Resistivity Testing

What do I need to know? How do I use it?

April 28th, 2022

Jason Weiss, Edwards Distinguished Professor
Oregon State University

JTRP Testing - January 2013

Why do we want electrical resistivity?

- On its own- We don't (generally)

Photo 28068527 © Martin Applegate | Dreamstime.com

Why do we want resistivity?

- It's a fast indirect measure of durability
- Specifically it's a measure of transport
- Great quality control measure as well

Photo 69694225 / Concrete © Satakorn | Dreamstime.com

What is Transport

- What is transport?
- Fluid movement in concrete:
  - Permeation (flow due to pressure)
  - Ion Diffusion (concentration)
  - Sorption (wetting events)
  - Drying processes
  - Wicking (combination of others)
- Transport is driven by pore solution volume and connectivity

'Looking to reduce Soprano style pores'

In History, New Ideas Come Forward

- In 1515 Copernicus proposed that the earth was a planet that circled the sun
- He waited till 1543 to publish this but was largely seen as a heretic
- Bruno was burned at the stake for teaching of a heliocentric world
- Galileo – house arrest

Photo 89780342 © Lukasz Janyst | Dreamstime.com

Background - Ohms Law

- German Physicist and Mathematician
- Found that there is a proportionality between:
  - potential difference (voltage, V) and
  - resulting current (I)
- The proportionality constant is what we call electrical resistance (R)

V = I R

- In 1827 "The Galvanic Circuit Investigated Mathematically" received 'cold reception'

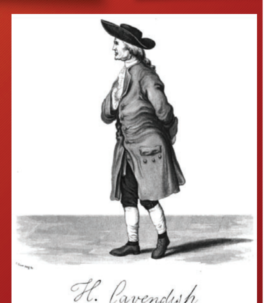
George Ohm

Ohms Law was Discovered by

- Henry Cavendish (1731-1810)
- Solitary, Eccentric, Shy
- Many folks today believe he was autistic (Asperger)
- The bulk of his work was not known until James Clerk Maxwell did a review in 1879 (He was het first Cavendish Professor a Cambridge)

V = I R

- It is worth noting that Ohm was studying this along with mechanical response and heat transfer



Henry Cavendish

Resistance, Resistivity, and Geometry

- Analogy to Mechanics

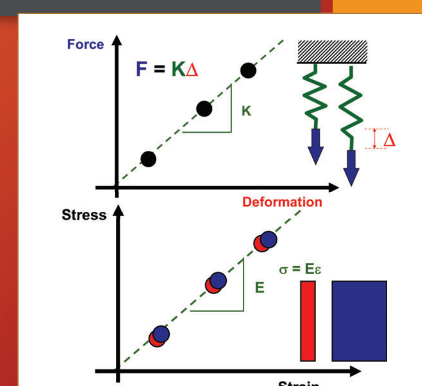
$$F = K\delta$$

- However stiffness is not a material property

$$\frac{F}{A} = K\frac{\delta}{L}$$

- Rather Modulus

$$E = K\frac{A}{L}$$



Resistance, Resistivity, and Geometry

- Analogy to Mechanics

$$F = K\delta$$

- However stiffness is not a material property

$$\frac{F}{A} = K\frac{\delta}{L}$$

- Rather Modulus

$$E = K\frac{A}{L}$$

- Ohms Law

$$V = RI$$

- However resistance is not a material property

$$\frac{V}{A} = R\frac{I}{L}$$

- Rather resistivity

$$\rho = R\frac{A}{L}$$

Why Does this Matter

- Simply said - electrical resistivity is a fundamental property of a material that measures how strongly it resists electric current.
  - It is independent of geometry (we will come back to this)
  - It is the inverse of conductivity

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

Geometry Factor (1/m)
Resistance (Ω)
Resistivity (Ωm)
Conductivity (S/m)

  - Silver 1.59 x 10^{-8} ohm m; Quartz 7.5 x 10^{17} ohm m

What is Concrete

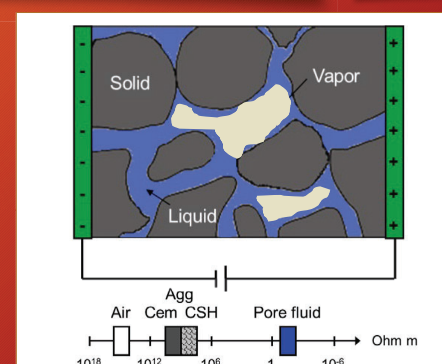
- Water
- Admixtures
- Cement
- SCM
- Air
- Sand
- Rock

