Electrical Methods for Estimating the Chloride Resistance of Concrete

Michael Thomas, Ted Moffatt & Huang Yi
University of New Brunswick

David E. Smith
Levelton Consultants Ltd.

Electrical Methods for Characterization and Monitoring of Concrete Materials and Structures

ACI Fall 2013 Convention, October 2013, Phoenix, AZ

Co-Sponsored by ACI 222, 228, ACI-ASCE 444
Electrical Methods for Estimating the Chloride Resistance of Concrete

- Resistivity
  - Conductivity
  - “Chloride Permeability”

- Migration tests
  - Chloride flux
  - Breakthrough

- Rapid migration test

Measuring Electrical Resistivity, $\rho$

\[ R = \frac{V}{I} \]

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

$\rho$ = resistivity (\(\Omega\cdot m\))

$R$ = resistance (\(\Omega\))

$V$ = potential (Volts)

$I$ = current (Amps)

$A$ = sample area (m\(^2\))

$l$ = sample length (m)

Electrical Conductivity, $\sigma$ (S/m)

\[ \sigma = \frac{1}{\rho} \]
D.C. Resistivity

Cycle voltage between 3 and 5 volts every 5 seconds for 15 minutes:

\[
\rho = \frac{(V_5 - V_3) \cdot A}{(I_5 - I_3) \cdot L}
\]

\(\rho\) = resistivity (\(\Omega\)-cm)

\(I_5\) = current (Amps) at \(V_5\) volts

\(I_3\) = current (Amps) at \(V_3\) volts

\(A\) = cross-sectional area (cm\(^2\))

\(L\) = length (cm)
Electrical Resistivity \[ \rho = \left(\frac{V}{I}\right) \cdot \left(\frac{\pi d^2}{4l}\right) \]

where:
- \( \rho \) = resistivity in \( \Omega \cdot m \)
- \( V \) = applied voltage, V
- \( I \) = current, A
- \( d \) = specimen diameter, m
- \( l \) = specimen length, m

Electrical Conductivity \[ \sigma = K \frac{I_1}{V} \cdot \frac{L}{D^2} \]

- \( \sigma \) = bulk electrical conductivity, mS/m,
- \( I_1 \) = current at 1 min, mA,
- \( V \) = applied voltage, V,
- \( L \) = average length of specimen, mm
- \( D \) = average diameter of specimen, mm,
- \( K \) = conversion factor = 1273.2

The SI unit for electrical conductivity is siemens/metre.
4-Point Probe

\[ \rho = 2\pi a \cdot \frac{V}{I} \]
If $\rho = 182 \text{ } \Omega \cdot \text{m}$ ($\sigma = 5.5 \text{ mS/m}$) the charge passed through a standard-size specimen ($\phi 3.75$-in. x 2-in.) in the “Rapid Chloride Permeability Test” (ASTM C 1202) would be approximately $1000 \text{ Coulombs}$ (6h at 60V).
Electrical resistance of saturated concrete is primarily dependent on:
Electrical resistance of saturated concrete is primarily dependent on:

- Pore structure
  - Volume, size & connectivity of pores
Electrical resistance of saturated concrete is primarily dependent on:

- **Pore structure**
  - Volume, size & connectivity of pores
- **Composition of pore solution**
  - Concentration of ions

More *ions* in solution – increased electrical conductivity – i.e. reduced electrical resistance
Electrical resistance of saturated concrete is primarily dependent on:

- **Pore structure**
  - Volume, size & connectivity of pores
- **Composition of pore solution**
  - Concentration of ions

Chloride resistance of saturated concrete is primarily dependent on:
Electrical resistance of saturated concrete is primarily dependent on:

- Pore structure
  - Volume, size & connectivity of pores
- Composition of pore solution
  - Concentration of ions

Chloride resistance of saturated concrete is primarily dependent on:

- Pore structure
  - Volume, size & connectivity of pores
Electrical resistance of saturated concrete is primarily dependent on:

