Concrete Durability
And the Value of Electrical Testing

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Outline

- Background – Basic Terms
- Background – Why Measure Electrical Properties
- Background – What Influences the Results
- Background – Important Outside Influences
- Conditioning
- Test Kit -- Proceq Resipod
- Test Methods
  - Uniaxial
  - Surface
- Using the spreadsheet
Starting with Basic Terms

• I want to start today's discussion with a few basic terms that we will use to make sure everyone is on the same page

• Electrical Resistance
• Electrical Resistivity
• Electrical Conductance
• Electrical Conductivity

• All Terms are Related and We Want to Be Clear
Ohms Law

• For a wide variety of materials have a relationship between voltage and current that are directly proportional to each other

\[ V = IR \]

• Proportionality constant
• Named after Georg Ohm (1827)
• Actually Discovered by Cavendish (1731-1810)
• “A professor who preached such heresies was unworthy to teach science”
• Is resistance a material property?

```
R = V / I
```

**Resistance**
Resistivity
Independent of Geometry

\[ \frac{RA}{L} = \rho \]

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

- The inverse of resistivity is conductivity ($\sigma$)

$$\sigma = \frac{1}{\rho} = \frac{L}{RA}$$
Uniaxial Test Geometry

\[ \rho = R \cdot \frac{A}{L} \]
OK – Now What

• So we measure resistance and compute a resistivity that is geometry independent
• But why are we doing this… Said simply who cares or why should we care about the electrical resistivity of the concrete
• Simply said – resistivity is related to durability but how is this the case
• We will see math but I want to look at the concept not the math
Durability Related to Transport

- Concrete protects steel from deicing salts
- Salt can be absorbed or can diffuse in the pores and when it reaches the rebar it can depassivate the steel and cause corrosion

Diagram:

- Deicing Salt
- Cover
- Reinforcing Bar
How Long Does it Take Chloride to Reach the Bar

- The chloride will migrate to the bar over time
- How long does it take to reach a critical level
- Depends on the quality of the concrete and the depth of the reinforcement

![Graph showing the relationship between time and chloride concentration at the bar reaching a critical value.](image-url)
• Concrete protects steel from deicing salts

\[ 1 - \text{erf} \left( \frac{x}{\sqrt{4Dt}} \right) = \frac{Cx - Co}{Cs - Co} \]

- \( x \) distance from surface
- \( t \) is time
- \( C \) is the chloride concentration
- \( D \) is a material property that describes the diffusion rate
Simply Said

- Higher D causes ions to move faster
  - High w/c (high porosity)
  - High paste content
- Lower D causes ions to move slower
  - Lower w/c
  - Supplementary SCM
- The Diffusion Coefficient is Difficult, Time Consuming and Costly to Obtain
Diffusion Coefficient

- D is Related to Electrical Properties of Concrete Using the Nernst-Einstein Eqn.

\[
\frac{\sigma_{Sample}}{\sigma_{Fluid}} = \frac{D}{D_{ion}} = \frac{\rho_{Fluid}}{\rho_{Sample}}
\]

\[
D = \sigma_{Sample} \cdot \frac{D_{ion}}{\rho_{Fluid}} = \frac{1}{\rho_{Sample}} \rho_{Fluid} D_{ion}
\]

\[
D = \sigma_{Sample} \times \text{Constant}
\]
Concrete as a Porous Material

- Which phases influence transport

  - Aggregate – Typ. low porosity and low transport
  - Paste - Transport occurs Hydration products, vapor, and fluid
Where Do Pores Come From

- Initially cement is the particles in the space and the water is the porosity.
- Over time cement reacts and the porosity fills in (densifies).
- The porosity ($\phi$) is related to the w/c.

\[
\phi = \frac{w/c}{w/c + \rho_w/\rho_c} \quad \rho_w = 1000 \text{ kg/m}^3 \quad \rho_c = 3150 \text{ kg/m}^3
\]
Power’s Model for Paste Fractions

Transport is largely driven by the capillary pores.