Photo 33337841 / Concrete © Chris Van Lennep | Dreamstime.com

What is Concrete viewed Electrically

- Three Phases (Rajabipour 2006)
  - Solid 10^9 ohm-m (Aggregate, cement, CSH)
  - Liquid 0.05 to 1 ohm-m (Pore fluid)
  - Gas 10^{15} ohm-m (Vapor and air phases)

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



Simple Model for Resistors in Parallel

R= ρ L/A

$$\frac{1}{R_{Bulk}} = \frac{1}{R_{Liquid}} + \frac{1}{R_{Vapor}} + \frac{1}{R_{Solid}}$$

$$\frac{1}{\rho_{Bulk}} = \frac{\emptyset_{Liquid}\beta_{Liquid}}{\rho_{Liquid}} + \frac{\emptyset_{Vapor}\beta_{Vapor}}{\rho_{Vapor}} + \frac{\emptyset_{Solid}\beta_{Solid}}{\rho_{Solid}}$$

H.O.T.s

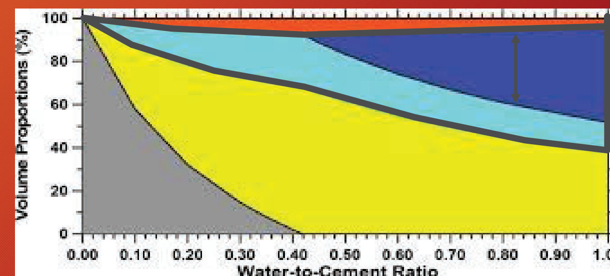
H.O.T.s

$$\rho_{Total} = \frac{\rho_{Liquid}}{\emptyset_{Liquid}\beta_{Liquid}} = \frac{\rho_{Pore\ Soln}}{\emptyset_{Pore\ Soln}\beta_{Pore\ Soln}}$$

Our Base Equation

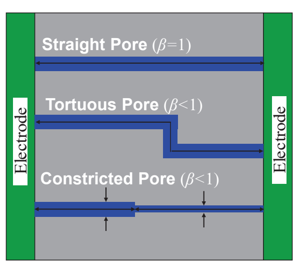
- Three Factors
- Porosity
- Connectivity
- Solution

$$\rho_{Total} = \frac{\rho_{Pore\ Soln}}{\emptyset_{Pore\ Soln}\beta_{Pore\ Soln}}$$



What is Connectivity (β)

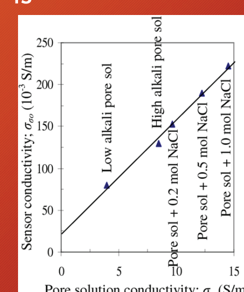
- Connectivity is impacted by
- Number of connected paths
- Tortuosity of the paths
- Constriction of the paths

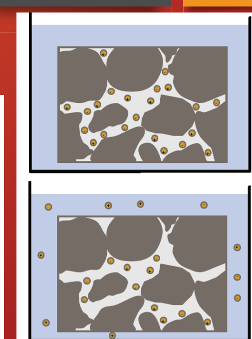


$$\rho_{Bulk} = \rho_{Pore} \cdot \frac{1}{\phi\beta} = \rho_{Pore} \cdot F$$

Solution Resistivity

- Many people do not realize how important the pore solution resistivity is
- If you have a system with more alkali in the cement or SCM the pore solution will be less resistive
- This plot shows a material as the solution is changed
- The solution impacts the results





Spragg et al. 2013

Temperature and Maturity

- Conductivity is a function of Maturity (hydration) and Temperature (conductivity)

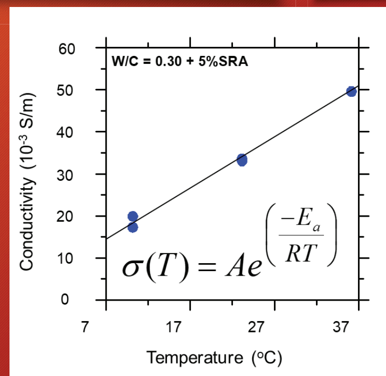
$$\sigma(t) = f(M) \cdot f(T)$$

$$f(M) = \int_0^t \exp\left[\frac{E_{aR}}{R} \cdot \left(\frac{1}{T} - \frac{1}{T_{REF}}\right)\right] \cdot dt$$

