DOT's Need for an Improved Test Method and Examples of Implementation of Surface Resistivity

Resistivity Measurements in Concrete
April 13, 2016

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Louisiana Transportation Research Center

Outline

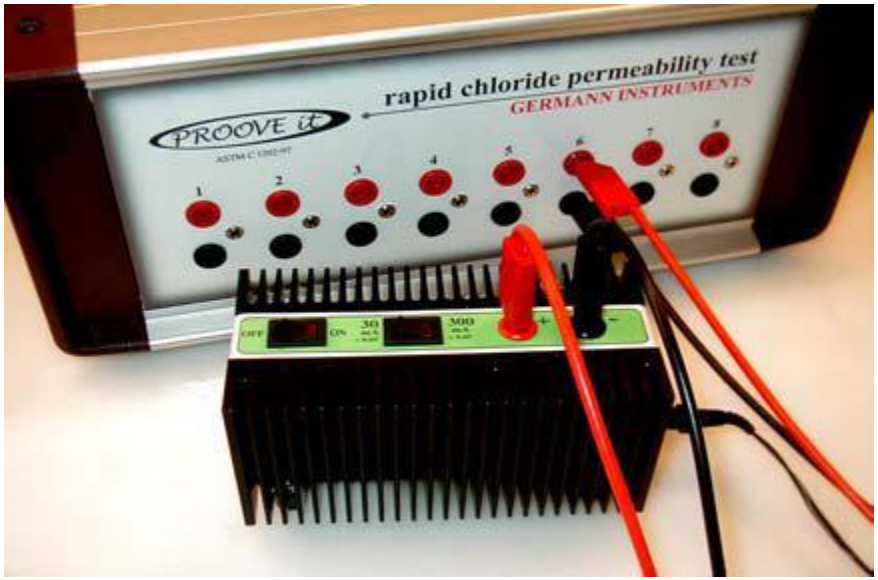
- Background
- Need for a new (or at least improved) test method
- DOT's state of the practice
- Implementation efforts

Background

- Permeability specifications abound
- ASTM C 1202 most widely accepted test
- ASTM C 642 as an alternative
- Surface resistivity

Background

- ASTM C 1202
  - "Quick"
  - 2 days of 'testing'
  - Mostly sample preparation
  - Expensive



Background

- Wenner Probe
  - Much quicker
  - Less expensive
  - Shorted curing time
  - Non-destructive
  - Bulk or surface resistivity

Why the Need?

- Grandpa's concrete does not cut it anymore
- Different construction strategies
  - Get in, get out, stay out is preferred
  - Do more with less. . .
- Different winter maintenance strategies
  - New and more aggressive deicer solutions
- Ever shrinking budgets
  - Construction and maintenance

DOT State of Practice

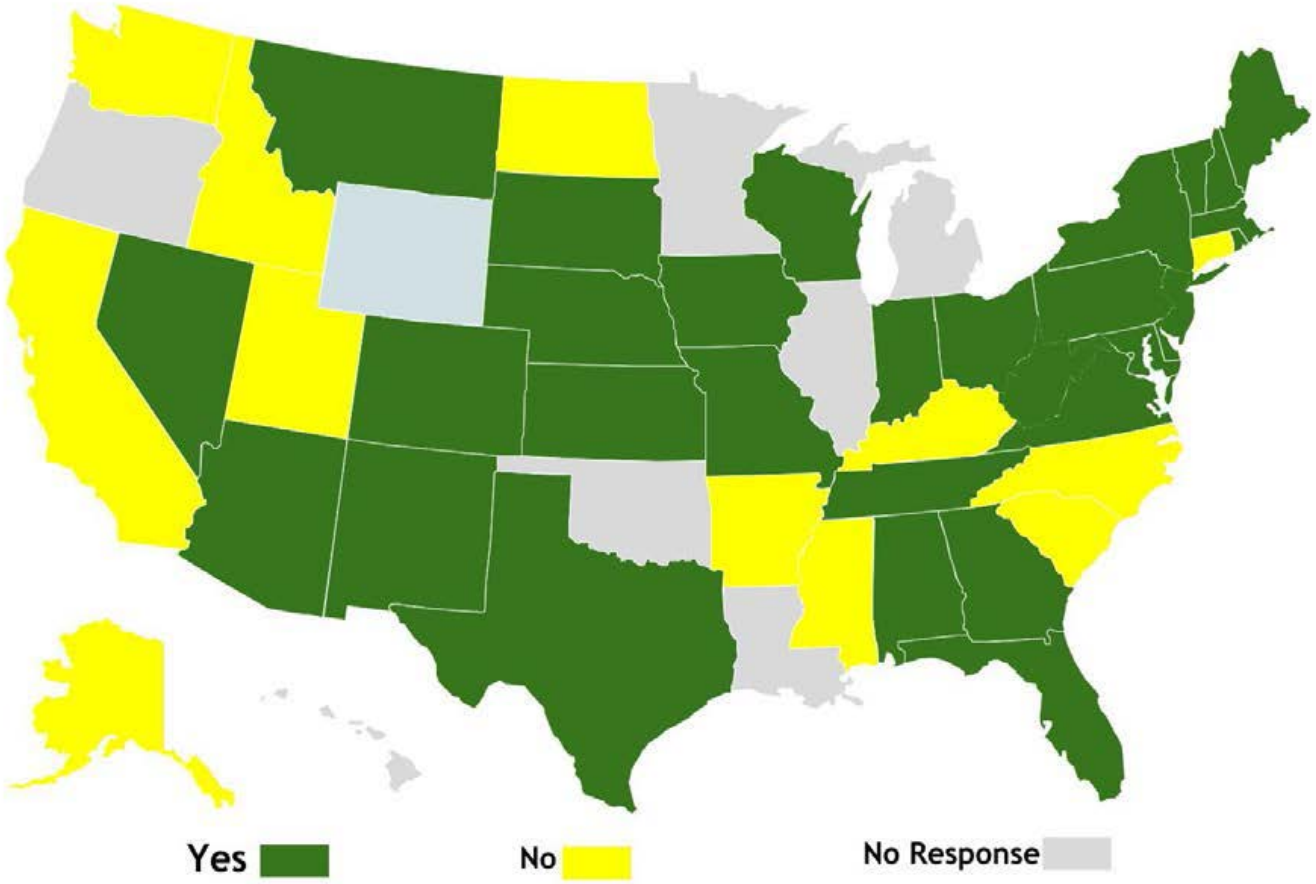
- Three major options
  - Measure permeability
    - Boil, RCP, or now resistivity
  - Specify mixture proportions
    - Generally specify a HPC for structural concrete
    - Could require the use of pozzolans
  - Bury the head in the sand
    - Believe they do not have a problem
    - Belief exists that it is too expensive

DOT State of Practice

- NCHRP Project 20-07 Task 331
  - Report on the methods and standards to measure the permeability of concrete
- Survey of state practices

DOT State of Practice

Evaluates Permeability



DOT State of Practice

- 30+ states evaluate permeability
  - 90+ % of those states utilize ion permeability in the form of RCP, boil, or salt ponding
  - Additionally 50% of those states are either moving to or using surface or bulk resistivity

Typical Permeability Classes

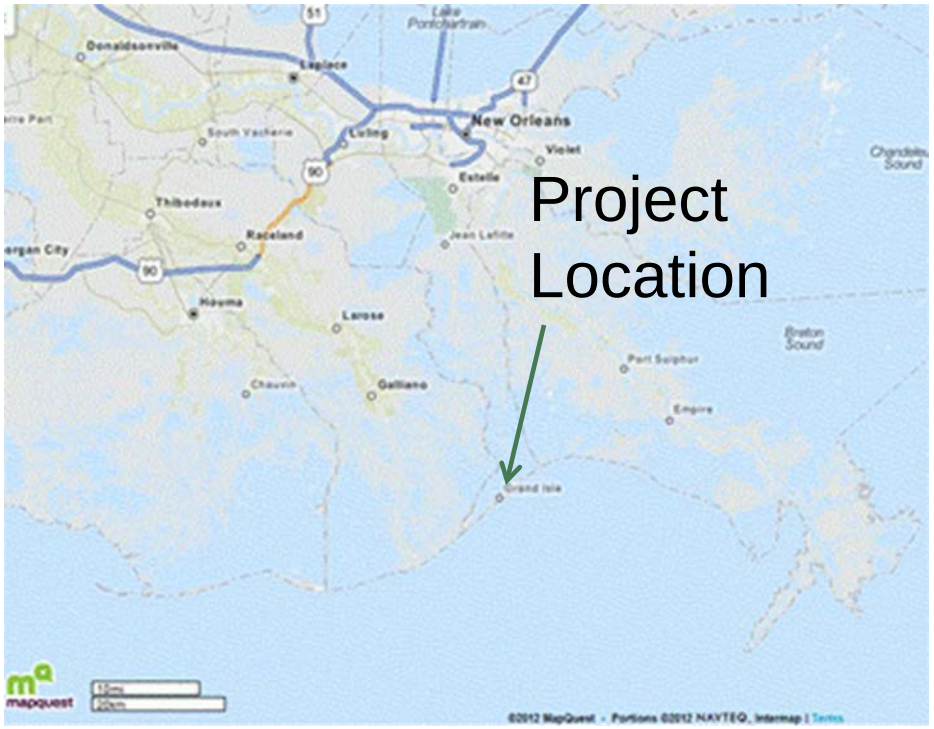
Table 1 Chloride Ion Penetrability Based on Charge Passed	
Chloride Ion Penetrability	Charge Passed (coulombs)
High	>4,000
Moderate	2,000 - 4,000
Low	1,000 - 2,000
Very Low	100 - 1,000
Negligible	<100

Table 2 Surface Resistivity - Permeability	
Chloride Ion Permeability	Surface Resistivity Test kΩ-cm
High	< 12
Moderate	12 - 21
Low	21 - 37
Very Low	37 - 254
Negligible	> 254

Implementation Efforts

- Florida, Kansas
  - Mix design approval
- Louisiana
  - Mix design approval, QA/QC, pay item
- Missouri, Iowa, Michigan, Wisconsin, Minnesota, Ohio, Indiana, South Dakota, Texas, Pennsylvania, Nebraska, Virginia, and many others

Implementation Project



Project Specifics

- 7 hour round trip from job location to LTRC
- Three month duration
  - 1 trip per week
- Total number of test lots for 3 months was 42

Savings Realized?

- Time savings
  - $117 per week for a total of $1,400
- Mileage savings
  - @$0.50 per mile and about 140 miles saved per week
    - $70 per week for a total of $840
- Testing costs
  - ASTM C1202 - $8,402
  - DOTD TR233 - $332
  - Savings - $7,711
- **TOTAL SAVINGS = $9,951**

More Savings!

- Saved about $10,000 in first project implementation efforts
  - About $40,000 per year or $160,000 for the life of the project
- Using an average of 50 structures under construction per year by LADOTD @ a conservative savings of $20,000 per year
  - DOTD will save about $1,000,000 in operational costs per year
- Does not include savings from increased service life!

Implementation Effort Fast-Tracked

- DOTD TR 233 was developed
- 1 day training session to educate LADOTD personnel
  - Included a video and a performance exam

Implementation Lessons Learned

- Expect the savings to grow exponentially when bridge design shifts to permeability requirements for all structures
- Expect the savings for Contractor QC to be equal to or greater than DOTD Operational savings
- Led to a change in future specifications for structures
  - 27 kΩ-cm (4 x 8 in. sample @ 28-days of age)

Summary

- DOT's resources are strained
- Need for a new or improved method to measure earlier with more precision
- Public is more aware of costs, and less tolerant of closures, repairs, etc.