- Pore structure
  - Volume, size & connectivity of pores

- Composition of pore solution
  - Concentration of ions

Chloride resistance of saturated concrete is primarily dependent on:

- Pore structure
  - Volume, size & connectivity of pores

- Composition of cement hydrates
  - Ability of hydrates to bind chlorides
Electrical resistance of saturated concrete is primarily dependent on:

- Pore structure
  - Volume, size & connectivity of pores
- Composition of pore solution
  - Concentration of ions

Chloride resistance of saturated concrete is primarily dependent on:

- Pore structure
  - Volume, size & connectivity of pores
- Composition of cement hydrates
  - Ability of hydrates to bind chlorides
Electrical resistance of saturated concrete is primarily dependent on:

- Pore structure
  - Volume, size & connectivity of pores
- Composition of pore solution
  - Concentration of ions

Hydraulic conductivity is primarily dependent on:

- Pore structure
  - Volume, size & connectivity of pores
ASTM C 1556 Test to Determine the Bulk Diffusion Coefficient of Concrete

Concrete sample is immersed in NaCl solution for time $t$ (minimum 35 days)
Sample then ground in approx. 1-mm depth increments
Dust samples analyzed for chlorides →
To produce chloride profile ↓

\[
\frac{C_x}{C_0} = 1 - \text{erf}\left(\frac{x}{2\sqrt{D_a \cdot t}}\right)
\]

$C_0$ and $D_a$ found by fitting the equation shown to the measured profile.

Values of $D_a$ typically in the range:

$1 \times 10^{-13}$ to $1 \times 10^{-11}$ m$^2$/s
RCPT vs. Bulk Diffusion

RCPT (Coulombs) vs. Diffusion Coefficient (m²/s)

10^12 to 10^11

1000 Coulombs

PCA R&D Serial No. 2821a
RCPT vs. Electrical Resistivity

Resistivity (kΩ-cm)

RCP (Coulombs)
Superior performance of concrete with SCM at Treat Island has been confirmed for fly ash, slag and silica fume (and ternary cement blends with silica fume plus fly ash).

<table>
<thead>
<tr>
<th>Phase</th>
<th>Year</th>
<th>$w/cm$</th>
<th>SCM replacement level, % of total cementitious material content</th>
<th>Other details</th>
</tr>
</thead>
<tbody>
<tr>
<td>I(A)</td>
<td>1978</td>
<td>0.40 to 0.60</td>
<td>0, 25, 45, 65 SG</td>
<td>—</td>
</tr>
<tr>
<td>I(B)</td>
<td>1978</td>
<td>0.50</td>
<td>None</td>
<td>AE and non-AE</td>
</tr>
<tr>
<td>II</td>
<td>1979</td>
<td>0.40 to 0.60</td>
<td>0, 25 FA, 20/40 and 20/60 FA/SG</td>
<td>—</td>
</tr>
<tr>
<td>III</td>
<td>1980</td>
<td>0.40 to 0.60</td>
<td>0, 25, 45, 66 SG</td>
<td>LWA</td>
</tr>
<tr>
<td>IV</td>
<td>1981</td>
<td>0.40 to 0.60</td>
<td>0, 25 FA</td>
<td>—</td>
</tr>
<tr>
<td>V(A)</td>
<td>1982</td>
<td>0.40 to 0.60</td>
<td>0, 80 SG</td>
<td>—</td>
</tr>
<tr>
<td>V(B)</td>
<td>1982</td>
<td>0.60</td>
<td>0, 10, 15, 20 SF</td>
<td>AE and non-AE</td>
</tr>
<tr>
<td>VI</td>
<td>1985</td>
<td>0.40 to 0.60</td>
<td>0, 6.5 SF, 13.5 FA</td>
<td>Steel fibers</td>
</tr>
<tr>
<td>VII</td>
<td>1986</td>
<td>0.26, 0.33</td>
<td>6, 7.5 SF</td>
<td>Ready mixed concrete</td>
</tr>
<tr>
<td>VIII</td>
<td>1987</td>
<td>0.40 to 0.45, 0.31 to 0.35</td>
<td>Control (no SCM) 56 FA</td>
<td>—</td>
</tr>
<tr>
<td>IX</td>
<td>1987</td>
<td>0.50</td>
<td>0, 10 SF, 25 FA, 50 SG</td>
<td>Steel bars with 20 to 70 mm (3/4 to 2.75 in.) nominal cover</td>
</tr>
<tr>
<td>X</td>
<td>1988</td>
<td>0.36, 0.40</td>
<td>7 SF</td>
<td>LWA</td>
</tr>
<tr>
<td>XI</td>
<td>1990</td>
<td>0.38</td>
<td>56 FA</td>
<td>LWA</td>
</tr>
<tr>
<td>XII</td>
<td>1991</td>
<td>0.45, 0.60</td>
<td>None</td>
<td>Epoxy-coated and plain steel bars</td>
</tr>
<tr>
<td>XIII</td>
<td>1992</td>
<td>0.33</td>
<td>56 FA</td>
<td>—</td>
</tr>
<tr>
<td>XIV</td>
<td>1994</td>
<td>0.40</td>
<td>0, 10 SF, 20 and 30 FA</td>
<td>Reactive aggregate</td>
</tr>
</tbody>
</table>