Capillary Porosity

Capillary Pores

Gel Water

Hydrated Solid

Unhydrated Cement

Volume Proportions (%)

Degree of Hydration (%)
Volume of Paste Phases (Sealed - Maximum Hydration)

Higher w/c, more capillary pores, higher permeability
Approximate Approach (Technically Not Correct but)

• The porosity can be fluid or vapor
• If the concrete is saturated the porosity is fluid filled
• Lets assume that all the phases of concrete are conductive, we can assume that the sample is the weighted average of the product of phase fractions ($\phi$) and the connectivity ($\beta$) of the phase fractions

$$\sigma_{\text{sample}} = \sigma_{\text{Fluid}} \phi_{\text{Fluid}} \beta_{\text{Fluid}} + \sigma_{\text{Solid}} \phi_{\text{Solid}} \beta_{\text{Solid}} + \sigma_{\text{Vapor}} \phi_{\text{Vapor}} \beta_{\text{Vapor}}$$
Mechanism of Electrical Conduction

- Solid phase (Cement, CSH, CH,…);
  \[
  \frac{1}{\rho_{\text{sol}}} \approx 10^{-9} \text{ S/m} 
  \]
  (Rajabipour 2006 based on results of Hammond and Robson 1955)

- Liquid phase (pore solution);
  \[
  \frac{1}{\rho_{\text{liq}}} \approx 1 \text{ S/m to } 20 \text{ S/m} 
  \]
  (Christensen 1993)

- Vapor phase (air voids, emptied pores);
  \[
  \frac{1}{\rho_{\text{vap}}} \approx 10^{-15} \text{ S/m} 
  \]
  (Aplin 2005)

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\sigma_{\text{sample}} = \sigma_{\text{Fluid}} \phi_{\text{Fluid}} \beta_{\text{Fluid}} + \sigma_{\text{Solid}} \phi_{\text{Solid}} \beta_{\text{Solid}} + \sigma_{\text{Vapor}} \phi_{\text{Vapor}} \beta_{\text{Vapor}}
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\[
\sigma_{\text{sample}} = \sigma_{\text{Fluid}} \phi_{\text{Fluid}} \beta_{\text{Fluid}}
\]

\[
\rho_t = \frac{\rho_0}{\phi \beta} = \rho_0 F
\]
What to we know

- Conductivity/Resistivity is related to

\[ \rho_c = \rho_o \cdot \frac{1}{\phi \beta} \]

- The properties of the fluid (electrolyte) ($\rho_o$)
  - Contains free ions - electrically conductive
  - Na+, K+, Ca2+, Mg2+, Cl-, HPO42-, HCO3

- The Volume of the Pores ($\phi$)

- The connectedness of the pores ($\beta$)
Other Electrical Measurements

- **Existing Standards:**
  
  ASTM C1202 / AASHTO T277

\[ V = IR \]

\[ Q = \int_0^{6h} Idt \]

\[ Q = \int_0^{6h} \frac{1}{\rho} \cdot [Vk] \, dt \]

**Limitations:**

- Expensive equipment
- Time consuming
- Heating effect
A Comment on Temperature and Moisture

Electrical Resistivity

Testing Temperature (°C)

Degree of Saturation, (S)

Degree of Saturation, (S) vs. Testing Temperature (°C)

Class C Concrete - 28 d

Class C Concrete - 120 d

w/c = 0.50

Experimental Data

VCCTL Simulation

VCCTL Simulation
Relationship to w/c

![Graph showing the relationship between electrical resistivity (ρ in ohm·m) and water-cement ratio (W/C). The resistivity decreases as the water-cement ratio increases.](chart.png)
Simple Summary

- Resistivity – Independent of Geometry
- Resistivity is related to Speed of Ions (Cl-) Moving in Concrete (Diffusion Coefficient)
- Resistivity is related to the volume of the pores and the connectedness of the pores
- One needs to think about pore solution
- One needs to keep in mind - test influenced by moisture (drying) or temperature changes
- The benefit – its fast and its non destructive
Testing Devices in Indiana

Components Being Used Conventionally
While there are a few manufacturers we will use Resipod today
Resipod

Power Button
Calibration -> Easy to do and needed to check results

Battery -> The Resipod should be put on the charger at least once a month. Incorrect readings will show up even before “low battery” warning
Uniaxial Resistivity

\[ \rho = R \cdot \frac{A}{L} \]