Summary

- Bulk or surface resistivity can meet the DOT needs if implemented properly
- Generally the savings in personnel time will offset the cost of the equipment
- Savings over the life of the structure considerably increase the cost to benefit ratio
- Fully implemented in several states

Acknowledgements

- FHWA
- LADOTD and LTRC
- Randy Young, Shane Laws, Matt Tircuit
- Scott Reech, Benjamin Shearer, Jacob Newgard, Anthony Saladino, Brandon Pitre, and Brennon Hughes, Katie Johnson
- Mike Ricca
- NCHRP Assistance
  - Cecil Jones, Laura McCauley, Ed Harrigan

Further Information

- Training Video Link
  - http://www.ltrc.lsu.edu/videotraining/Resistivity/Resistivity.swf
- TR Procedure Link
  - http://www.dotd.la.gov/highways/construction/lab/testproc/tr_233_final.pdf

Surface Resistivity Standard Test Method Development

TRB Webinar
April 13, 2016

Kenneth A. Snyder
Materials and Structural Systems Division
National Institute of Standards and Technology

Concrete Surface Resistivity:

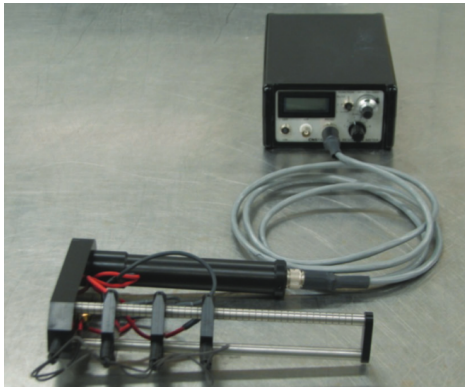
Objectives: “understand the…”

- … difference between Resistance & Resistivity
- … difference between surface and bulk concrete measurements
- … minimum information needed to conduct a resistivity measurement
- … factors affecting an accurate resistivity measurements
- … requirements of commercial surface resistivity test equipment
- … status of the ASTM method under development

Surface vs. Bulk Resistivity Test Equipment

Surface Resistivity (Ken):

Four evenly-spaced electrodes on the curved surface of a concrete cylinder



Bulk Resistivity (Doug):

Platens on the flat ends of the cylinder

Resistance vs. Resistivity

Resistance: (Extrinsic Property)

- Ratio of voltage (V) to current (I) passing through an object
- Depends on the shape and size of the “resistor”
- Depends upon the geometry of the electrodes applying the voltage

Resistivity: (Intrinsic Property)

- Independent of shape and size of the specimen
- Independent of the electrode geometry - IMPORTANT!
- A given specimen has only one resistivity, regardless of the electrode geometry

Analogous to mass (extrinsic) vs. density (intrinsic)

“Measuring” Resistivity:

Practical Limitations:

- You can’t directly measure resistivity
- You can only measure RESISTANCE (V/I)

But Wait!:

- … if the resistance I measure depends on the shape/size of the specimen,
- … if the resistance I measure depends on the geometry of the electrodes,
- I could get many different resistance values from the same sample!
- Why don’t I get multiple resistivity values from the same sample?

You measure RESISTANCE, you calculate RESISTIVITY

Converting Resistance to Resistivity

Geometry Conversion Factor:

R: resistance [Ohm]
ρ: resistivity [Ohm Length]
β: geometry conversion [Length]

$$\rho = \beta R$$

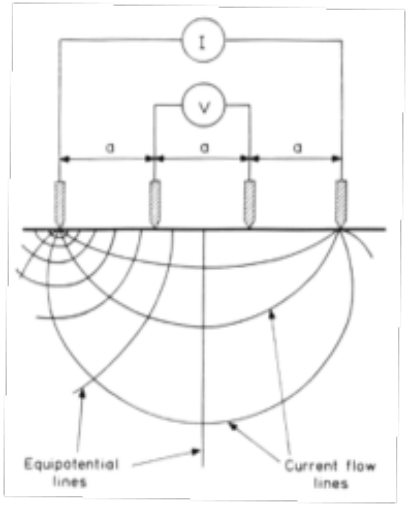
Every measurement geometry has a specific value for β

For a homogeneous material, different specimen/electrode geometries:
- multiple resistance values
- a single resistivity value

Surface Resistivity: Soils

Wenner Test of Soil Resistivity: (1916 - NBS)

- 4 uniformly spaced rods (along a line) inserted into the ground
- Alternating current is applied across the outside electrodes
- (Alternating) voltage measured between the inside electrodes



$$\rho = 2\pi a\, R = 2\pi a \left(\frac{V}{I}\right)$$

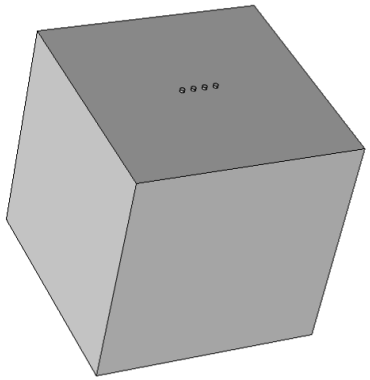
a: spacing between each electrode

Only applicable to electrodes placed on a BIG, flat sample…

Surface Resistivity: Concrete

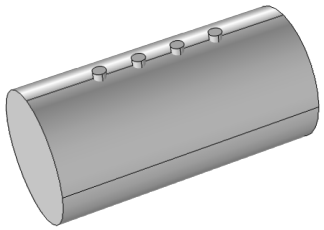
Geometry Correction Factor (*k*):

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

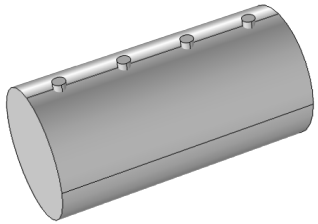


$k = 1.0$

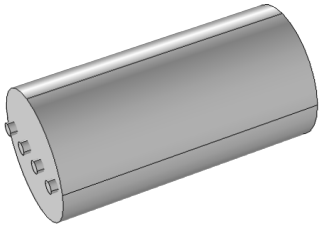
$k = 1.6$



$k = 2.7$



$k = 1.5$



Surface Resistivity: Concrete Cylinders

Geometry Correction Factors (*k*):

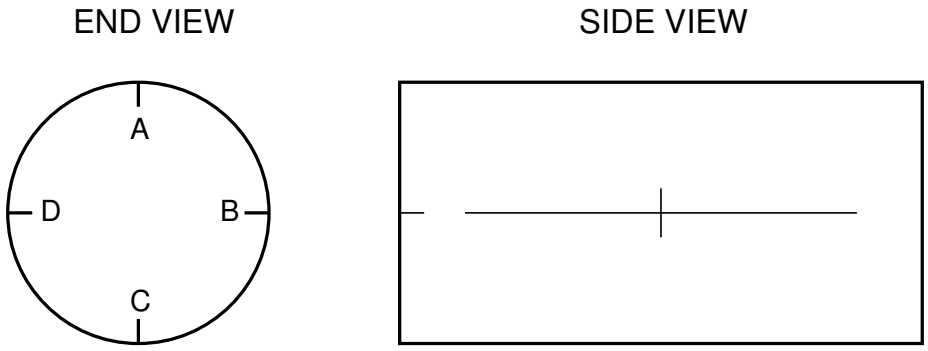
Cylinder Size	*a* (mm)	*k*
100 mm x 200 mm	25	1.41
	30	1.58
	35	1.80
	38	1.95
	40	2.06
150 mm x 300 mm	38	1.42
	40	1.46
	45	1.58
	50	1.73
	60	2.06

The standard includes an equation for estimating *k* for geometries that are not in the table that is provided in the draft standard.

Process:

Taking Measurements:

- Wet the electrodes per manufacturer's instructions
- On one end, mark every 90 degrees
- Mark side of cylinder, aligned with end marks
- Take measurements on side of cylinder, centered longitudinally
- Measure all four marks, then repeat - 8 readings
- Calculate the average value
- Make any necessary conversions (units, geometry factors, etc.)



Homogeneity:

Homogeneous Specimen:

- The surface/bulk methods estimate the same quantity
- The only difference: The geometry conversion factor

Inhomogeneous Specimen:

- Source: drying or leaching
- The two methods depend differently on inhomogeneities
- Unless the inhomogeneity is well-characterized:

Each test method will give a different wrong/meaningless result from an inhomogeneous specimen

Commercial Device Requirements:

ASTM Test Method Development

The intent is to be as inclusive as possible
- no “one” standard device

Requirements:

- alternating current - a DC measurement will not work
- minimum electrode spacing: 25 mm - depends on aggregate size
- display resistivity or resistance (to a specified precision)
- operator must be able to determine the device’s geometry factor

Status of new ASTM test method

- No standardized “curing”
- Have a precision and bias statement
- Undergoing C09.66 Subcommittee balloting

Additional interested parties are welcome to join C09.66!

Development of Bulk Resistivity Test Methods

R. Doug Hooton,
NSERC/CAC Industrial Research Chair in Concrete Durability & Sustainability

UNIVERSITY OF TORONTO
DEPT. CIVIL ENGINEERING

TRB Webinar April 13, 2016

With thanks to Ms. Gita Charmchi MASc 2015, and Ms. Ester Karkar, MASc 2013

Background

- While the ASTM C1202 (AASHTO T277) test has been useful as a relatively **rapid index test** for an indication of fluid penetration resistance, it could be replaced by rapid and inexpensive, yet reliable and reproducible bulk resistivity.
- ASTM has moved in this direction with the adoption of the ASTM C1760 bulk conductivity test in 2012 (using C1202 equipment).
- AASHTO TP-95 is surface resistivity test (Wenner probe)
- It is no surprise that that there is an excellent correlation between ASTM C1202 which measures conductivity (the inverse of resistivity) but then integrates it over 6 hours to get charge passed in coulombs

Bulk vs Surface Resistivity

Both tests can be measured on entire, saturated cylinders or cores before strength testing

Surface

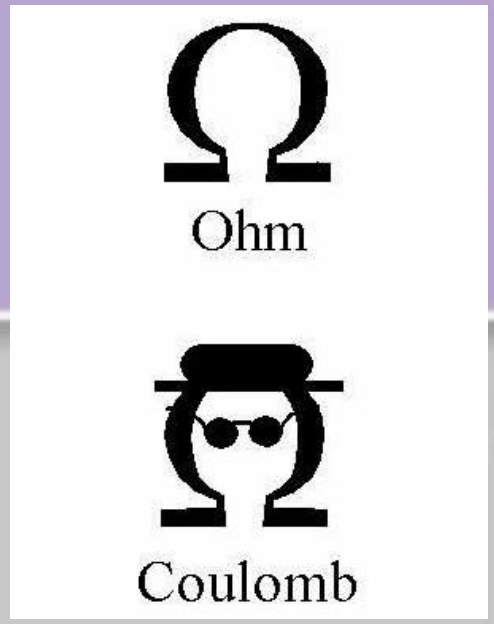
- Easy to perform but results are more variable and affected by near surface variables.
- While it has potential for field use, variations in **moisture condition, temperature, nearby rebar**, carbonation, curing and age confuse interpretation.

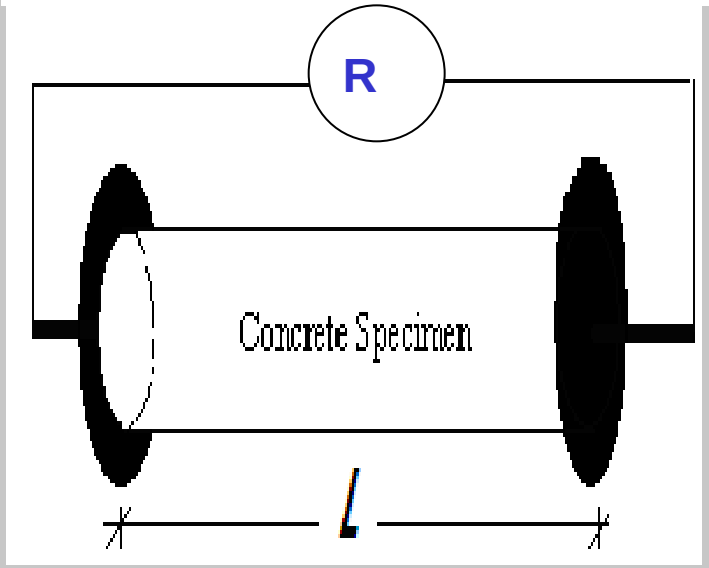
Bulk

- Measures through the thickness of concrete sample, so gives good indication in one measurement.

