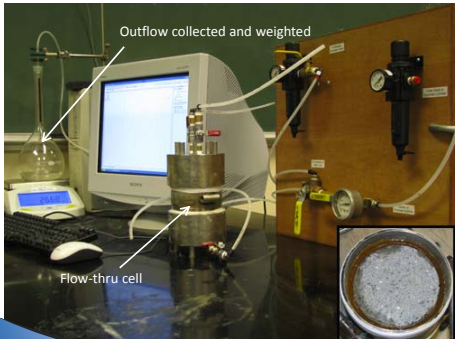
$$D_{Composite} = D_{Matrix} \phi_{Matrix} \beta_{Matrix} + D_{Crack} \phi_{Crack} \beta_{Crack}$$

σ : Electrical Conductivity (S/m)
 D : Diffusion Coefficient (m²/s)
 ϕ : Volume fraction (-)
 β : Connectivity factor (-)



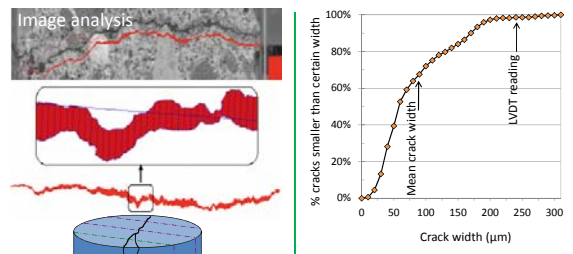
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Saturated permeability measured using a flow-thru cell (10psi)



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Image analysis was used to quantify crack geometry



Crack profile quantified on top, bot. faces, and at 3 vertical cross sections

- LVDT reading is not representative of average crack width

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Effective crack width determined based on combination of Darcy's and Parallel Plate theories

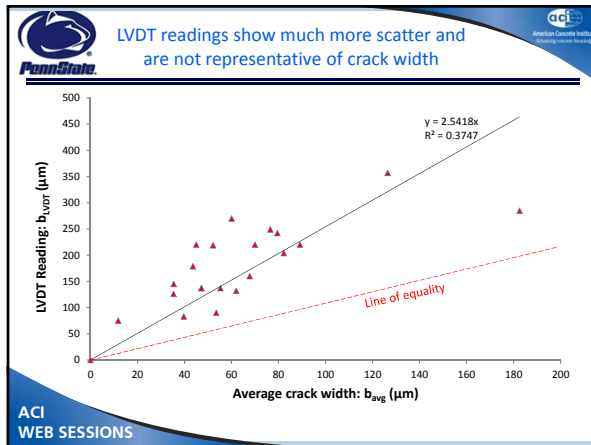
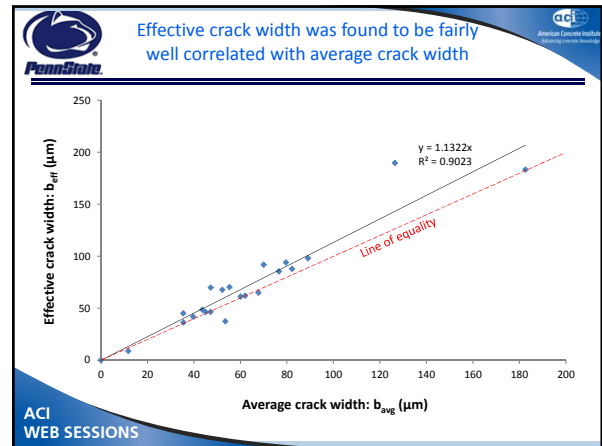
Natural single fracture → Local parallel plates → Parallel plates

Fracture aperture b

For flow in y-direction:

$$b_{eff} = \sqrt[3]{\frac{n}{\sum_{i=1}^n \left(\frac{1}{b_{ij}^3}\right)}}$$

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Theory: Permeability inside Smooth Parallel Plate Gap

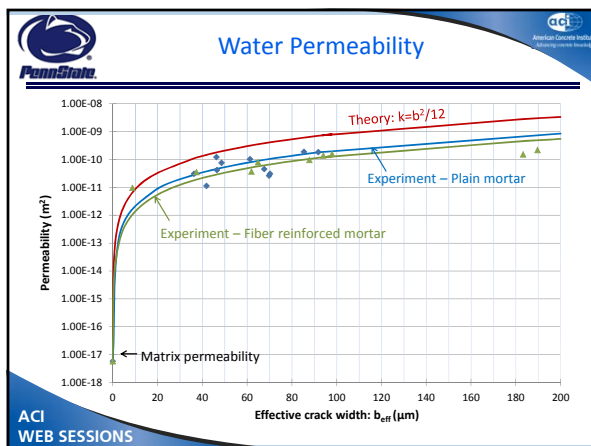
$V(z) = \frac{1}{2\eta} \left(\frac{\Delta P}{\Delta x}\right) (H^2 - z^2)$

