

## Resistivity Testing

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

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JTRP Testing - January 2013

## Why do we want electrical resistivity?

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



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## 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)



'Looking to reduce Soprano style pores'

- Transport is driven by pore solution volume and connectivity



## 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



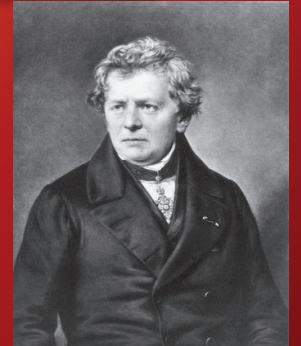
Photo 89780342 © Lukasz Janyst | Dreamstime.com

## 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'

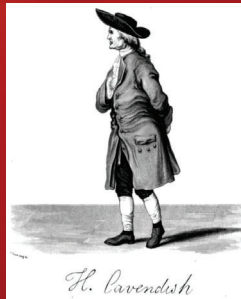


George Ohm

## 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 the first Cavendish Professor at Cambridge)

$$V = I R$$



Henry Cavendish

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

## Resistance, Resistivity, and Geometry

- Analogy to Mechanics

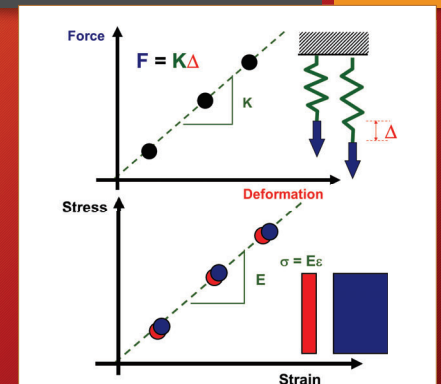
$$F = K \delta$$

- 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

$$F = K\delta$$

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

- 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

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

$\sigma$  ← Conductivity (S/m)  
 $\rho$  ← Resistivity ( $\Omega\text{m}$ )  
 $k$  ← Geometry Factor (1/m)  
 $R$  ← Resistance ( $\Omega$ )

- Silver  $1.59 \times 10^{-8}$  ohm m; Quartz  $7.5 \times 10^{17}$  ohm m

## What is Concrete

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

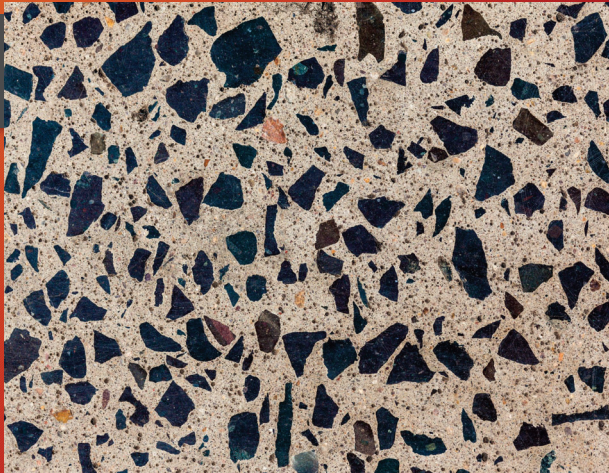


Photo 33337841 / Concrete © Chris Van Lennep | Dreamstime.com

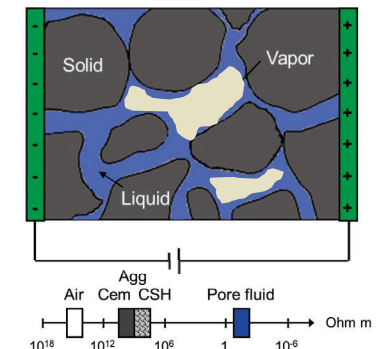
## What is Concrete viewed Electrically

- 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

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

$R = \rho L/A$

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

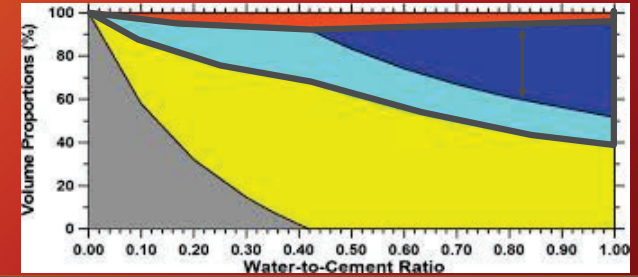
H.O.T.s

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

## Our Base Equation

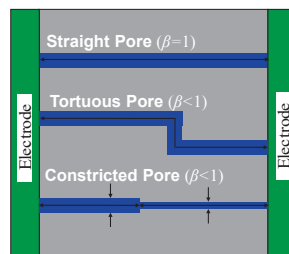
- Three Factors
- Porosity
- Connectivity
- Solution

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



## What is Connectivity ( $\beta$ )

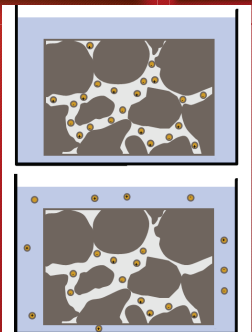
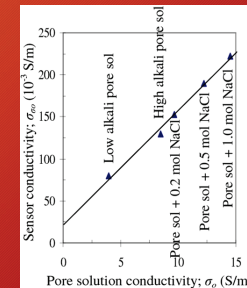
- Connectivity is impacted by
- Number of connected paths
- Tortuosity of the paths
- Constriction of the paths