Bulk Resistivity

- Simply measure the electric resistance through a wet concrete cylinder or core prior to strength tests

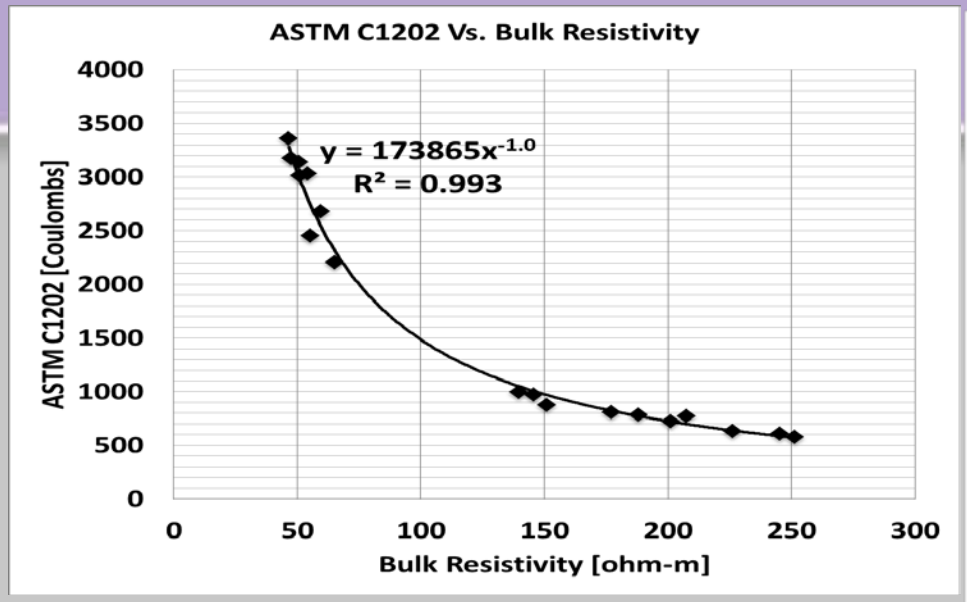


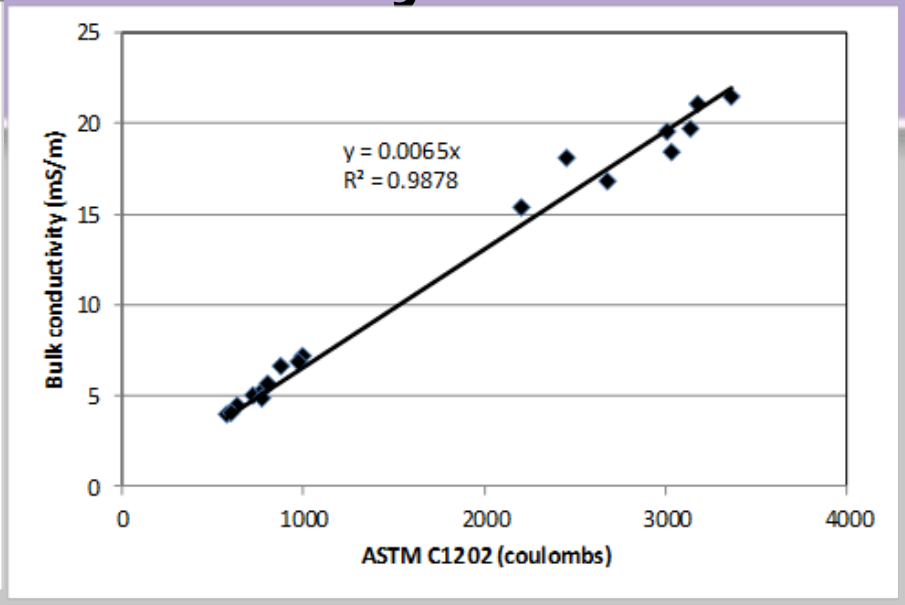


Then calculate resistivity accounting for Area and Length of sample

$$\rho = R\,(A/L)$$

ASTM C1202 vs Bulk Resistivity & Bulk Conductivity



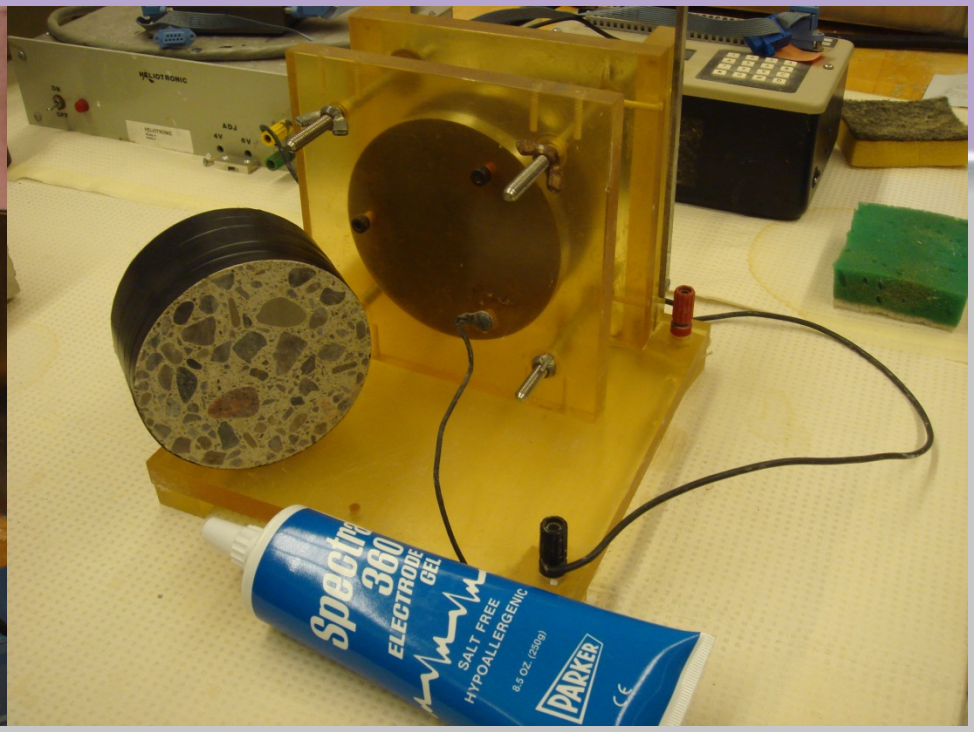


Possible Equivalent Acceptance Values

ASTM C1202 Coulombs	Bulk Resistivity Ohm-m	Conductivity mS/m
1000	130	7.7
1500	90	11
2000	70	14

Charmchi 2015

Earlier use of Bulk Resistivity Tests



Monfore at PCA developed a resistivity test ~1968 using cyclic DC current. Fixed DC is not suitable due to polarization effects that build up at the electrodes. So he countered this by cycling between 2 voltages, allowing correction for polarization

Why is a standard test taking so long?

- Because the different commercial devices operate differently, a performance-based standard for bulk resistivity of concrete needs to be developed.
- Rather than specifying the details of the equipment to be used, a verification cell using precision resistors is proposed to determine the accuracy of results obtained using any commercially available resistivity test device.
- In addition, some test details needed to be evaluated:

(a) conductive coupling gels or water,

(b) different curing solutions, &

(c) time of surface drying.

Various Instruments for Measuring Bulk Resistivity are Commercially Available

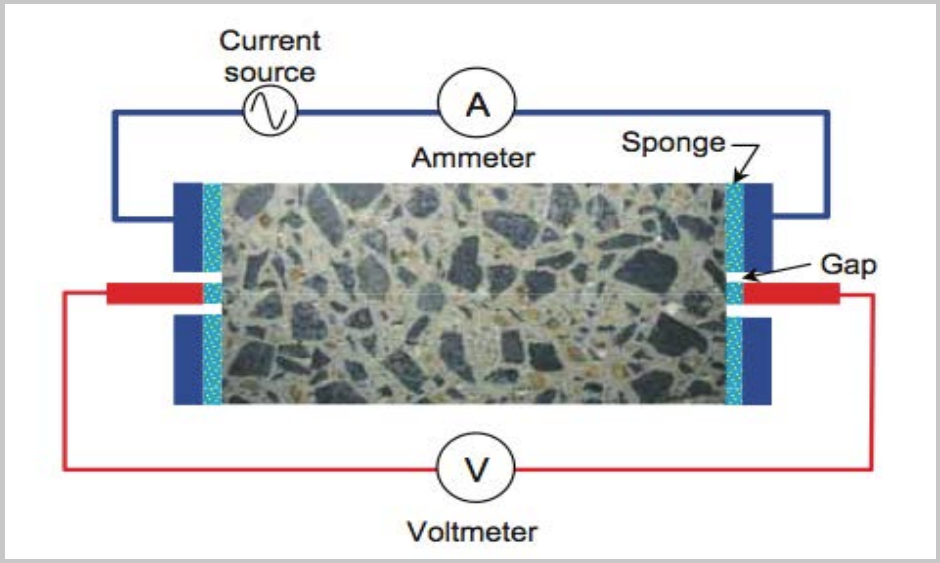
Ones used in this study were:

1. Germann Instruments, Merlin
2. Giatec Scientific, RCON
3. Prosec, Resipod

This is not meant as an endorsement, but as will be discussed, these devices all operate differently, and this has influenced the development of a standard.

1. Germann Instruments Merlin

- The electrical resistance, *R*, of concrete of length *L* and uniform cross-sectional area, *A* is measured using a fixed AC frequency of 325 Hz

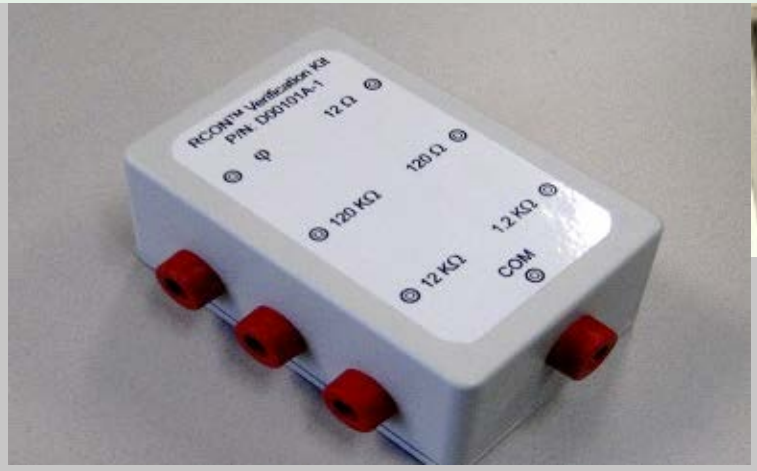


Merlin Verification cylinder (5 resistivity values)

Resistor Setting	[ohm-m]
0	0
1	0.3927 ± 1%
2	3.9270 ± 1%
3	39.270 ± 0.1%
4	392.70 ± 0.1%
5	3927.0 ± 0.1%
6	39270 ± 0.1%
7	Open

2. Giatec RCON

Reading Range	Frequency spectrum	Phase measurement
1 ~ 100 Ω	1Hz ~ 30KHz	0 ~ 180°
100 ~ 1000 Ω		
1 ~ 10 KΩ		
10 ~ 100 KΩ		
100 KΩ ~ 1 MΩ	1Hz ~ 10KHz	