$Q = \int_{-H}^{+H} V(z) dz = \frac{\kappa A}{\eta} \left(\frac{\Delta P}{\Delta x}\right)$

$\kappa = \frac{b^2}{12}$

- Permeability is a function of crack width square

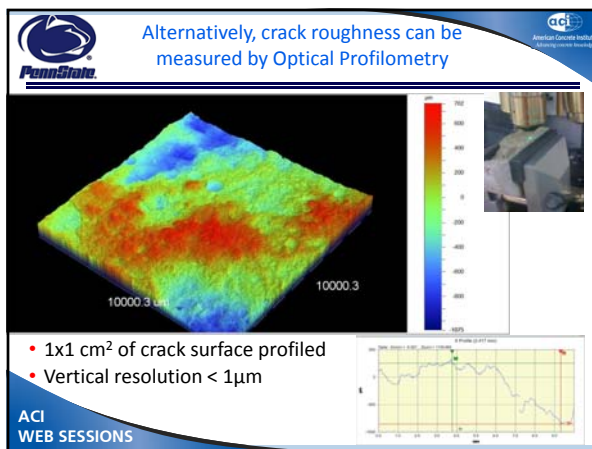
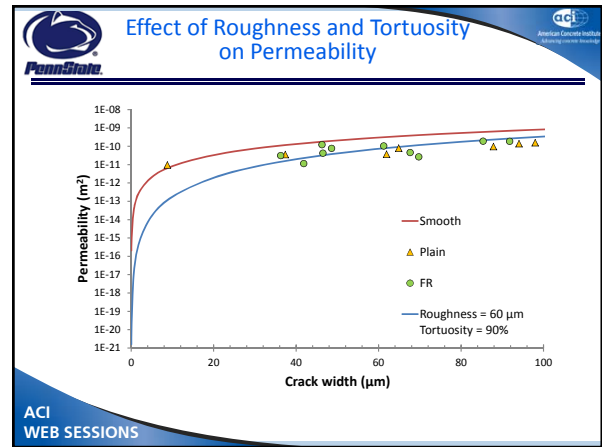
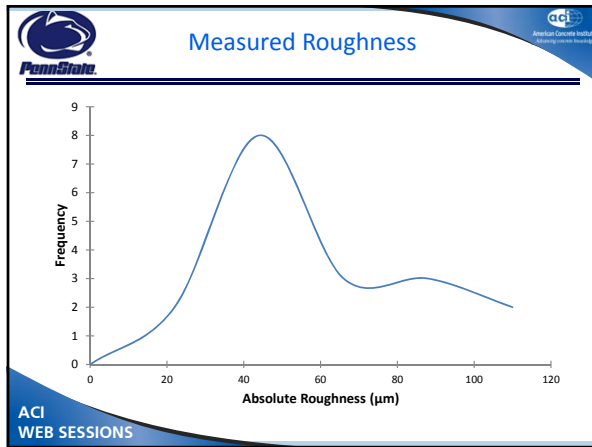
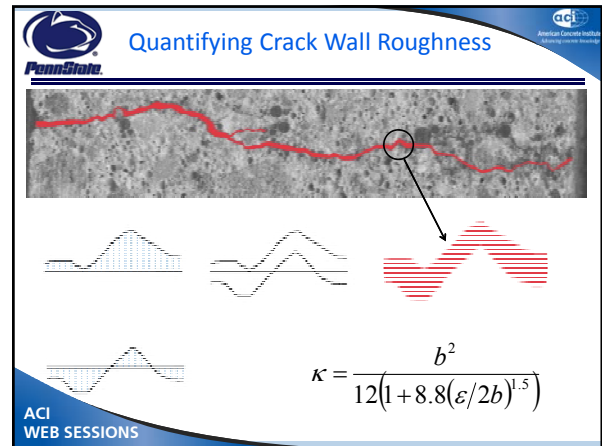
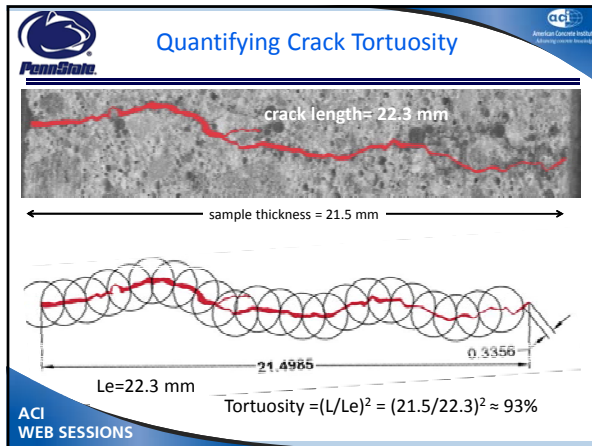
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Water Permeability – Observations