LWA is lightweight aggregate; AE is air-entrained concrete; SG is slag cement; FA is fly ash; and SF is silica fume.
25-Year-Old Marine-Exposed Concrete Blocks

Surface Resistivity, $\rho$ (Ω·m)

Diffusion Coefficient, $D$ ($\times 10^{-12}$ m²/s)

- 65% Slag
- 45% Slag
- 25% Slag
- 0% Slag

PCA R&D Serial No. 2821a
Factors Affecting Resistivity

- Degree of saturation
  - Self-desiccation
  - Drying
- Leaching
- Chloride ingress
- Carbonation
- Rebar

Resistivity, $\rho$ (\(\Omega\cdot m\))

Graph showing:
- Stored in 1% CO$_2$ (60% RH)
  - Resaturated before test
- Stored in N$_2$ (60% RH)
  - Resaturated before test

Cycles

Resistivity, $\rho$ (\(\Omega\cdot m\))

PCA R&D Serial No. 2821a
- Degree of saturation
  - Self-desiccation
  - Drying
- Leaching
- Chloride ingress
- Carbonation
- Rebar

Factors Affecting Resistivity

Tests conducted on mortar cubes

Resistivity, \( \rho \) (\( \Omega \cdot m \))

stored in tap water

stored in "model" pore solution

Age (days)
- Degree of saturation
  - Self-desiccation
  - Drying
- Leaching
- Chloride ingress
- Carbonation
- Rebar

Factors Affecting Resistivity

Resistivity, $\rho$ (\(\Omega\cdot m\))

Age (days)

Insitu surface measurements
Tests on cores
Factors Affecting Resistivity

- Degree of saturation
  - Self-desiccation
  - Drying
- Leaching
- Chloride ingress
- Carbonation
- Rebar
Maxwell’s Eqn:

\[
\frac{\rho_m - 1}{\rho} = \frac{V_a}{\rho_m + 2} \frac{\rho_m - 1}{\rho_a + 2} \]

\(\rho_m\) = resistivity of matrix
\(\rho\) = resistivity of composite
\(\rho_a\) = resistivity of aggregate
\(V_a\) = volume fraction of aggregate
Chloride Resistance: Rapid-Set Cements

ASTM C 1202
“Rapid Chloride Permeability”

PC-CAC-C$ is a ternary blend of:
- Portland cement
- Calcium-aluminate cement
- Gypsum

CSA-C2S is a blend of:
- Calcium-alumino-sulfate (Klein’s compound)
- Belite

Charged Passed (Coulombs)