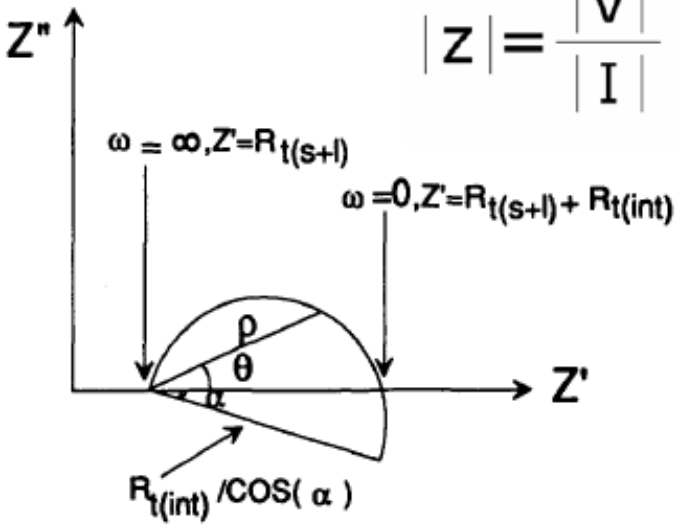
6 value resistance calibration box

Uses a frequency sweep to determine optimum frequency to avoid impedance effects, or can be used at fixed frequency (1000 Hz recommended)

Note: can use 2kg weight on top plate instead of bolts

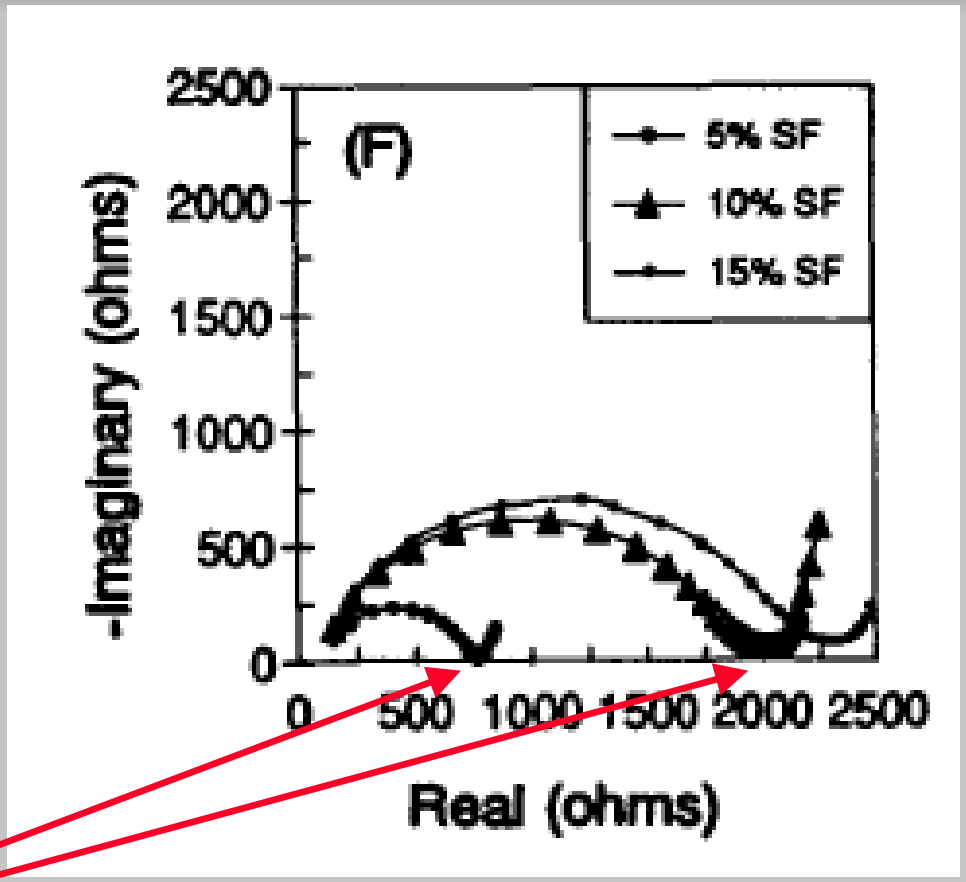
AC Impedance Measurements

$$|Z| = \frac{|V|}{|I|}$$



Measures resistance over a wide range of frequencies.

True resistance is where electrode arc drops to x-axis (no impedance).



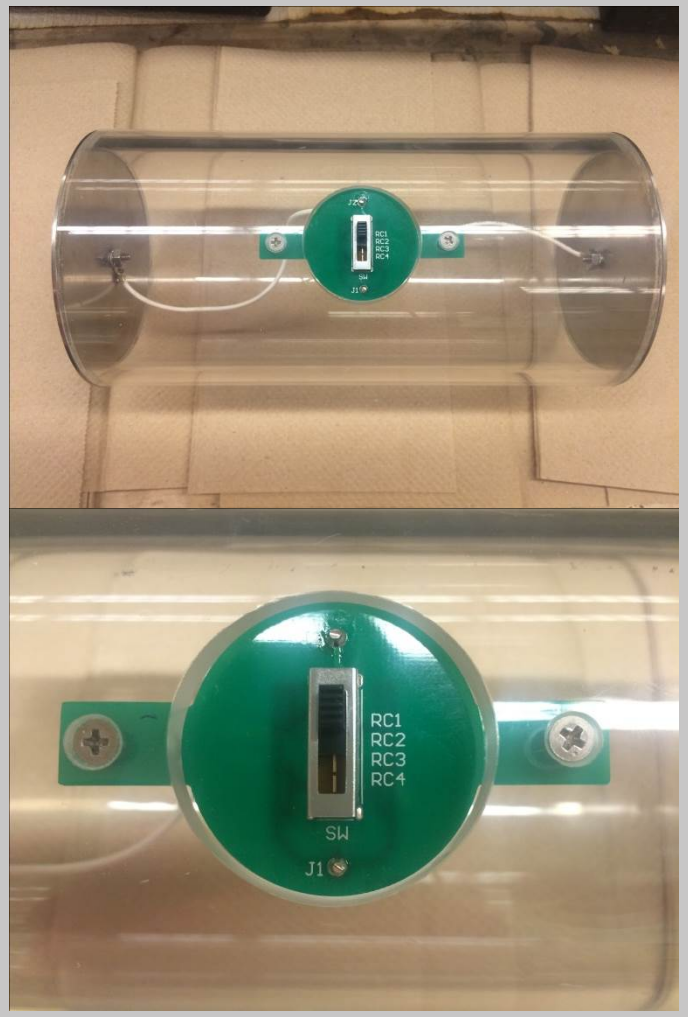
Ref: Ping et al, CCR 2003

Tests on Effect of Capacitance on Resistivity Results (Charmchi 2015)

Capacitors were added together with resistors in a new verification cell to better mimic concrete.

Result: Essentially this provided no advantage over verification with precision resistors alone

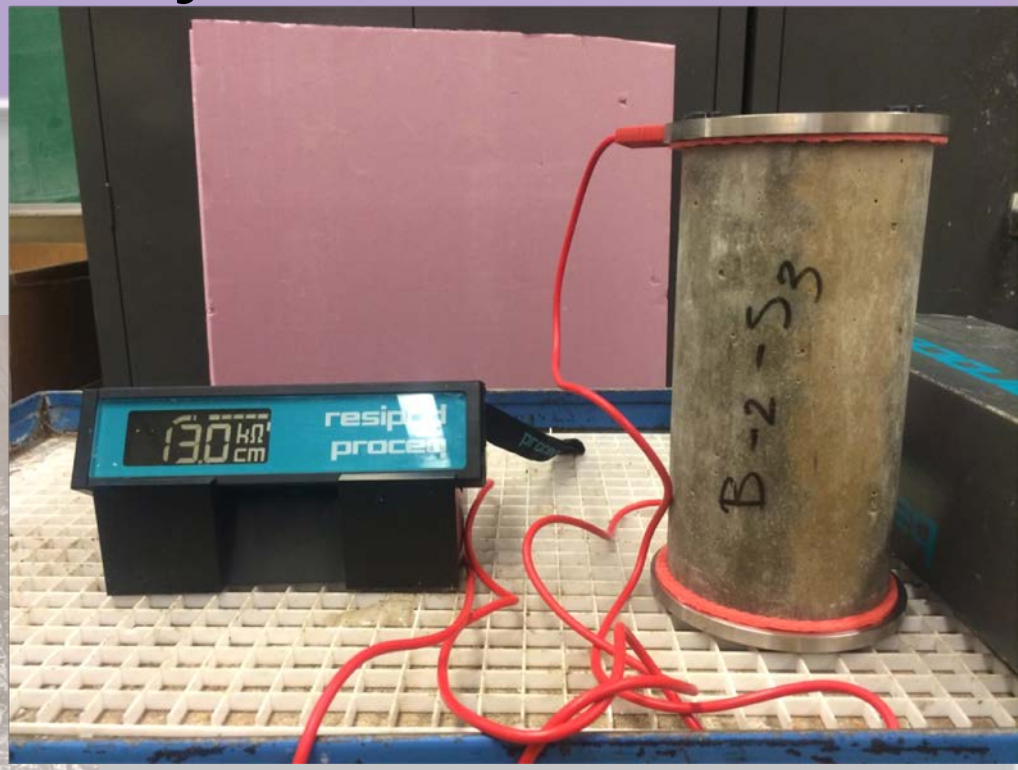
Resistor Setting	[ohm]	[pF]
1	500	2000
2	1000	1000
3	5000	200
4	10000	100