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

## 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

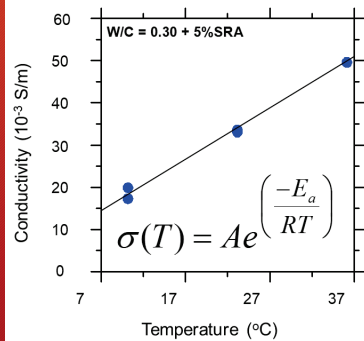
## Temperature and Maturity

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

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

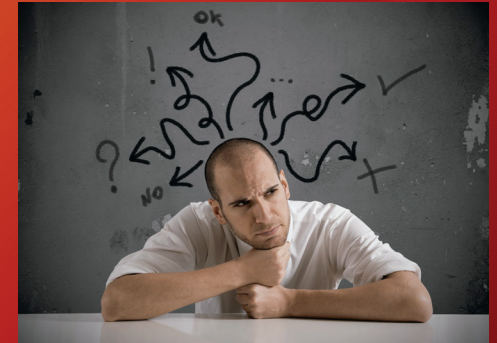
$$f(M) = \int_0^t \exp\left[\frac{E_{aR}}{R} \cdot \left(\frac{1}{T} - \frac{1}{T_{REF}}\right)\right] \cdot dt \quad E_{aR} = 39.50 \text{ KJ/mole}$$

$$f(T) = \frac{\sigma(T)}{\exp\left(-\frac{E_{aC}}{R} \cdot \left(\frac{1}{T} - \frac{1}{T_{REF}}\right)\right)} \quad E_{aC} = 10 \text{ KJ/mole}$$



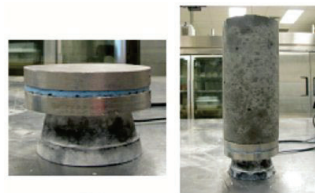
## How Do we Test - Geometry

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



## 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



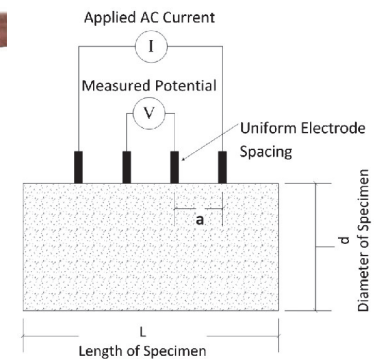
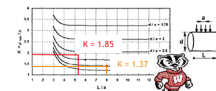
$$\rho = \frac{V}{I} \frac{A}{L} = \frac{RA}{L}$$

## Resistivity - From Surface Measures

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



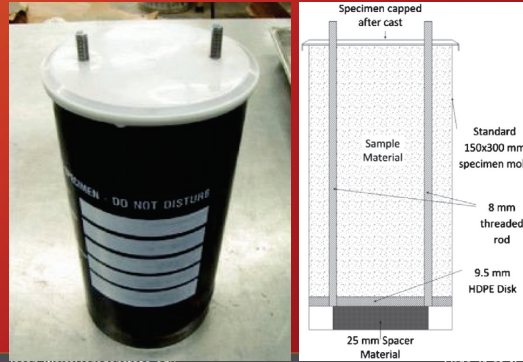
$$\rho = \frac{V}{I} \cdot 2\pi a \cdot \kappa$$





## 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 accelrated 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)

$$Q = \int_0^{6 \text{ hr}} I \, dt = \int_0^{6 \text{ hr}} \frac{V}{R} \, dt = \int_0^{6 \text{ hr}} \frac{V A}{\rho L} \, dt$$

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

Weiss et al. 2016

ASTM C1202 Classification <sup>1</sup>	Charge Passed (Coulombs) <sup>1</sup>	Resistivity (kOhm·cm) <sup>2</sup>
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

<sup>1</sup>From ASTM C1202-12.

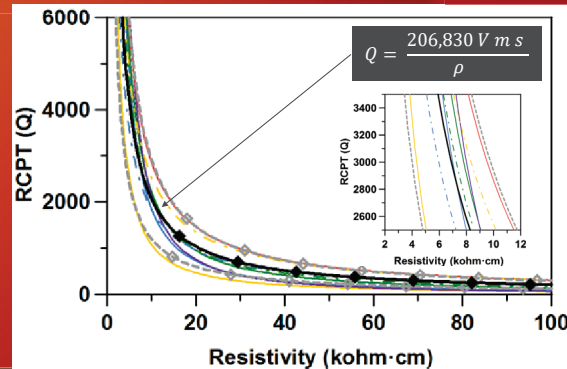
<sup>2</sup>Calculated using first principles.