- Crack permeability is a function of crack width square
- The results of experimental measurements of permeability are smaller than values predicted by the parallel plate theory by a factor of 4~5
- Why?
 - Crack tortuosity
 - Crack wall roughness
 - Fibers

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Results:

Crack Diffusion Coefficient

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Determination of Crack Diffusion Coefficient

- Modified parallel law:

$$D_{Composite} = D_{Matrix} \phi_{Matrix} \beta_{Matrix} + D_{Crack} \phi_{Crack} \beta_{Crack}$$
- Since $\beta_{Matrix} \approx \beta_{Crack} \approx 1$ and $D_{Crack} \approx D_o$ (ion diffusivity in bulk water) and $\phi_{Crack} + \phi_{Matrix} = 1$ and finally by combining the Nernst-Einstein Eq.:

$$\frac{\sigma_{Matrix}}{\sigma_o} = \frac{D_{Matrix}}{D_o}$$

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Theory suggests that $D_{Composite}$ is a linear function of ϕ_{Crack}

$$\frac{D_{Composite}}{D_o} = \phi_{Crack} \left(1 - \frac{\sigma_{Matrix}}{\sigma_o} \right) + \frac{\sigma_{Matrix}}{\sigma_o} = \frac{\sigma_{Composite}}{\sigma_o}$$

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Theory suggests that $D_{Composite}$ is a linear function of ϕ_{Crack}

$$\frac{D_{Composite}}{D_o} = \phi_{Crack} \left(1 - \frac{\sigma_{Matrix}}{\sigma_o} \right) + \frac{\sigma_{Matrix}}{\sigma_o} = \frac{\sigma_{Composite}}{\sigma_o}$$

- Theory and experiments generally agree although test data shows some scatter
- Diffusion coefficient of cracked concrete is a linear function of volume fraction of cracks
- Diffusivity of saturated crack is similar to bulk solution
- The effect of crack width seems to be less significant
- Further testing is needed to verify these observations

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Conclusions

- Permeability is primarily a function of crack width square
- Roughness of crack wall can reduce permeability by 30 to 80 percent
- Crack tortuosity was found to be low: $(L/Le)^2=93\%$
- Diffusion coefficient of cracked concrete is primarily a function of volume fraction of cracks
- Either effective or average crack width can be used to estimate transport properties (LVDT reading are not representative)

Thank You

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Jason Weiss, Professor of Civil Engineering and Director of the Pankow Materials Laboratory. He is actively involved in research on cement and concrete materials. He earned a B.A.E. from the Pennsylvania State University and a MS and Ph.D. from Northwestern University in 1999. He is a member of the American Concrete Institute, American Society of Civil Engineers, RILEM, Transportation Research Board, American Society for Testing and Materials, and is an associate editor of the ASCE journal of Civil Engineering Materials and the RILEM journal Materials and Structures. He has been involved in research on concrete for 15 years. Dr. Weiss has authored over 200 publications with over 70 peer-reviewed journal articles or book chapters and over 100 peer-reviewed conference proceedings. He is recipient of the NSF Career Award, the RILEM L'Hermite Medal, the ACI W. P. Moore and ACI Wason Awards, the ESCSI Erskine Award, and the TRB Burgraff and Mather Awards for outstanding research and publications. He is a fellow of ACI and is also the recipient of seven awards for outstanding teaching.