3. Prosec, Resipod set up for bulk resistivity

Uses low frequency: ~64Hz

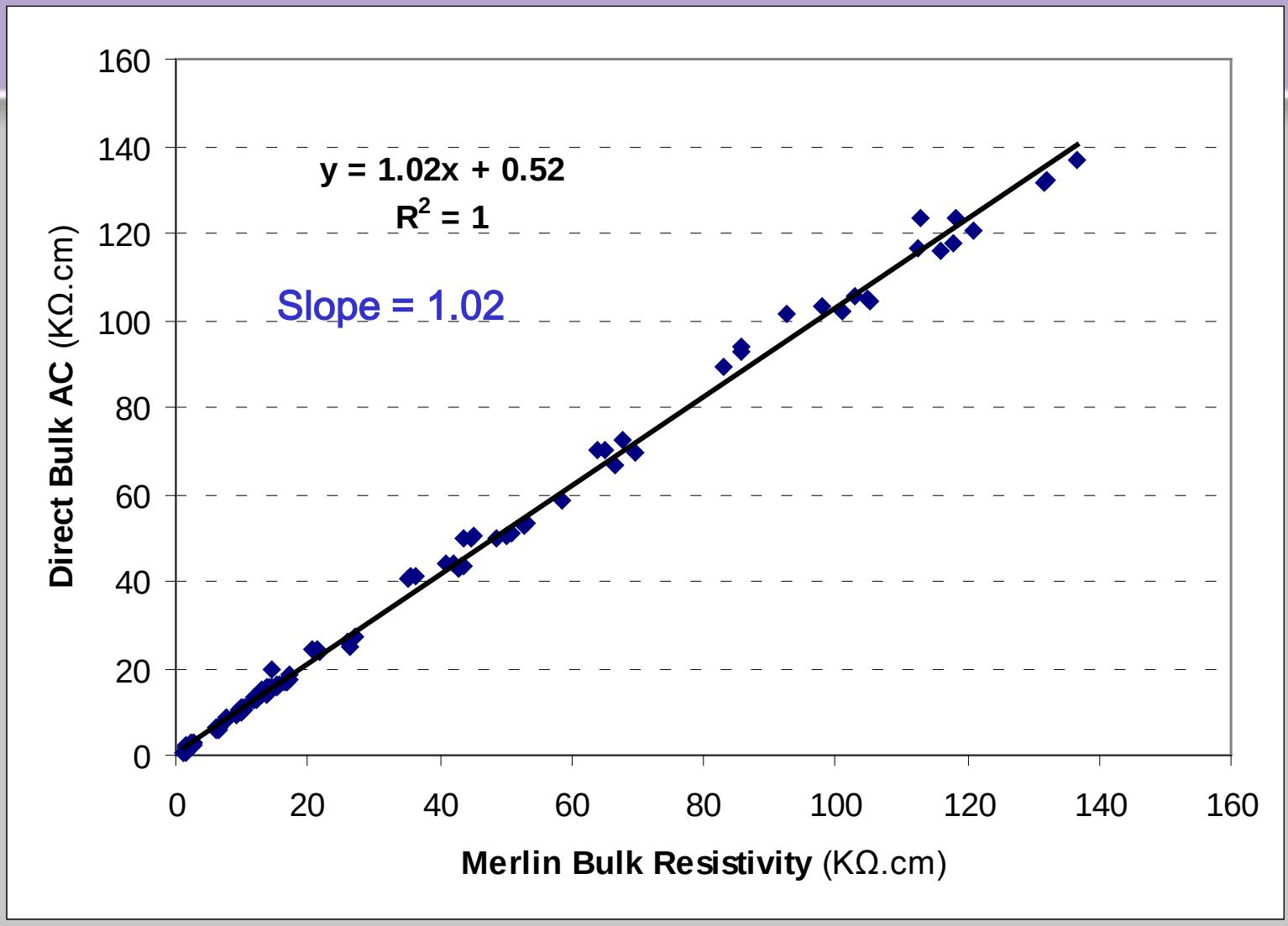
Resistance verification strip



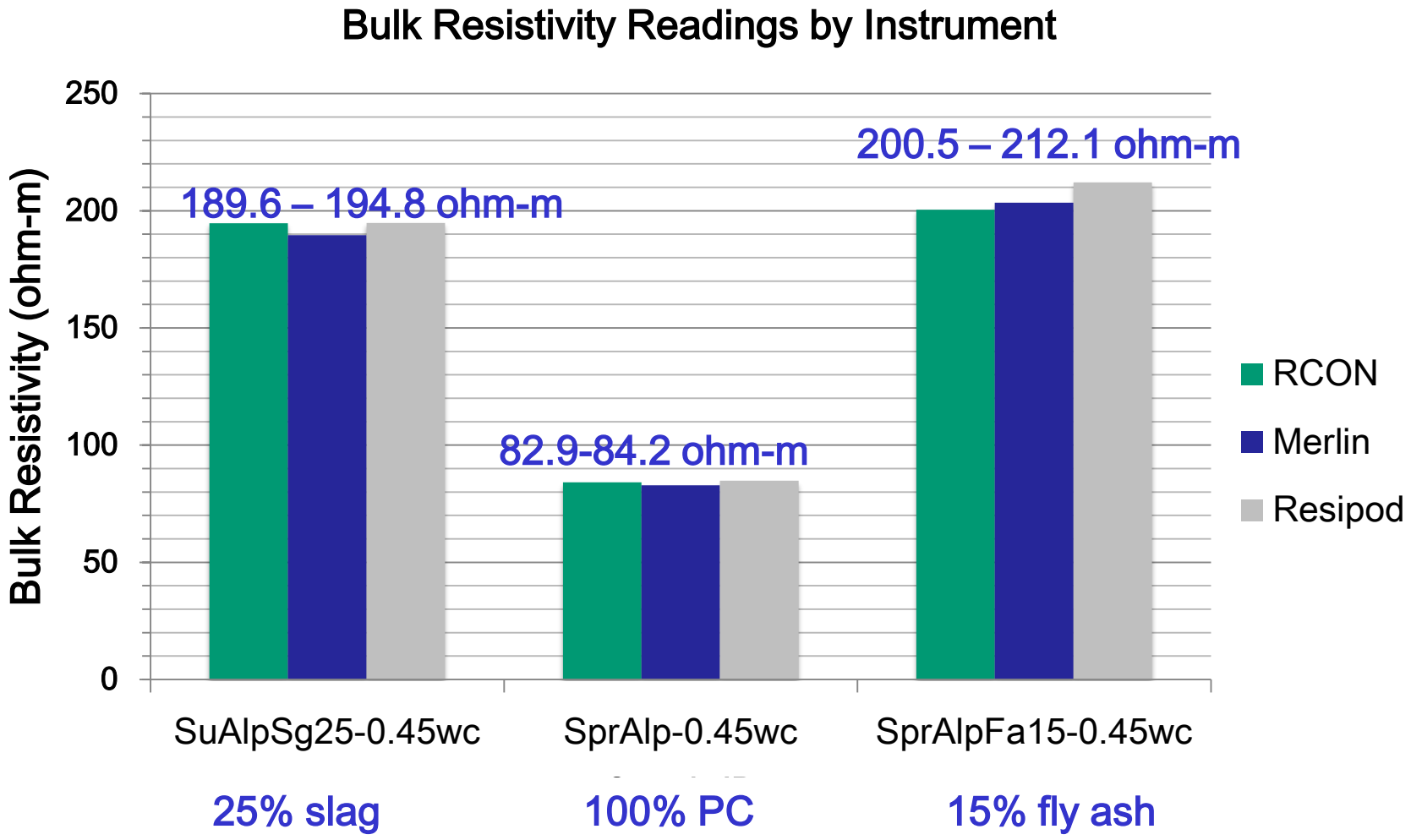
Wires from plates are attached to Wenner probe tips.

Wet sponges are used to make connection to concrete

Example Correlation: Bulk Resistivity: Prosec vs Merlin device



Comparison of Resistivity Results (for 0.45 w/cm concretes)

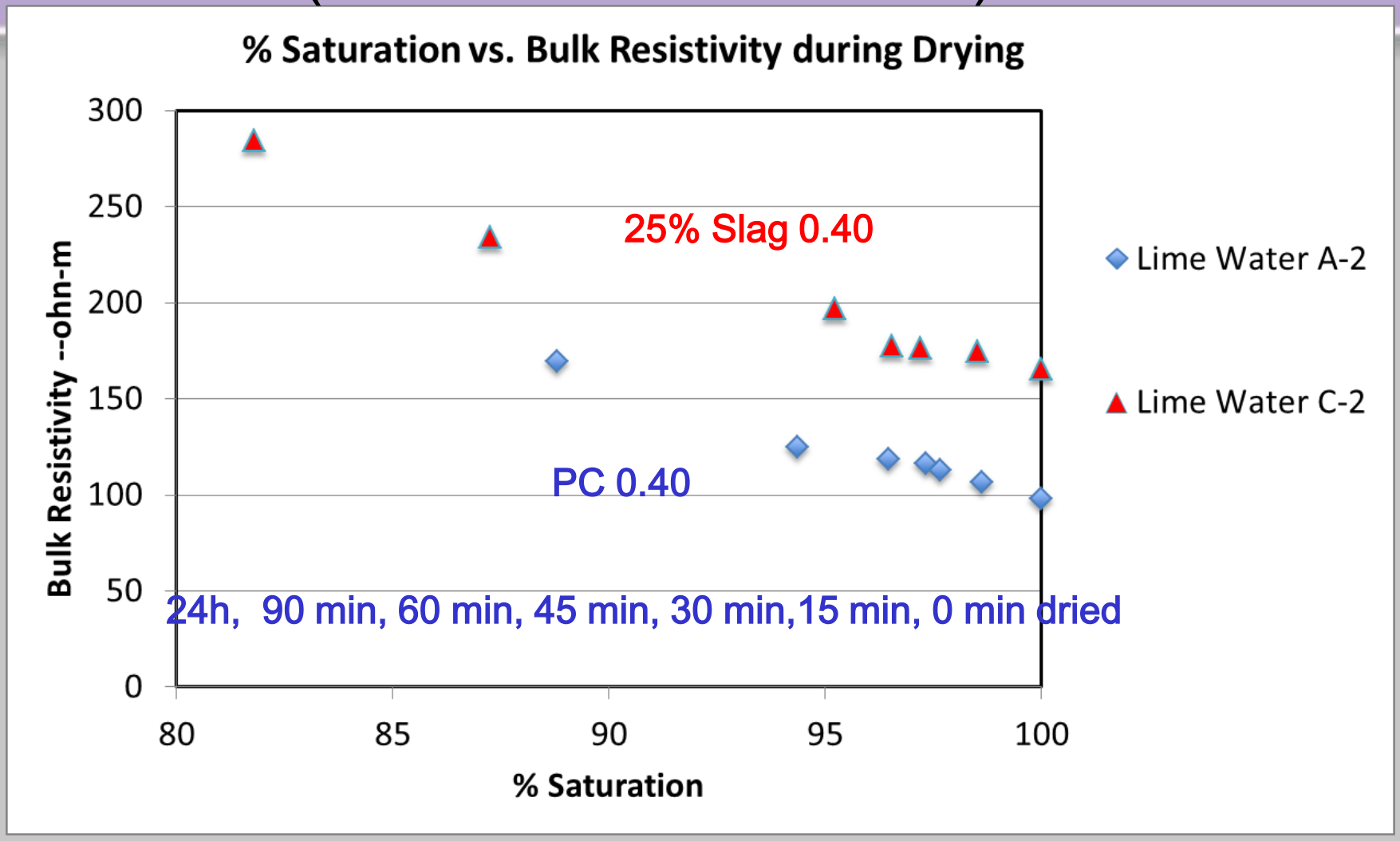


% Increase in Bulk Resistivity Reading due to time of Drying in air at 23°C

Concretes must be saturated to get reproducible results. How sensitive are results to short period of drying?

0.40 w/cm Concretes	**% Increase** in Bulk Resistivity Reading		
23°C	**(0-15min.)**	(15-30min.)	(0-24h)
OPC-Limewater	**9.1**	5.4	42.3
25% slag-limewater	**6.6**	1.1	34.9
50% slag-Limewater	**5.6**	0.9	41.9
OPC- pore sol'n	**19.4**	2.0	35.2
25% slag-pore sol'n	**33.8**	1.7	35.8
50% slag- pore sol'n	**16.5**	0.9	30.6

Effect of 23°C air drying on Change in Bulk Resistivity of 100x200 mm cylinders (taken from lime water)



