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Electrical Methods to Characterize and Monitor Concrete

ACI Fall 2013 Convention
October 20 - 24, Phoenix, AZ

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Electrical Methods for Estimating the Chloride Resistance of Concrete

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LEVELTON

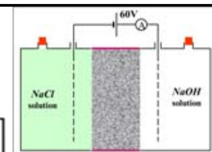
Electrical Methods for Characterization and Monitoring of Concrete Materials and Structures

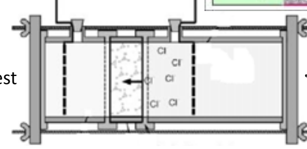
ACI Fall 2013 Convention, October 2013, Phoenix, AZ

Co-Sponsored by ACI 222, 228, ACI-ASCE 444

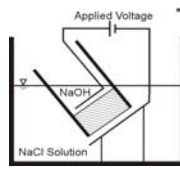
Electrical Methods for Estimating the Chloride Resistance of Concrete

- Resistivity
  - Conductivity
  - "Chloride Permeability"
- Migration tests
  - Chloride flux
  - Breakthrough
- Rapid migration test





$$J = D_{fx} C \cdot \frac{zFE}{RT}$$



$$D_{nssm} = \frac{RTL}{zFU} \cdot \frac{x_d - \alpha\sqrt{x_d}}{t}$$

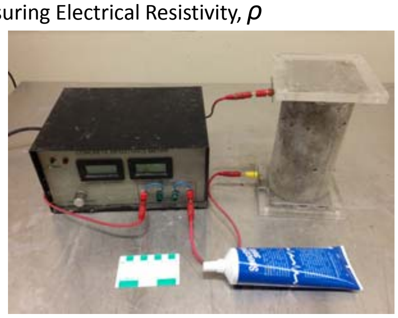
Stanish, K.D., Hooton, R.D., and Thomas, M.D.A., 2001, *Prediction of Chloride Penetration in Concrete*, US Department of Transportation, Federal Highway Administration, Publication No. FHWA-RD-00-142.

Measuring Electrical Resistivity, ρ

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

$$\rho = R \cdot \frac{A}{l}$$

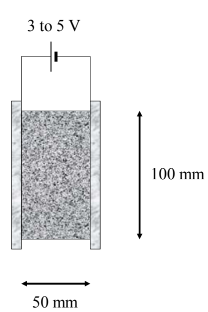
ρ = resistivity (Ω·m)
R = resistance (Ω)
V = potential (Volts)
I = current (Amps)
A = sample area (m²)
l = sample length (m)



Electrical Conductivity, σ (S/m)

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

D.C. Resistivity

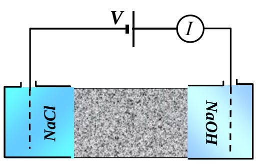


Cycle voltage between 3 and 5 volts every 5 seconds for 15 minutes:

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

ρ = resistivity (Ω-cm)
I_5 = current (Amps) at V_5 volts
I_5 = current (Amps) at V_5 volts
A = cross-sectional area (cm²)
L = length (cm)

ASTM C 1760 Bulk Conductivity of Concrete



Electrical Resistivity $\rho = \left(\frac{V}{I}\right)\cdot\left(\frac{\pi d^2}{4l}\right)$

where: ρ = resistivity in Ω-m
V = applied voltage, V
I = current, A
d = specimen diameter, m
l = specimen length, m

ASTM C 1760

- Cylinders 100 x 200 mm
- Cores ≥ 100 mm long
- PC cure for 28 days at 23°C
- SCM cure for 56 days at 23°C or 7d at 23°C & 21d at 38°C

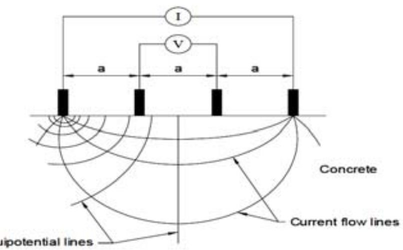
Electrical Conductivity $\sigma = K\frac{I_1}{V}\cdot\frac{L}{D^2}$

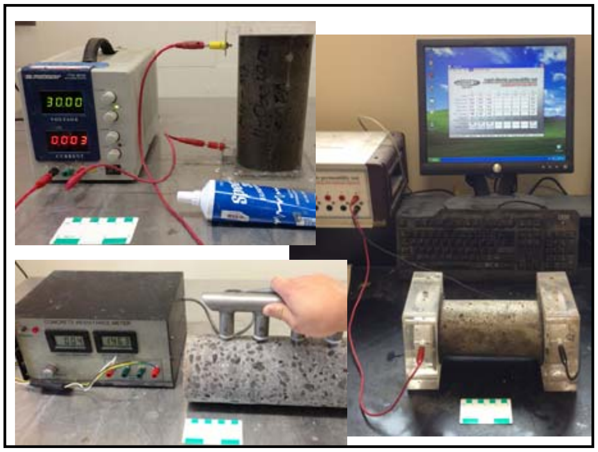
σ = bulk electrical conductivity, mS/m,
I_1 = current at 1 min, mA,
V = applied voltage, V,
L = average length of specimen, mm
D = average diameter of specimen, mm,
K = conversion factor = 1273.2.