Benefits

- Less Impact of Conditioning
- Less Geometry Effects
Uniaxial Resistivity

![Uniaxial Resistivity Diagram](image)
Uniaxial

Measure Top & Bottom Sponge

- Additional Resistance: We can correct for these!
- Contact Weight: Resistance Loss
Uniaxial Measure Sample
Resipod automatically makes a few “corrections”

\[ \frac{43.2 \text{kΩ} \cdot \text{cm}}{24 \text{ cm}} = 1.8 \text{kΩ} \]

\[ \frac{2 \cdot 3.14 \cdot 3.8 \text{ cm}}{2 \pi a} = 24 \text{ cm} \]

\[ 1.8 \text{kΩ} \cdot \frac{A}{L} = 1.8 \text{kΩ} \cdot 4 \text{ cm} \]

\[ 7.2 \text{kΩ} \cdot \text{cm} \]

For a 4x8 cylinder:

\[ \frac{A}{L} = \frac{\pi \cdot (4 \cdot 2.54)^2 \text{cm}^2}{(8 \cdot 2.54) \text{ cm}} = 4 \text{ cm} \]

These steps are done automatically by the excel program described and available on the take-home discs.
### Road School – Electrical Resistivity

#### Sample Geometry

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<thead>
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<th>Length (mm)</th>
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<td>102</td>
<td>202</td>
</tr>
<tr>
<td>101</td>
<td>200</td>
</tr>
</tbody>
</table>

#### Sponge Resistances

- **Measured with:**
  - **TOP:** 0
  - **BOTTOM:** 0

#### Factors

- **SR:**
  - 1: 1.95
  - 2: 1.95
  - 3: 1.93

- **Meter:**
  - 24

- **DR:**
  - 4

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Date</th>
<th>Dark Temperature (°C)</th>
<th>Surface Configuration (kΩ·m cm)</th>
<th>Effective Surface Resistivity (kΩ·m cm)</th>
<th>Testing Age (d)</th>
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<th>Dark Resistivity (kΩ·m cm)</th>
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</table>

![RESISTIVITY CURVE](image)

- **RESISTIVITY CURVE**
  - **Surface Resistivity**
  - **Bulk Resistivity**
Surface Resistivity

\[ \rho = \frac{V}{I} \cdot \frac{2\pi a}{k} \]

**Benefits**

- Easy Test

**Drawbacks**

- Surface Effects
- Secondary Geometry Effects
• Originally for use in soil surveys “infinite half-space”

\[
\rho = \frac{V}{I} \cdot 2\pi a
\]

• Use in concrete cylinders shows add’l geometry influence

\[
\rho = \frac{V}{I} \cdot \frac{2\pi a}{k}
\]

For a 4x8,

\[
d/a = 2.7 \\
L/a = 5.3
\]

Morris, 1996
Surface Mark Specimen

- Lines are 90 degrees
- Helps to get a more representative measurement
Surface Measure Sample

• Take 2 measurements for each set of marks
• Ensure good contact on the cylinder
Surface Interpretation

\[ \rho = \frac{V}{I \cdot \frac{2\pi a}{k}} \]

Resipod automatically applies \(2\pi a\)

This is dependent on geometry, a good first approximation for a 4x8 cylinder:

\[ k = 1.9 \]

\[ \frac{11.0 \, k\Omega \cdot cm}{k} = \frac{11.0 \, k\Omega \cdot cm}{1.9} \]

\[ 5.9 \, k\Omega \cdot cm \]

These steps are done automatically by the excel program described and available on the take-home discs.
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**RESISTIVITY CURVE**

- Surface Resistivity
- Bulk Resistivity

Mixed data points showing a trend in resistivity over mixture age.
## Road School – Electrical Resistivity

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### Sponge Resistances

<table>
<thead>
<tr>
<th>Plate</th>
<th>TOP</th>
<th>BOTTOM</th>
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</thead>
<tbody>
<tr>
<td>Measured with</td>
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### Factors

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<tr>
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### Resistivity Curve

- **Surface Resistivity**
- **Bulk Resistivity**

### Resistivity Testing - Curve Development

- Contractor: Lab Mixture
- Cast Date/Time: 8/4/2011

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**Spreadsheet**

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**RESISTIVITY CURVE**

- **Surface Resistivity**
- **Bulk Resistivity**

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- **Resistivity (kOhm-cm)**
- **Mixture Age (d)**

---

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</table>
Volume of solution surrounding is important

For standardization, we are recommending:
3 – 4x8s in a 5 gal. bucket of saturated lime water

Samples are covered by 1.5 inches of lime water

Sol / Samp = 2.0
We have 3 stations for hands-on

We will practice:
- Surface Testing
- Uniaxial Testing
- Calibrating Equipment
- Marking Samples
- Filling out spreadsheet