Binder

- PC
- PC-CAC-C$
- C$A-C2S

28-day
91-day
Chloride Resistance: Rapid-Set Cements

**ASTM C 1202**
“Rapid Chloride Permeability”

- **PC**
- **PC-CAC-C$\$**
- **C$\$A-C2S**

<table>
<thead>
<tr>
<th>Charged Passed (Coulombs)</th>
<th>28-day</th>
<th>91-day</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>2000</td>
<td>1000</td>
</tr>
<tr>
<td>PC-CAC-C$$</td>
<td>4000</td>
<td>3000</td>
</tr>
<tr>
<td>C$$A-C2S</td>
<td>3000</td>
<td>2000</td>
</tr>
</tbody>
</table>

**ASTM C 1567**
“Chloride Diffusion”

- **PC**
- **PC-CAC-C$\$**
- **C$\$A-C2S**

<table>
<thead>
<tr>
<th>Chloride Content (%)</th>
<th>Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>0</td>
</tr>
<tr>
<td>1.0</td>
<td>10</td>
</tr>
<tr>
<td>0.8</td>
<td>20</td>
</tr>
<tr>
<td>0.6</td>
<td>30</td>
</tr>
<tr>
<td>0.4</td>
<td>40</td>
</tr>
</tbody>
</table>

Chloride Resistance: Rapid-Set Cements

**ASTM C 1202**
“Rapid Chloride Permeability”

- **PC**
- **PC-CAC-C$\$**
- **C$\$A-C2S**

<table>
<thead>
<tr>
<th>Charged Passed (Coulombs)</th>
<th>28-day</th>
<th>91-day</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>2000</td>
<td>1000</td>
</tr>
<tr>
<td>PC-CAC-C$$</td>
<td>4000</td>
<td>3000</td>
</tr>
<tr>
<td>C$$A-C2S</td>
<td>3000</td>
<td>2000</td>
</tr>
</tbody>
</table>

**ASTM C 1567**
“Chloride Diffusion”

- **PC**
- **PC-CAC-C$\$**
- **C$\$A-C2S**

<table>
<thead>
<tr>
<th>Chloride Content (%)</th>
<th>Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>0</td>
</tr>
<tr>
<td>1.0</td>
<td>10</td>
</tr>
<tr>
<td>0.8</td>
<td>20</td>
</tr>
<tr>
<td>0.6</td>
<td>30</td>
</tr>
<tr>
<td>0.4</td>
<td>40</td>
</tr>
</tbody>
</table>
### Table 5.5: Recommended Chloride Ion Penetrability Based on Resistivity

<table>
<thead>
<tr>
<th>Risk</th>
<th>RCPT (Coulombs)</th>
<th>Wenner (Ω-m)</th>
<th>//Plate – 200mm (Ω-m)</th>
<th>//Plate – 50mm (Ω-m)</th>
<th>AC-Cell (Ω-m)</th>
<th>DC-Cell (Ω-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>&gt;4000</td>
<td>&lt;50</td>
<td>&lt;70</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;50</td>
</tr>
<tr>
<td>Moderate</td>
<td>2000-4000</td>
<td>100-50</td>
<td>130-70</td>
<td>100-50</td>
<td>80-50</td>
<td>100-50</td>
</tr>
<tr>
<td>Low</td>
<td>1000-2000</td>
<td>200-100</td>
<td>250-130</td>
<td>200-100</td>
<td>170-80</td>
<td>200-100</td>
</tr>
<tr>
<td>Very Low</td>
<td>100-1000</td>
<td>2300-200</td>
<td>2300-250</td>
<td>2600-200</td>
<td>2000-170</td>
<td>2000-200</td>
</tr>
<tr>
<td>Negligible</td>
<td>&lt;100</td>
<td>&gt;2300</td>
<td>&gt;2300</td>
<td>&gt;2600</td>
<td>&gt;2000</td>
<td>&gt;2000</td>
</tr>
</tbody>
</table>