E_{aR} = 39.50 KJ/mole

$$f(T) = \frac{\sigma(T)}{\exp\left(-\frac{E_{aC}}{R} \cdot \left(\frac{1}{T} - \frac{1}{T_{REF.}}\right)\right)}$$

E_{aC} = 10 KJ/mole



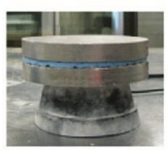
How Do we Test – Geometry

- Three Geometries
  - Uniaxial (Bulk)
  - Surface
  - Embedded Probes

Photo 28918875 © Alphaspirit | Dreamstime.com

Resistivity – From Bulk Measures

- Measures from end plate to end plate
- Uses conductive sponges that can be accounted for
- Least sensitive to surface curing or leaching
- Probes the largest volume of the sample

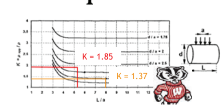


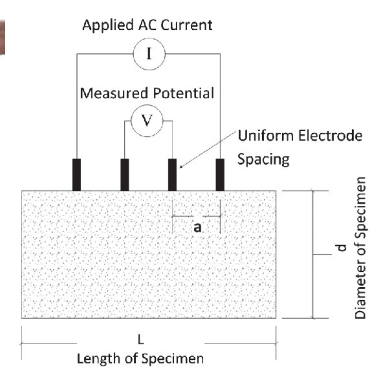
$$\rho = \frac{V}{I}\frac{A}{L} = \frac{RA}{L}$$

Resistivity – From Surface Measures

- Measures Between Pins
- Requires 8 measurements
- Moderately sensitive to surface curing or leaching

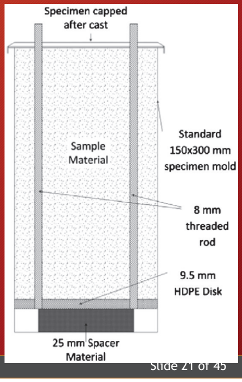
$$\rho = \frac{V}{I} \cdot 2\pi a \cdot \kappa$$





Resistivity – Embedded probes

- Individual geometry correction factors
- A lot of times sealed samples
- Will be the direction sensors move



When to Perform the Test

- In solution, we need to have atleast 7 days to allow the solutions to try to equilibrate
- It can be required at any time (generally 28 days (56 and 91 are used)
- For SCM
  - We want later age data when possible
  - This should not be 'matchy-matchy' (28d accelerated vs 91d)
  - This was based on one sided accelerated 28 day testing to get **atleast 91 day**
- Sealed can be continual (huge benefit)

Photo 28676185 © Andreykuzmin | Dreamstime.com

When Does it Matter (Testing Age)

- We can set criteria at any age … in concept
- What we really want is to know how the concrete will resist transport at later ages 3 mos.
- That said there is a contract time issue to get information back to contractors
- We have proposed a master curve and check to that curve as one approach

Illustration 101926093 © Ernest Akayeu | Dreamstime.com

What do the Numbers Mean

- Many folks have experience with the RCPT test
- We typically measure the charge passed (Q) at 6 hours
- The first column of this table is very familiar
- The second column can be directly calculated (painful detail shown above)

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

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

Weiss et al. 2016

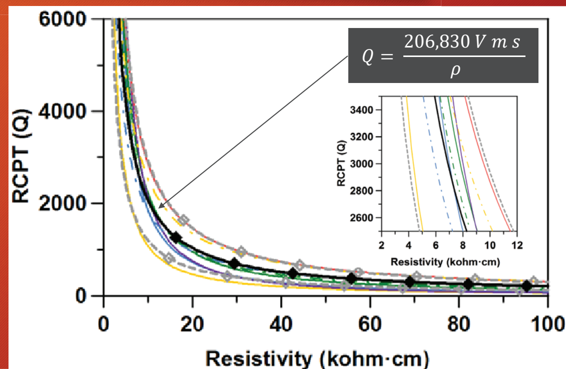
ASTM C1202 Classification[1]	Charge Passed (Coulombs)[1]	Resistivity (kOhm·cm)[2]
High	>4,000	<5.2
Moderate	2,000–4,000	5.2–10.4
Low	1,000–2,000	10.4–20.7
Very low	100–1,000	20.7–207
Negligible	<100	>207

[1]From ASTM C1202-12.
[2]Calculated using first principles.