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Purdue University

Toward a Rapid QC/QA Test for Transport – Electrical Properties


Robert Spragg,
Javier Castro,
Chiara Villani,
Amir Poursaee,
Tommy Nantung,
Jason Weiss

wjweiss@purdue.edu

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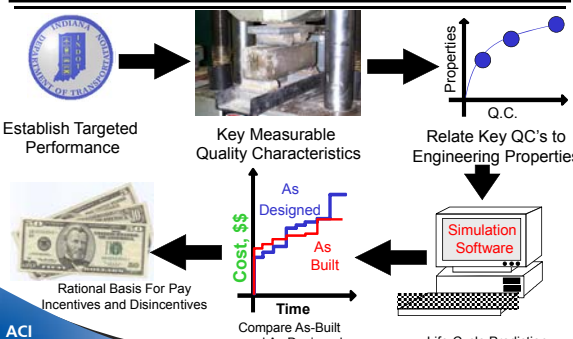
Motivation for the Study

- Historically concrete has been specified and placed using prescriptive specifications
- States and agencies have begun the shift from prescriptive specifications to end result or performance based specifications.



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A PRS Example – INDOT 2000



Establish Targeted Performance → Key Measurable Quality Characteristics → Relate Key QC's to Engineering Properties → Simulation Software → Life-Cycle Prediction → Compare As-Built and As Designed → Rational Basis For Pay Incentives and Disincentives

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Application of A PRS

Final PRS Conducted in I-465 East Side of Indianapolis

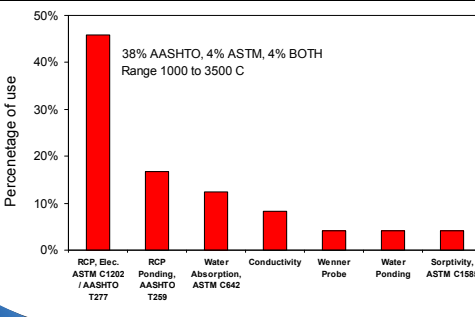
Project Specific Design Acceptance Quality Characteristics

AQC Value	Target Mean	Target Standard Deviation	Rejectable Quality Limit (ROL)	Maximum Quality Limit (MQL)
Strength	665 psi	50 psi	<570 psi	760 psi
Thickness	14 in	0.5 in	<13 in	15 in
Smoothness	7 in/mile	3 in/mile	>10 in/mile	5 in/mile

- Though several states have experimented with performance specifications, this has been slowed by a lack of testing procedures, especially as they relate to transport

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Transport Tests in Use by DOTs




Test Method	Percentage of Use
RCP, Elec. ASTM C1202 / AASHTO T277	38%
RCP Ponding, AASHTO T259	4%
Water Absorption, ASTM C642	4%
Conductivity	~10%
Wenner Probe	~5%
Water Ponding	~5%
Sortivity, ASTM C1585	~5%

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Review Tests Available, First Principles, Cost, Data

- For Each Test – Review Stimulus-Response
- Scientific principle
- Cost
- Time
- Conditioning Samples
- Accuracy
- Data Obtained
- Permeability (Gas, Fluid), Absorption (Fluid), Electrical Analogies
- Advantages and Disadvantages

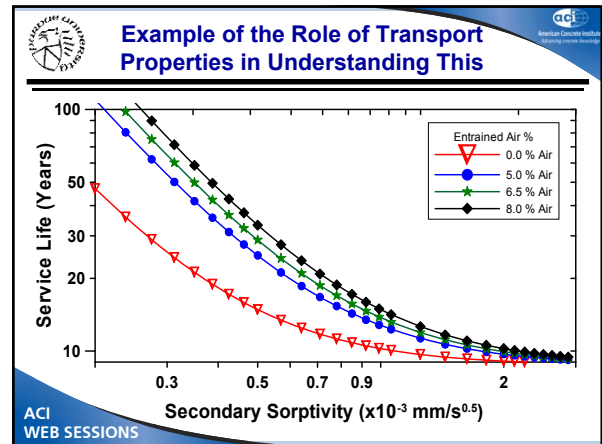
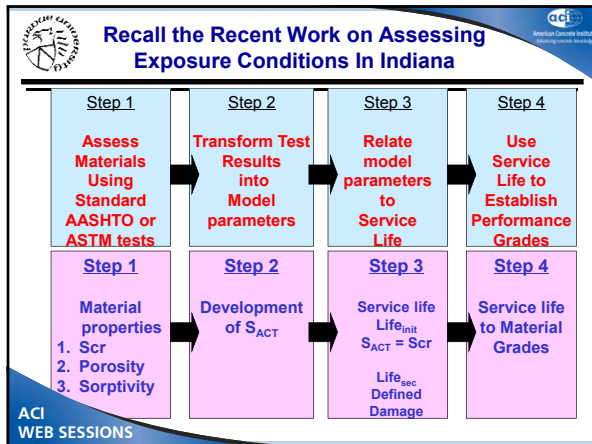