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



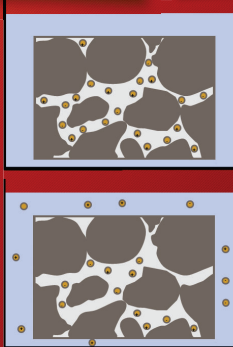
## What can you control - Increasing resistivity

- If you have a low water content -  $\phi$  decreases
- If you have less paste -  $\phi$  decreases
- If you have a lower w/cm or dense SCM -  $\beta$  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<sup>+</sup>, K<sup>+</sup>) 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

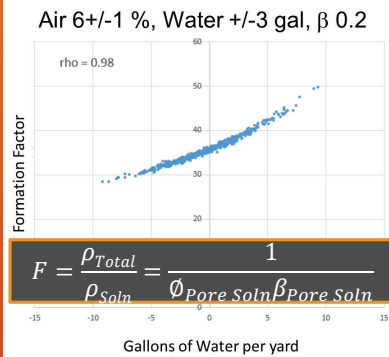


## What can you control - Increasing resistivity

- If you have a low water content -  $\phi$  decreases
- If you have less paste -  $\phi$  decreases
- If you have a lower w/cm -  $\beta$  decreases
- If you leach alkalis -  $\rho_{ps}$  increases (but this is not a material measure it's a testing artifact)

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

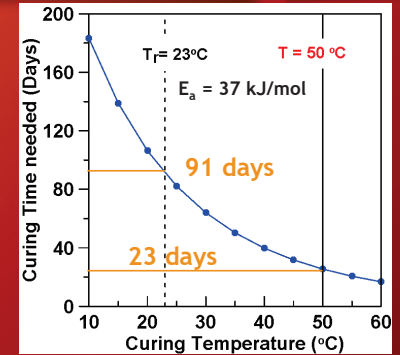
## The Number one Issue



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

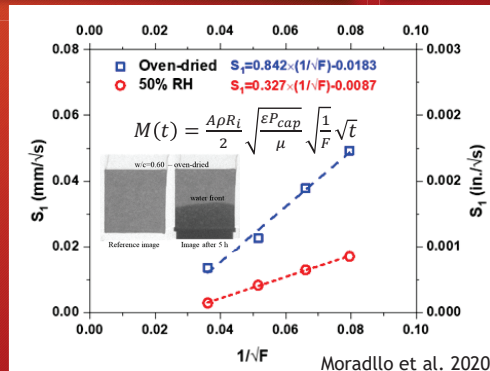
## Accelerated Curing

- 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

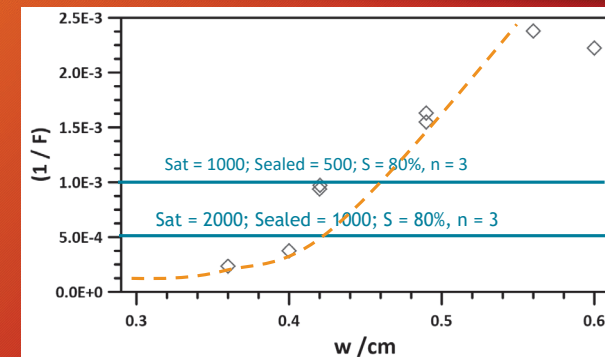


## Correlation with Water Absorption

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



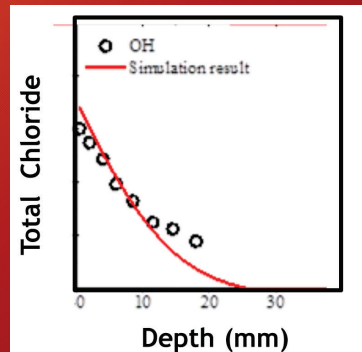
## Relationship Between w/cm and 1/F





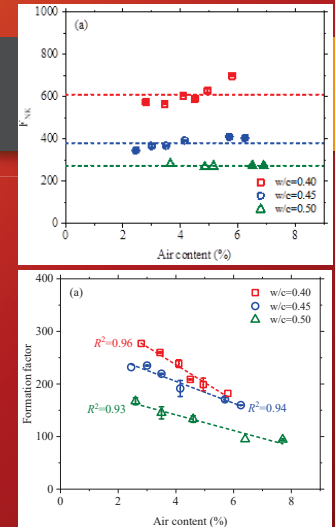
## Chloride Ingress Approach

- 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



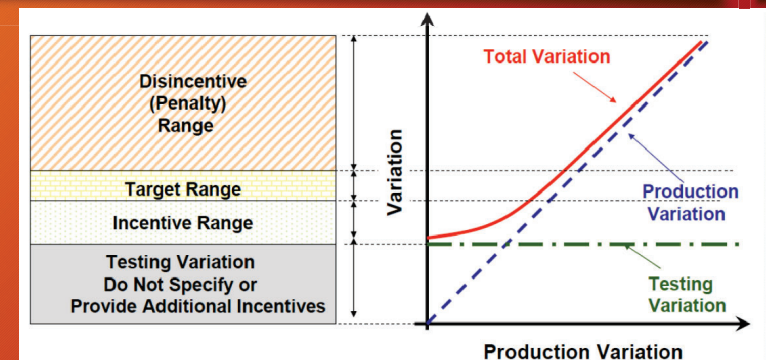
## What's Next ?

- 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



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## 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)