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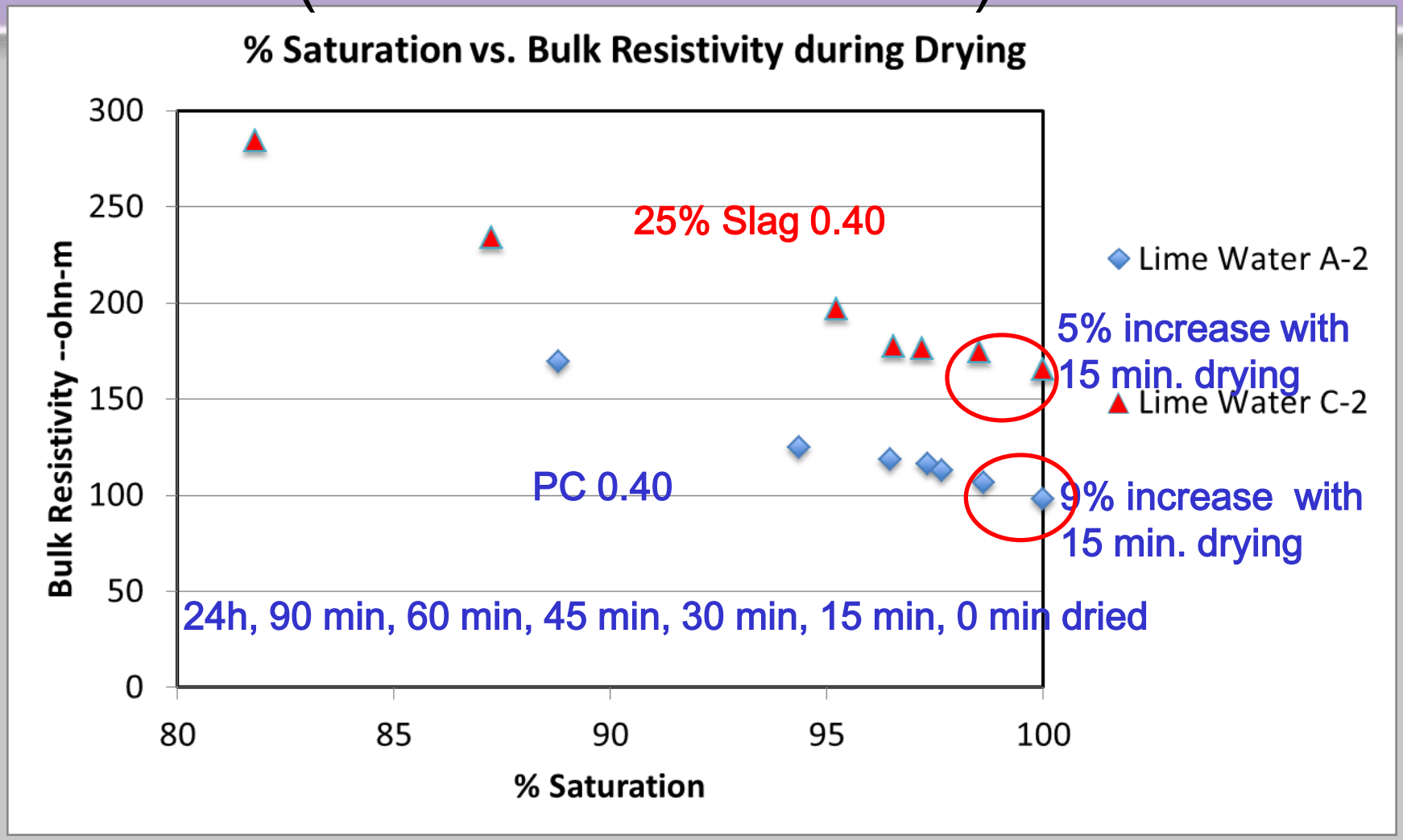


Conductivity of Different Fluids

Note: Conductivity is very sensitive to temperature, so test in temperature controlled lab

Solution	Tap Water	Lime Water	Pore Soln'
Conductivity	9.07	13.01	118.6
[ms/cm]			
TEMP: 21.6C			

Simulated Pore fluid conductivity (based on alkalis in PC and Slag)
100% PC = 118.6 mS/cm
25% Slag = 125.3 mS/cm
50% Slag = 138.1 mS/cm
Conductive coupling gel = 1967 mS/cm

Effect of Electrode Coupling Fluid (gel vs tap water) on Resistivity

Sponges were saturated either with water or conductive coupling fluid

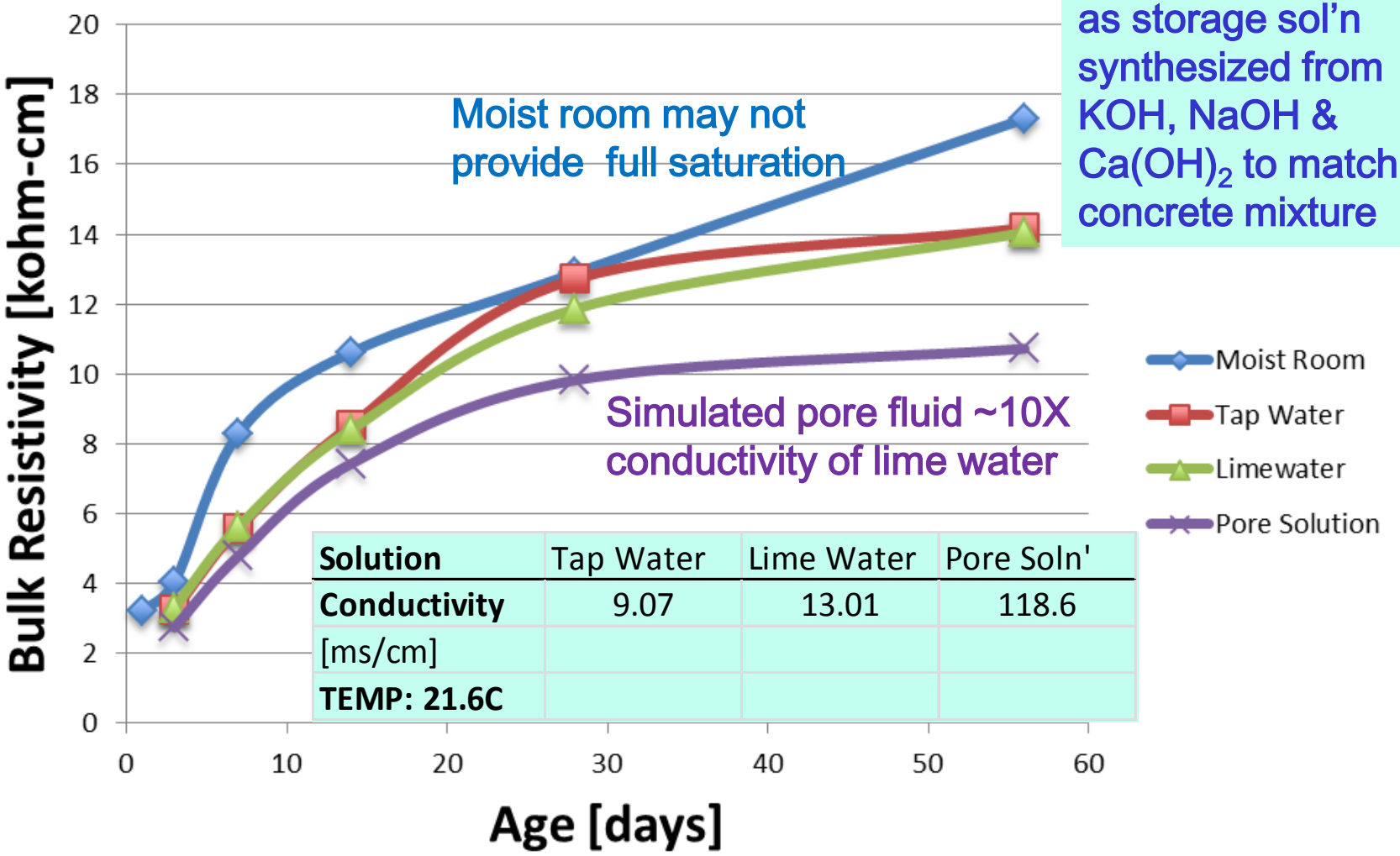
Average Resistivity Values	Verification Cell Resistivity Setting	RCON (water)	RCON (gel)	Resipod (water)	Resipod (gel)	Merlin (water)	Merlin (gel)
	[ohm-m]	[ohm-m]	[ohm-m]	[ohm-m]	[ohm-m]	[ohm-m]	[ohm-m]
Setting 3	39.27	39.6	39.9	41	41	40.33	39.8
Setting 4	392.7	396.4	393.0	396	393.5	393.3	392.8

Using Merlin verification cell, differences ranged from 0 to 1%

Electrode Connections using saturated sponges

- Placing a 2 kg (5lb) weight on top of top electrode plate to get better connection of electrodes reduces resistivity results by 8-9%.
- Using a weight to clamp ends is faster than bolts.
- Merlin C-Clamp is adequate without added weight

Effect of Curing Medium on Resistivity (50% Slag Concrete w/cm = 0.40)



Moist room may not provide full saturation

Simulated pore fluid ~10X conductivity of lime water

Pore solution used as storage sol'n synthesized from KOH, NaOH & $Ca(OH)_2$ to match concrete mixture

Solution	Tap Water	Lime Water	Pore Soln'
Conductivity	9.07	13.01	118.6
[ms/cm]			
TEMP: 21.6C			

Conclusions

- The results from the verification cell tests demonstrate that all three commercially available test devices are accurate within 4.5% at low resistivity levels (39 ohm-m) and within 1.0% at higher resistivity levels (390 ohm-m).
- Use of water-soaked sponges to couple the concrete to the electrodes gave essentially the same results as when a conductive gel was used---but electrodes need to be firmly clamped or weighed down.
- Allowing the cylinders to dry out for 15 minutes before measurement raised bulk resistivity values by 5-9%.
- Pore fluid is far more conductive than lime-water--- so lime water raises resistivity. Moist room curing does not always provide full saturation, or may leach alkalis---artificially raising resistivity values.

Next Step in Standardization

- Finish detailed write up of test method
- Work with Jason Weiss to include calculation of Formation Factor in Test method or in Appendix

Thoughts About Resistivity Testing, the Formation Factor, and Specifications

Jason Weiss, Oregon State University

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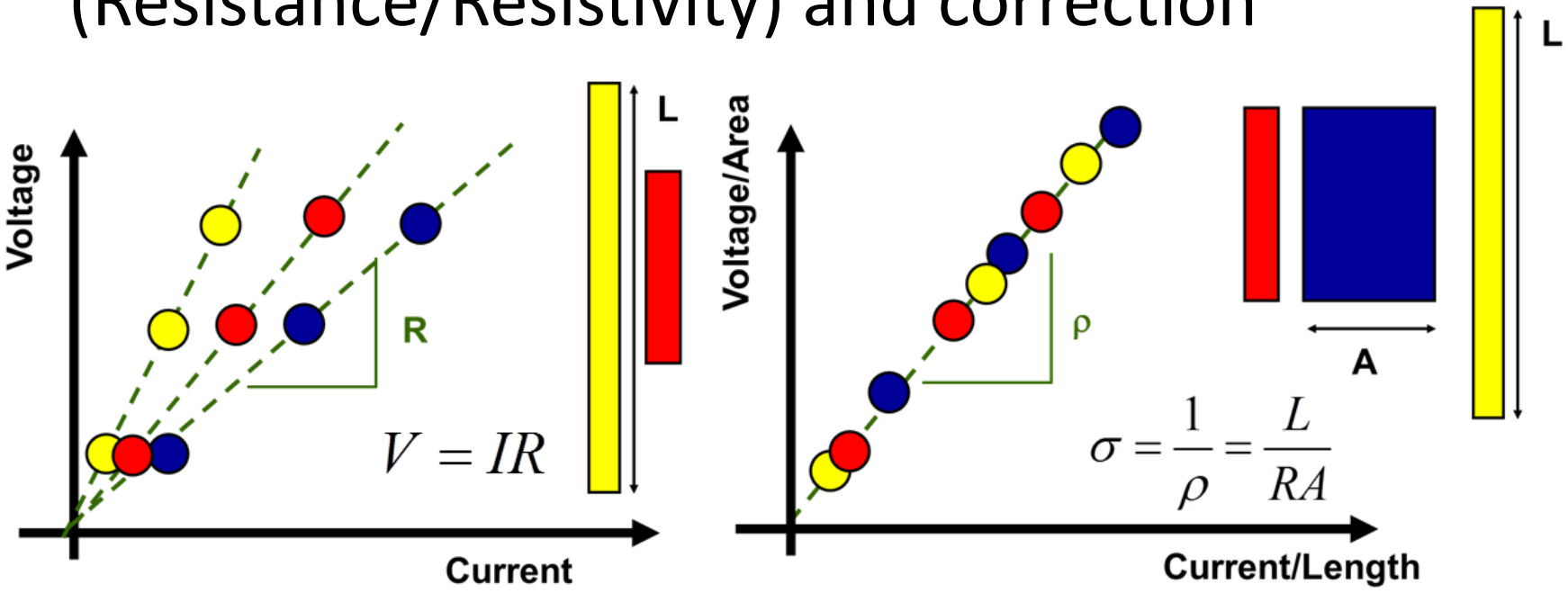
April 13th, 2016