Spragg et al. 2013

Review of Empirical RCPT vs Resistivity Data

- The black line is theory
- The data from literature is shown as the colored lines
- You will see that these vary from theory and it is our 'thought' that this is due to the sample preparation



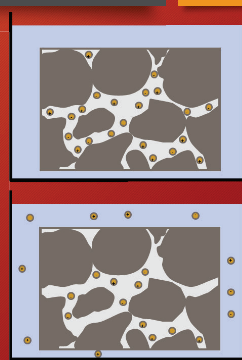
What can you control – Increasing resistivity

- If you have a low water content - ϕ decreases
- If you have less paste - ϕ decreases
- If you have a lower w/cm or dense SCM – β decreases

$$\rho_{Total} = \frac{\rho_{Liquid}}{\phi_{Liquid}\beta_{Liquid}} = \frac{\rho_{Pore\ Soln}}{\phi_{Pore\ Soln}\beta_{Pore\ Soln}}$$

Leaching – Alkali and CH

- Many people think of CH leaching; however, alkali (Na+, K+) can also leach.
- As a result the solution becomes less conductive and more resistive and this changes the measured response
- As a result, resistivity changes but the porosity and connectivity do not
- This is why the results change when one stores samples in water or in pore solution



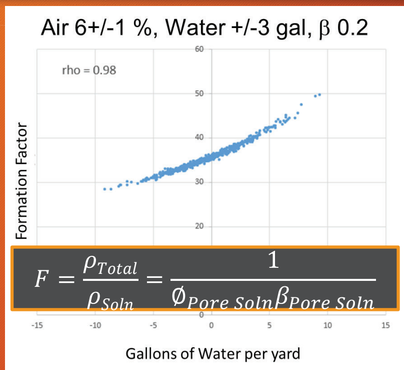
Spragg et al. 2013

What can you control – Increasing resistivity

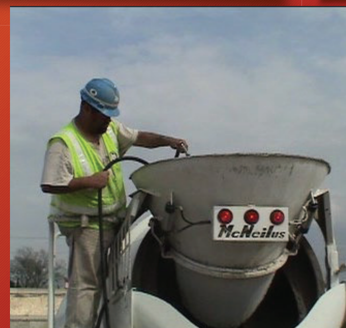
- If you have a low water content - ϕ decreases
- If you have less paste - ϕ decreases
- If you have a lower w/cm – β decreases
- If you leach alkalis - ρ_{ps} increases (but this is not a material measure it's a testing artifact)

$$\rho_{Total} = \frac{\rho_{Liquid}}{\phi_{Liquid}\beta_{Liquid}} = \frac{\rho_{Pore\ Soln}}{\phi_{Pore\ Soln}\beta_{Pore\ Soln}}$$

The Number one Issue



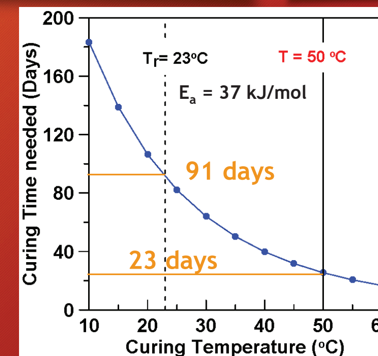
$$F = \frac{\rho_{Total}}{\rho_{Soln}} = \frac{1}{\phi_{Pore\ Soln}\beta_{Pore\ Soln}}$$



https://www.gardenstateconcrete.net/post/2016/10/10/adding-water-to-concrete-on-the-jobsite

Accelerated Curing

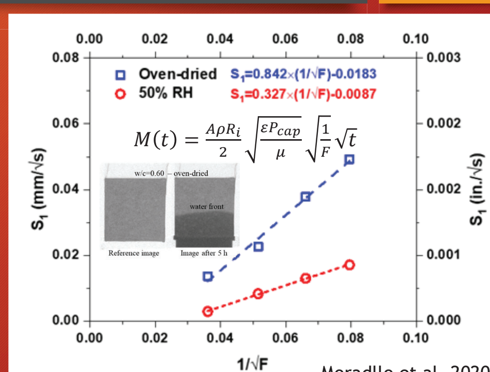
- For many mixtures with SCM folks want to know long term properties at early ages
- One sided statistical testing was developed to identify the correct activation energy and temperature to make sure the accelerated curing was 'atleast' 91 day values