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Example Review

Test method	Lab method	In-situ method	Duration	Simplicity*	Basic concept	Limitations	Commercially available price
Gas permeability							
Standard method	X	X	28 min	2	Vacuum the surface	Sensitive to the moisture condition	No
Surface Air Flow Test (SAF)	X	X	-	2	Vacuum the surface	Sensitive to the moisture condition	No
American	X	X	30 min	1	Surface pressure	Sensitive to the RH-80%	Yes • Ampcon NDT Ltd C200.ampcon.com
Turner Permeability Test	X	X	20 min	1	Free chloride vacuum cell	Merely permeable coefficient, sensitive to the moisture condition	Yes • Mueser Data.amsel.com • Phoenix Data.phoenix.com
TRB method (Bridgman-Miles) test	X	X	60 min	2	Drying a hole, anchoring nitrogen gas		No
Ring Porosity method	X	X	60 min + 1 day	2	Drying a hole, anchoring permeation air		No
Gravimetric Gas Permeation Test (ASTM 1900)	X	X	40 min	3	Drying a hole, anchoring CO ₂ gas	Sensitive to the moisture condition	Yes • Concrete Instruments Data.concreteinstruments.com
Constant method	X		Five hours	2	pressure permeation of the test gas between the two surfaces		No

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The Overarching Goal

- Much like Indiana Jones we seem to be on the impossible search for the "holy grail"
- We want a test for transport that is fast, accurate, inexpensive easy to interpret
- We think that electrical measurements can be a significant part of this approach

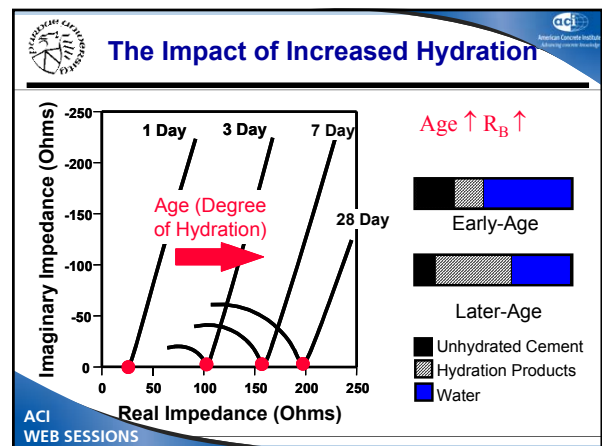
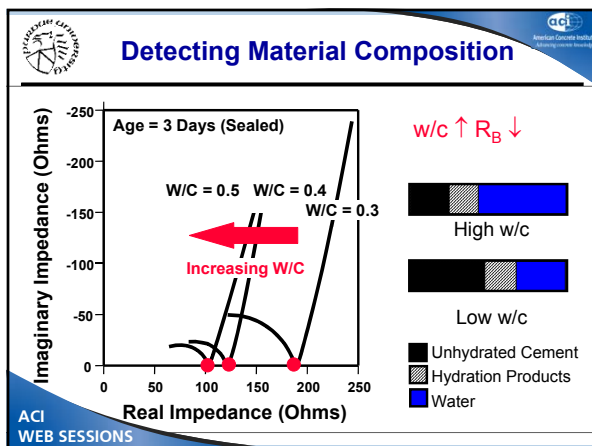
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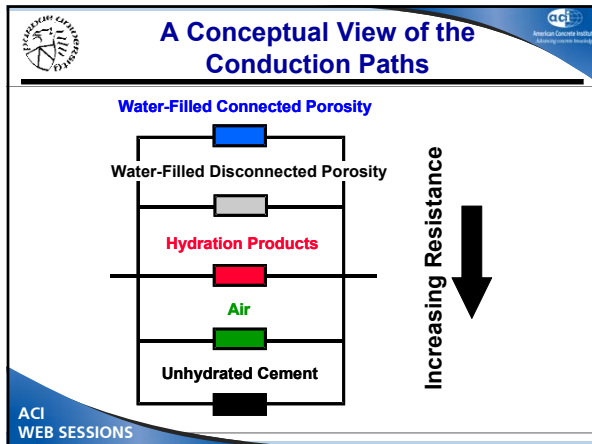
Electrical Methods Hold Promise