By Way of Review

- Great presentations from Tyson, Ken & Doug
- Understanding the role of geometry (Resistance/Resistivity) and correction



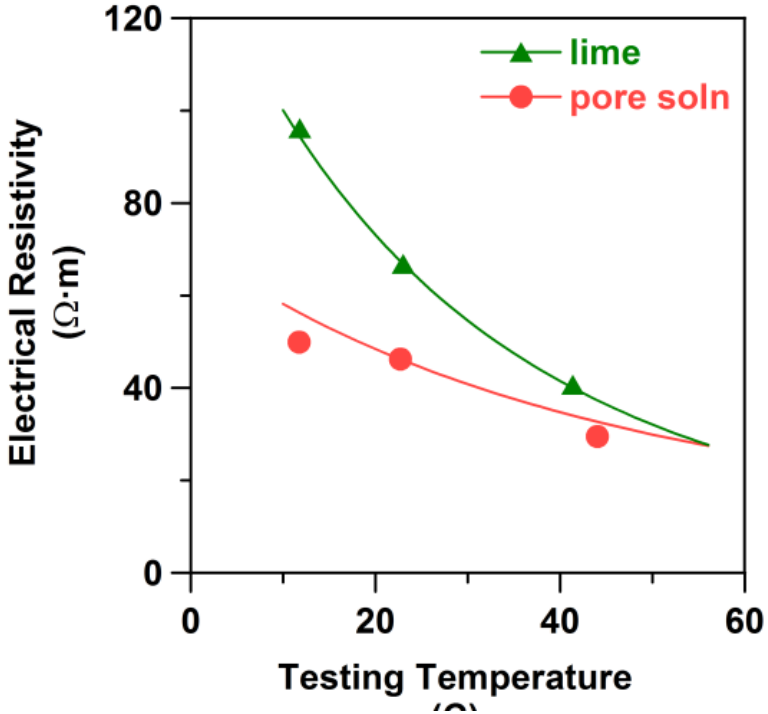
Weiss et al. 2010

Review – Temperature

- Testing temperature is very important

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

- Same material tested at different temp. has a different resistivity
- Very important for QC/QA testing
- Ongoing State/NCC study examining $E_{a\text{-}Con}$



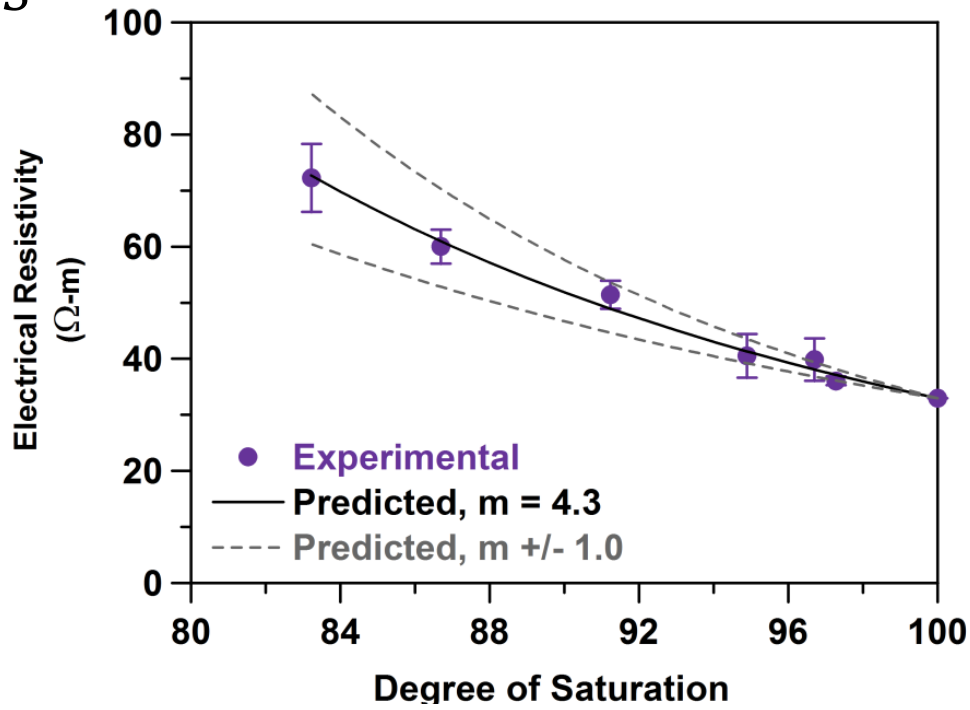
Rajabipour et al. 2007, Sant et al. 2008, Spragg et al. 2013

Review – Moisture Conditioning

- Moisture conditions are very important

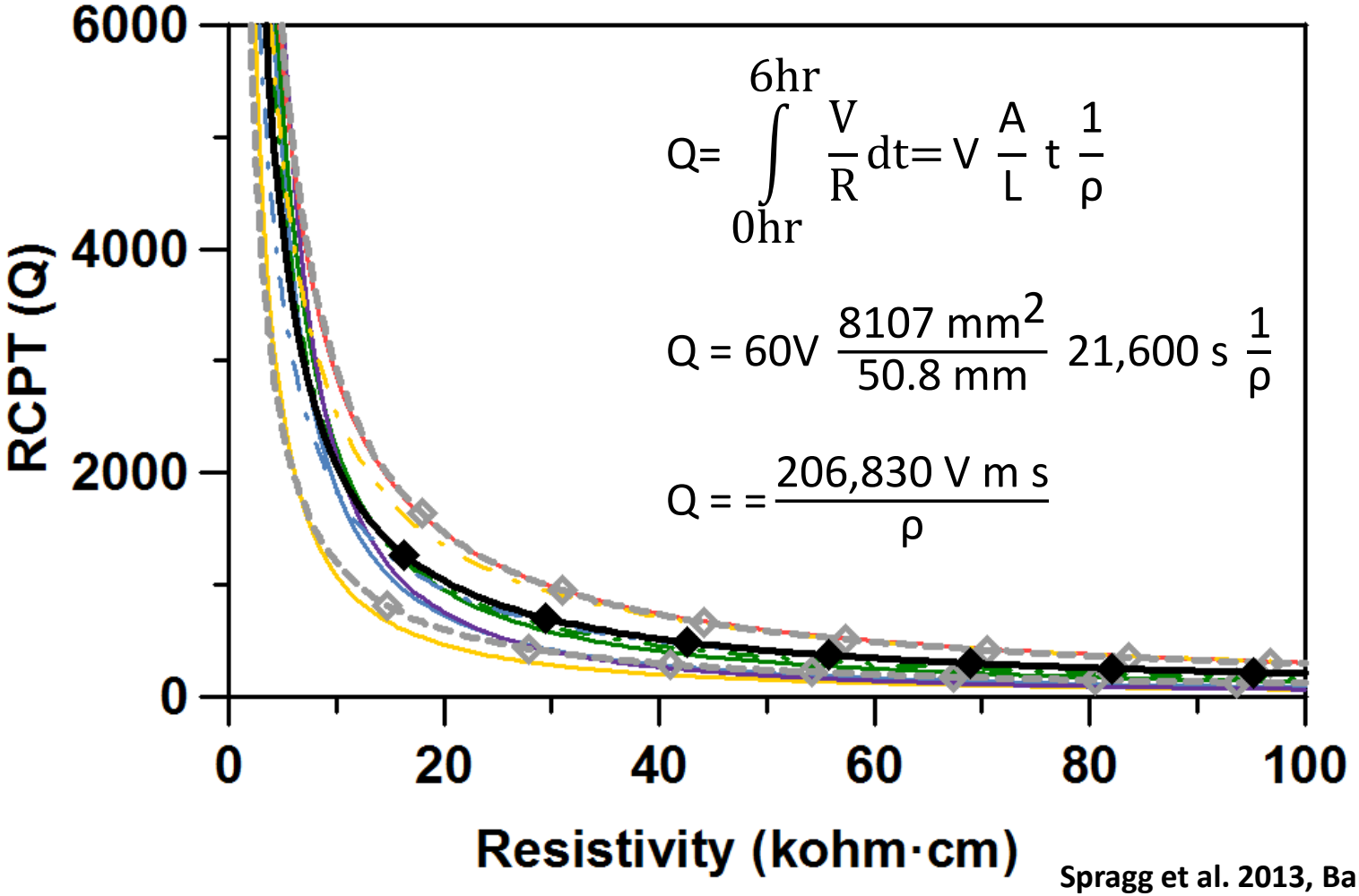
$$\frac{\rho_{DOS}}{\rho_{100\%DOS}} = S^{-m}$$

- Very important for QC/QA testing
- Samples in a bucket or in a moisture room are not saturated
- Samples leach ions



Weiss et al. 2012, Spragg et al. 2014

Comparing Resistivity to RCPT



$$Q = \int_{0hr}^{6hr} \frac{V}{R} dt = V \frac{A}{L} t \frac{1}{\rho}$$

$$Q = 60V \frac{8107\ mm^2}{50.8\ mm} 21{,}600\ s \frac{1}{\rho}$$

$$Q = = \frac{206{,}830\ V\ m\ s}{\rho}$$

Spragg et al. 2013, Barrett et al. 2015

RCPT, Resistivity, & Formation Factor

ASTM C1202 Classification[1]	Charge Passed (Coulombs)[1]	Direct Resistivity (kOhm-cm)[2]	Berke Empirical (kOhm-cm)	Paredes Empirical (kOhm-cm)[3]	Apparent Surface Resistivity (102mm × 205mm) (kOhm-cm)[4]
High	>4,000	< 5.2	< 4.9	< 6.5	< 9.7
Moderate	2,000 – 4,000	5.2 – 10.4	4.9 – 8.76	6.5 – 11.3	9.7 – 19.3
Low	1,000 – 2,000	10.4 – 20.8	8.8 – 15.6	11.3 – 19.9	19.3 – 38.6
Very Low	100 – 1,000	20.8 – 207	15.6 – 105.9	19.9 – 136.6	38.6 – 386
Negligible	< 100	> 207	> 105.9	> 136.6	> 386

[1]from ASTM C1202-10 [15]
[2]calculated using Ohm's law and geometry
[3]corrected for geometry from Kessler, et al. [28]
[4]bulk resistivity multiplied by geometry factor

Spragg et al. 2012

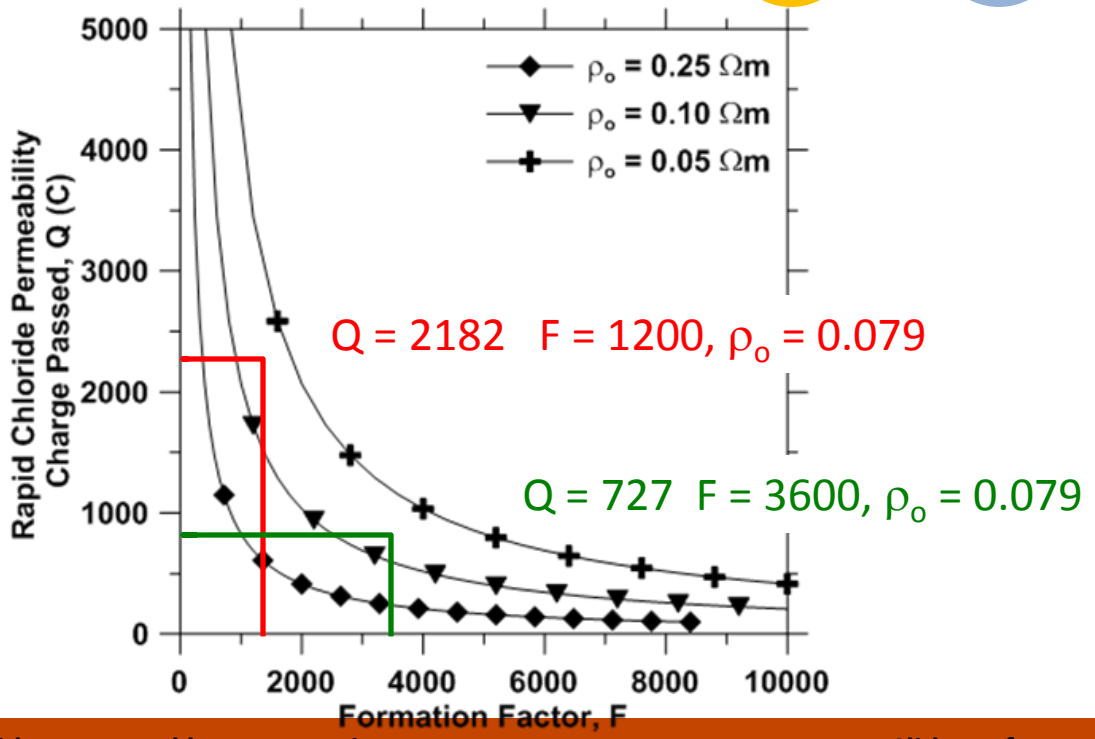
- Many people are focused on the test and ranking the results
- Can we look at this differently
- Can we use the formation factor