Bu et al. 2014

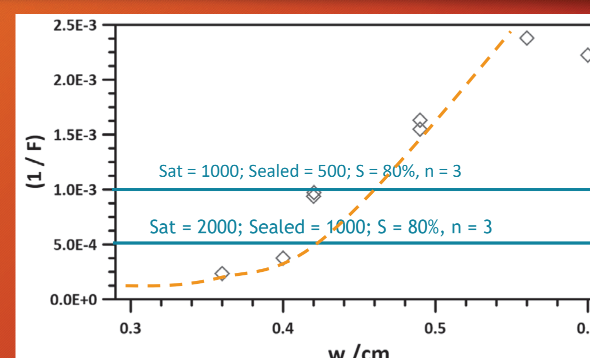
Correlation with Water Absorption

- Absorption is very important
- This allows resistivity to be used directly to obtain this test as well



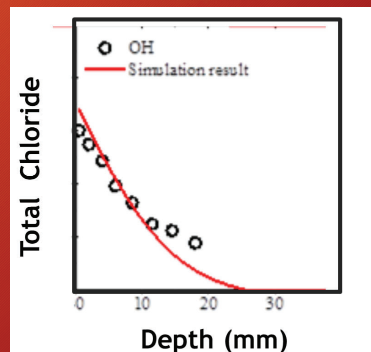
Moradllo et al. 2020

Relationship Between w/cm and 1/F



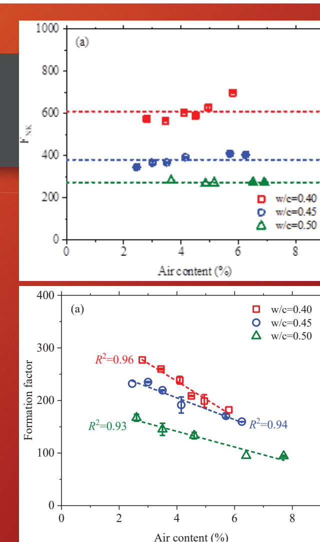
Chloride Ingress Approach

- We can use the resistivity (formation factor) to directly obtain the chloride profiles with and with out binding



Role of Air

- As discussed earlier air is non conductive, so why does RCPT or resistivity or formation factor depend on air content
- It has to do with vacuum saturation, we are 'artificially' filling in air voids with a conductive material
- If we only place concrete in solution these voids do not fill and air is not a factor

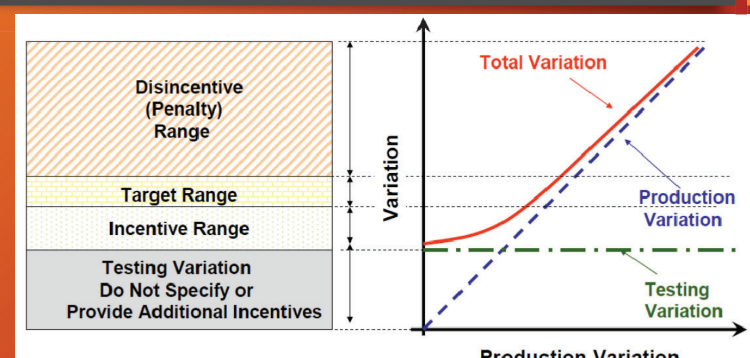


What's Next ?

- Previous precision and bias studies had slightly different protocols
- CP Tech leading FHWA study on Precision and Bias
  - Testing needed to separate operator variation (Pellinen et al 2009)
  - Curing variation (Spragg et al. 2013)
  - Production variation (Pellinen et al 2009)

Photo 80656638 / Whats Next © Aquarius83men | Dreamstime.com

Setting Variability Limits Based on "Performance"



Pellinen et al., 2005

Additional Item

- Many folks are ‘correcting’ for pore solution but not fully doing this correctly
- This really needs to be addressed
- We need to follow standards

Conclusion

- Resistivity – is a great tool for quality control and durability
- It is impacted by:
  - Test Geometry and Parameters - Geometry, signal (frequency/shape)
  - Mixture Characteristics - Pore volume, Pore connectivity, Pore Composition,
  - Sample Conditioning – Leaching, DOS, Temperature,
- However following directions in standards reduces these influences

Photo 34613323 © George Kroll | Dreamstime.com

Conclusion

- Standard Curing, Conditioning and Testing Procedures
  - Uniaxial TP 119 - Option A
  - Surface T 358 – Conditioning
- Curing and conditioning are two steps
- How do we design mixtures for good resistivity numbers – The same way we design good concrete mixtures
  - Medium/low w/cm with SCM
  - Low paste content (but not too low)