- Generally applied to electrical circuits
- "The current between two points is directly proportional to the potential difference (voltage drop or voltage) across two points and inversely proportional to the resistance between them"

$$V = IR$$

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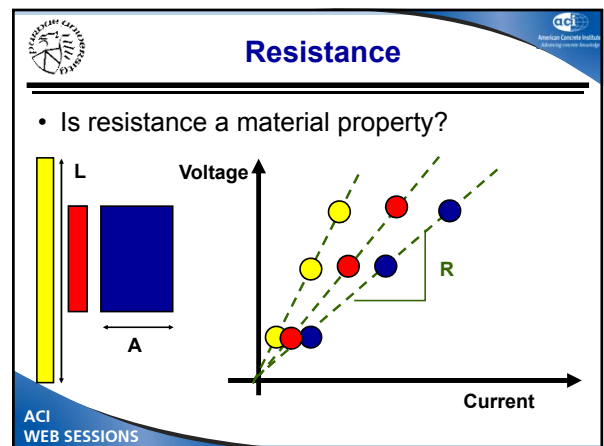
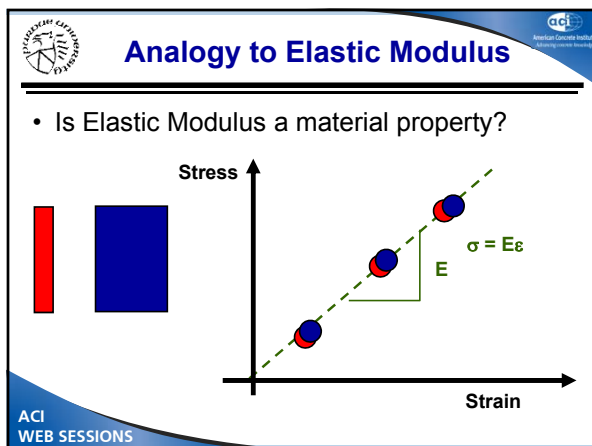
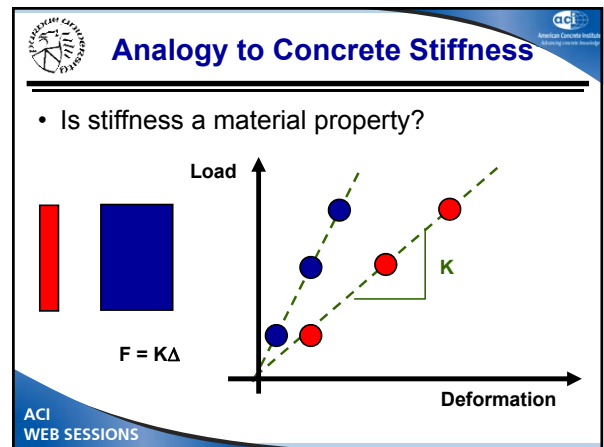
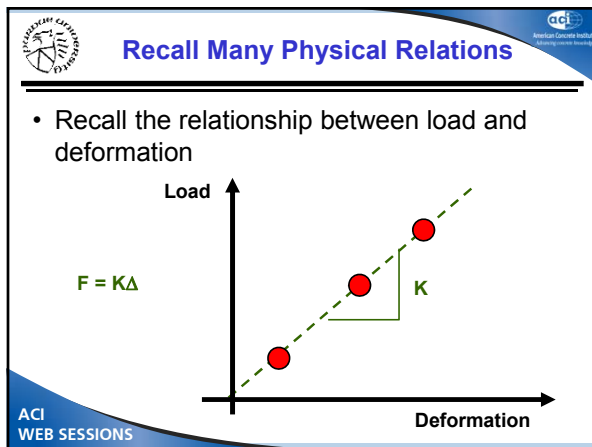




Main Points to Consider With Electrical Methods

- 1 – Requires properties that are independent of geometry
- 2 – Can this be related to a simple model that can describe the main features of the material
- 3 – How is this influenced by model inputs
- 4 – can we say something about all the electrical tests out there – if so very powerful

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Resistivity and Conductivity

$$\frac{RA}{L} = \rho \quad \sigma = \frac{1}{\rho} = \frac{L}{RA}$$

- Copper 1.68×10^{-8} ohm m
- Carbon $3 (60) \times 10^{-5}$ ohm m
- Glass $1 (10000) \times 10^9$ ohm m