Does this Relate to RCPT (Q)

- RCPT is inversely related to the formation factor

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

- However it is also related to the pore solution resistivity



Weiss et al. 2015

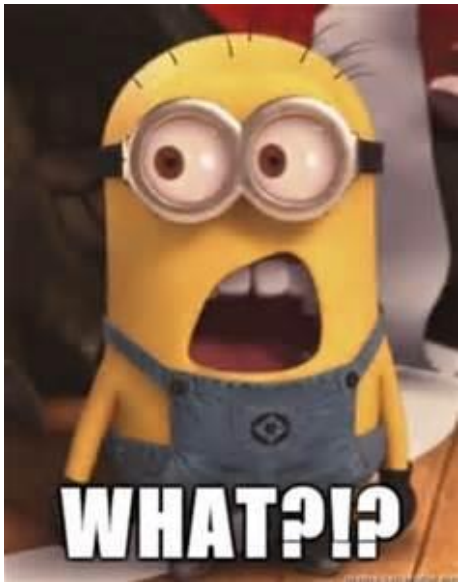
Ahh The Formation Factor

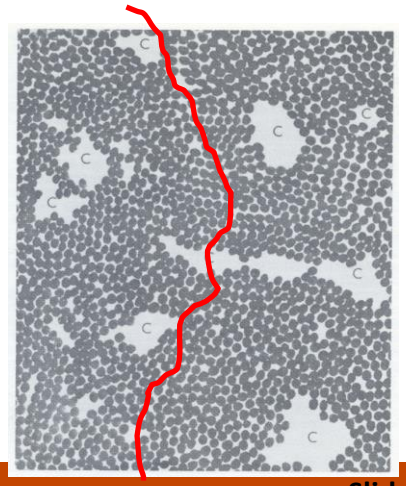
- The formation factor is the inverse of the porosity and connectivity of the pores

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

- ϕ is the volume of pores
- β is the connectivity of pores

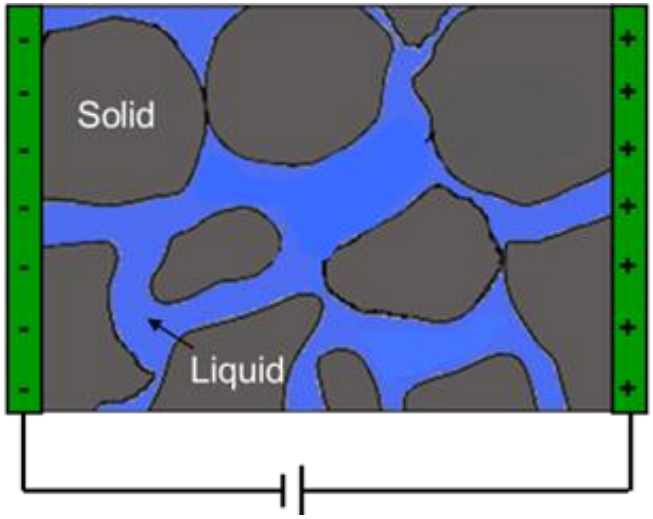
- Great measure of w/c, SCM



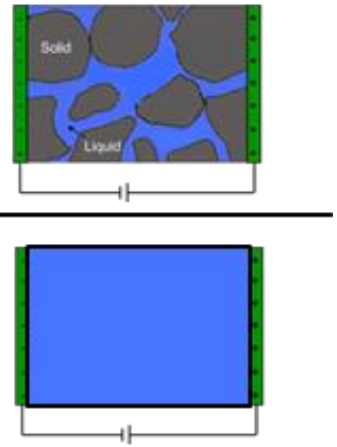


How Does This Relate to Resistivity

- We can measure the formation factor from electrical resistivity tests
- The formation factor is the ratio of the bulk resistivity and the resistivity of the solution



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



An Example of the Formation Factor

- Assume we want concrete bridge deck that lasts for 75 years
- 2.5 inches of cover
- Indianapolis Indiana
- Deicing salt application

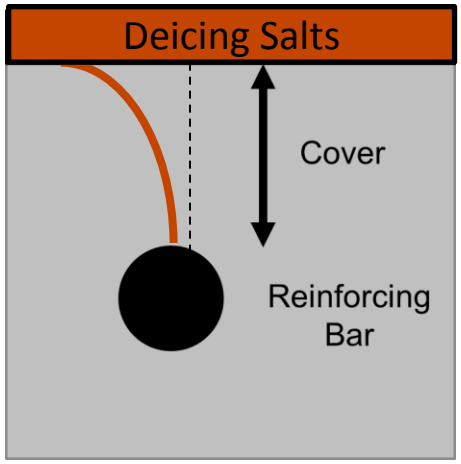
Barrett et al. 2015

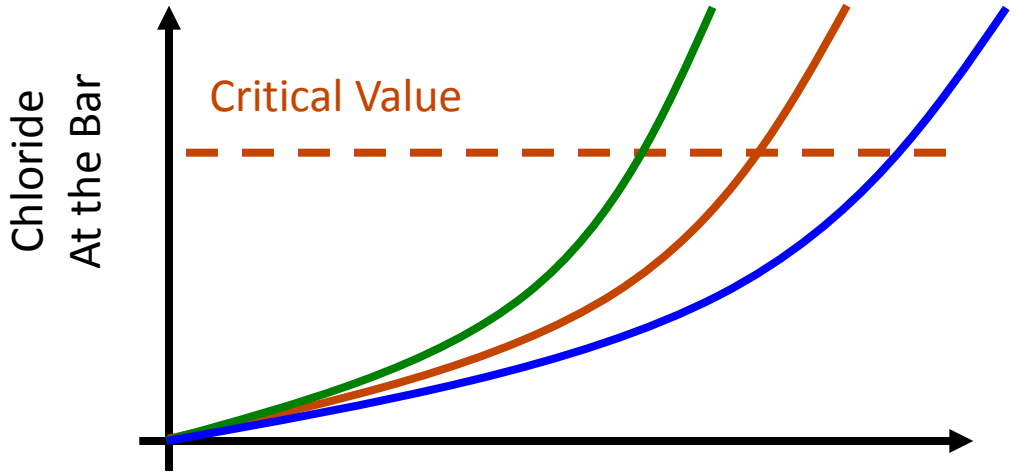
Fundamentally What Do We Want

- How long it will take chloride ions to be transported from the surface to reach a critical concentration at the bar

$$D_i = D_i^{\mu} \frac{1}{F}$$

$$D_{Cl} = \left(2.032x10^{-9} \frac{m^2}{s} \right) \frac{1}{F}$$



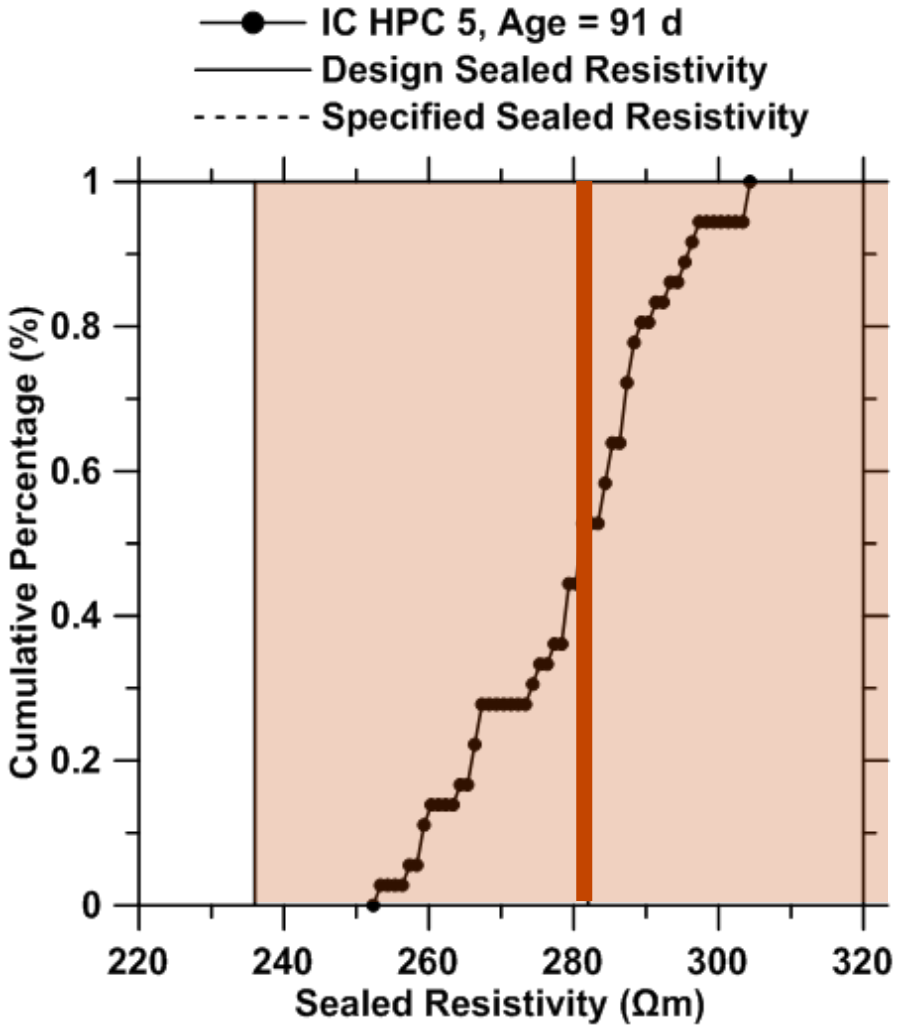


Specifying the Formation Factor

- 25 year – F_{SPEC} = 1200
- 50 year – F_{SPEC} = 2400
- 75 year – F_{SPEC} = 3600

- Pore solution (ρ_o) = 0.079 ohm m

- Concrete resistivity
  10% conf. = 282 ohm m
  low. bound = 236 ohm m



Barrett et al. 2015

Some Things to Consider

- Each project in a region has the same F but different resistivity based cement
- F changes by region due to differences in temperature and exposure conditions
- Resistivity here is shown for a sealed concrete which is very fast to perform
- Many samples can be tested on a bridge as shown in the last plot
- Variability is key, this enables quantification

Summary and Implementation

- Temperature, leaching and moisture are important and should be considered
- Formation factor is a fundamental property that can be obtained from resistivity
- One should specify formation factor and use the resistivity in the field as a quality control measure

Thank you
Are There Any Questions

Jason Weiss , Edwards Distinguished Professor

jason.weiss@oregonstate.edu

Additional Resources
http://cce.oregonstate.edu/resistivity