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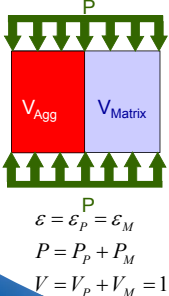
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An Analogy with Mechanics



Recalling the composite model for elastic modulus

$$E = E_M V_M + E_P V_P$$

We can write something similar for conductivity




$$\sigma = \sigma_M V_M + \sigma_P V_P$$

$\epsilon = \epsilon_P = \epsilon_M$
 $P = P_P + P_M$
 $V = V_P + V_M = 1$

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Composite Conductivity Models Single Conductive Phase

Second group: consider volume fractions and phase geometries

NAME	FORMULA	MICROSTRUCTURE
Modified Parallel	$\sigma_t = \sigma_o \phi_o \beta_o$	
Archie's	$\sigma_t = \sigma_o \phi_o^{m_s}$	Sedimentary Rocks
Maxwell	$\sigma_t = \sigma_o \left[\frac{(d-1)\phi_o}{d-\phi_o} \right]$	
DEM	$\sigma_t = \sigma_o \phi_o^{d/(d-1)}$	
Self-Consistent (SC)	$\sigma_t = \sigma_o \left[\frac{d\phi_o - 1}{d-1} \right]$	

• d describes spatial dimension not phase geometries
 • But, it has been used empirically to describe phase geometries

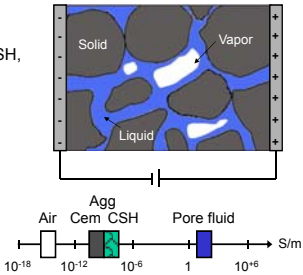
(McLachlan et al. 1990, Torquato 2002)

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Mechanism of Electrical Conduction

Concrete is a composite:

- Solid phase (unhyd Cement, CSH, CH,...); $\sigma_{sol} \approx 10^{-9}$ S/m (Rajabipour 2006 based on results of Hammond and Robson 1955)
- Liquid phase (pore solution); $\sigma_{liq} \approx 1$ S/m to 20 S/m (Christensen 1993)
- Vapor phase (air voids, emptied pores); $\sigma_{vap} \approx 10^{-15}$ S/m (Aplin 2005)



Flow of electricity is essentially ionic and through material's liquid phase

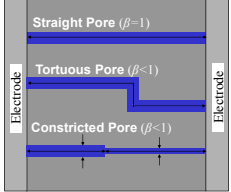
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Modified Parallel Law to Model Concrete Conductivity

- Considers pore fluid as the only conductive phase in concrete
- Pore fluid can be in capillary or gel pores or in aggregate pores

$$\sigma_t = \sigma_o \phi \beta$$

σ_t : concrete conductivity (S/m)
 σ_o : pore solution conductivity (S/m)
 ϕ : liquid volume fraction
 β : avg. liquid connectivity (describes liquid tortuosity and constrictedness)



(Garboczi 1990, Christensen et al. 1994, Rajabipour 2006)

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Migration vs. Diffusion

- Electrical conduction is essentially the same process as ion diffusion with a different driving force
- Conductivity obeys similar formulas as diffusivity

$$\sigma_{bulk} = \phi\beta\sigma_{pore} \quad D_{bulk} = \phi\beta D_{pore}$$


Nernst – Einstein equation:

$$\frac{\sigma_{bulk}}{\sigma_{pore}} = \frac{D_{bulk}}{D_{pore}}$$

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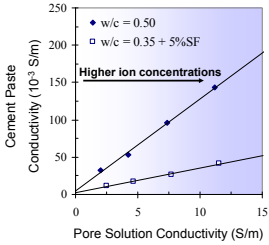
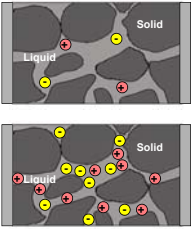
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What Parameters Affect Conductivity?

$$\sigma_t = \sigma_o \phi \beta$$

(Rajabipour and Weiss 2007)

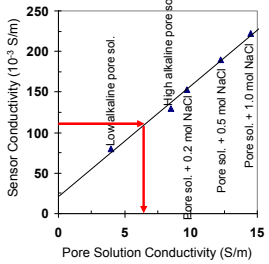
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Conductivity of Aqueous Solutions

$$\sigma_o = \sum_i z_i c_i \lambda_i$$

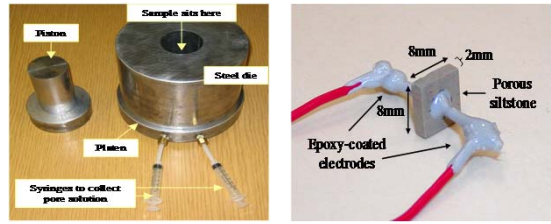
$$\sigma_t = \sigma_o \phi \beta$$

- σ : electrical conductivity (S/m)
- Z_i : ion valence (unitless)
- C_i : ion concentration (mol/m³)
- λ_i : ion equivalent conductivity (m²S/mol) – describes ion mobility



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The σ_o Sensor Pore Solution Conductivity Measurement



For porous siltstone:

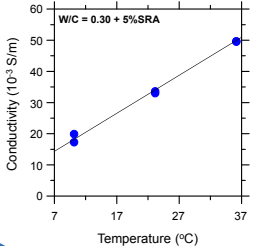
$$\sigma_t = \sigma_o \phi \beta$$

Stone conductivity ← Stone microstructural property (known and constant) → Pore solution conductivity

(Rajabipour and Weiss 2007)

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How is this Influenced by Temperature



- High Temperature: High mobility, fast ions High conductivity
- Low Temperature: Low mobility, slow ions Low conductivity

$$\sigma(T) = A e^{\left(\frac{-E_a}{RT}\right)}$$

- Higher temperature → higher conductivity

(Rajabipour 2006, Sant et al. 2008)

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How is this Influenced by Drying

Conductivity (10^{-3} S/m)

Moisture content (%)

— $w/c = 0.50$
— $w/c = 0.35 + 5\%SF$

Saturated
Drying

Liquid
Vapor

$\sigma_t = \sigma_o \phi \beta$

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Main Points to Consider With Electrical Methods

- 1 – Requires properties that are independent of geometry
- 2 – Can this be related to a simple model that can describe the main features of the material
- 3 – How is this influenced by model inputs
- 4 – can we say something about all the electrical tests out there – if so very powerful

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Direct, Embedded, RCPT and the Wenner Probe

$\frac{RA}{L} = \rho$

$\rho = \frac{2\pi V}{I}$

Conductivity vs Time

3.0% NiCl₂ / 0.3 M NiCl₂ / Concrete / Copper Mesh Electrodes / Epoxy Coating

To - Lead / To + Lead

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Geometry Factor

- Recall the need for a geometry factor
- 4 x 8 cylinder; $a = 1.5$ in
- $L/a = 8/1.5 = 5.26$ $d/a = 4/1.5 = 2.63$

$K = \frac{\rho_{app}}{\rho}$

L/a

$d/a = 1.75, 2, 2.5, 3, 4, 6$

$K = 1.9057$

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Comparing Wenner and the Direct Method

- Corrected Wenner test (Y-axis) with the direct measured resistivity (X-axis)
- Correction factor $K = 1.91$ from literature (4x8, 1.5)
- Direct approach is less sensitive to surface issues

Effective Surface Resistivity ($K\Omega\text{-cm}$)

$\rho_{eff} = \rho_{app} / K$

COV Direct typically less than Wenner

Direct Resistivity ($K\Omega\text{-cm}$), ρ_{direct}

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RCPT vs Resistivity


- Calculations can be done
- Empirical relationship (temperature effects are not considered for RCPT)
- Wenner/Direct ~ 1 minute per sample

RCPT	Current	Voltage	Resistance	Resistivity	Conductivity	4 x 8 Apparent Resistivity	4 x 8 Kessler Empirical
Coulombs	Amps	V	K-Ohms	kOhm-cm	S/cm	kOhm-cm	kOhm-cm
6000	0.278	60	0.22	3.5	285.7	6.7	4.7
5000	0.231	60	0.26	4.2	238.1	8.0	5.4
4000	0.185	60	0.32	5.3	190.4	10.0	6.5
3000	0.139	60	0.43	7.0	142.8	13.3	8.2
2000	0.093	60	0.65	10.5	95.2	20.0	11.5
1000	0.046	60	1.30	21.0	47.6	40.0	20.3
500	0.023	60	2.59	42.0	23.8	80.1	35.7
100	0.005	60	12.96	210.0	4.8	400.3	133.5

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Summary

- Provided background for PRS
- Electrical methods hold promise
- Simple Modified Parallel law
- Drying, Hydration, Geometry, Pore solution changes, Temperature
- All electrical methods lead to one conclusion
- We really want a fast method that is not sensitive to other factors – current aim



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Questions

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