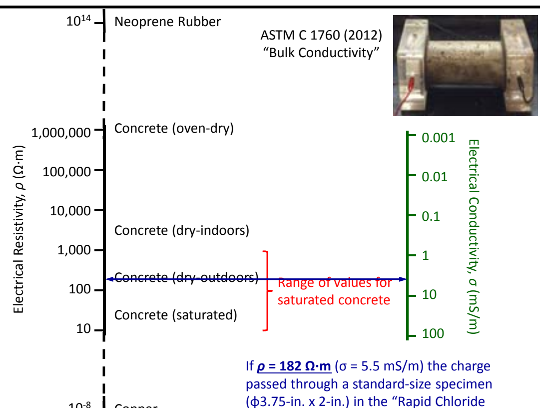
The SI unit for electrical conductivity is siemens/metre

4-Point Probe

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



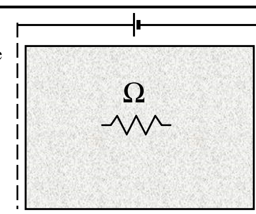




Adapted from Whiting & Nagi, 2003

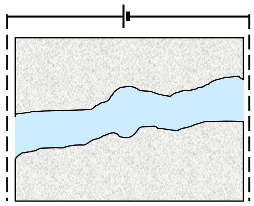
If **ρ = 182 Ω·m** (σ = 5.5 mS/m) the charge passed through a standard-size specimen (ϕ3.75-in. x 2-in.) in the "Rapid Chloride Permeability Test" (ASTM C 1202) would be approximately **1000 Coulombs** (6h at 60V)

Electrical resistance of saturated concrete is primarily dependent on:



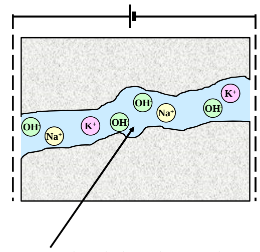
Electrical resistance of saturated concrete is primarily dependent on:

- ➢ 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

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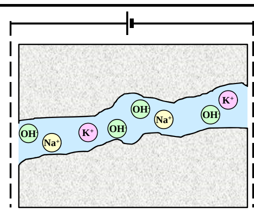

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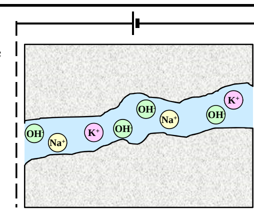

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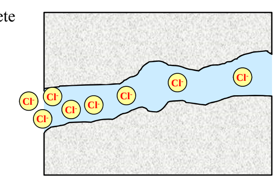

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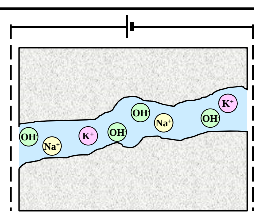
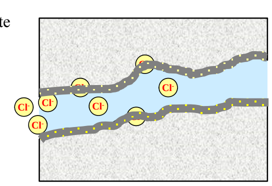


Chloride resistance of saturated concrete is primarily dependent on:

- ➢ Pore structure
  - Volume, size & connectivity of pores
- ➢ Composition of **cement hydrates**
  - Ability of hydrates to bind chlorides



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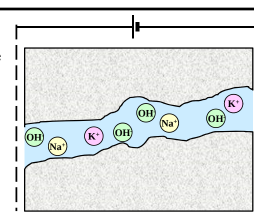

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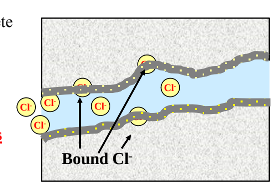

Electrical resistance of saturated concrete is primarily dependent on:

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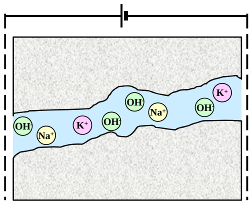
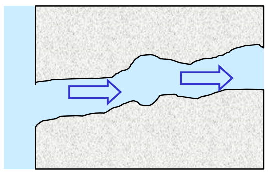
  - Volume, size & connectivity of pores
- Composition of **pore solution**
  - Concentration of ions



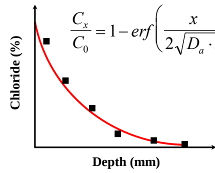
Hydraulic conductivity is primarily dependent on:

- 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 ↓

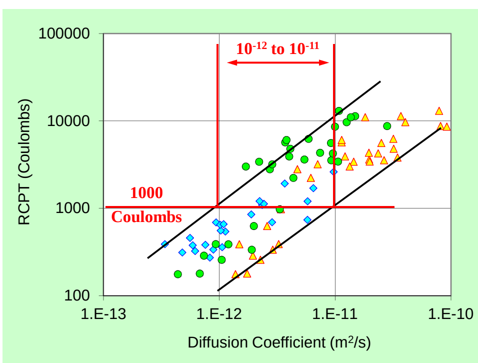


$$\frac{C_x}{C_0} = 1 - erf\left(\frac{x}{2\sqrt{D_a \cdot t}}\right)$$

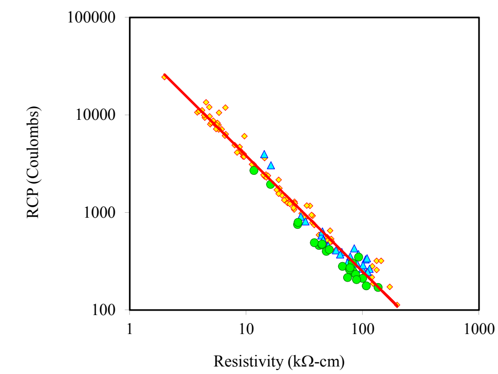
C_o and D_a found by fitting the equation shown to the measured profile.

Values of D_a typically in the range:
1 x 10^{-13} to 1 x 10^{-11} m^2/s

RCPT vs. Bulk Diffusion



RCPT vs. Electrical Resistivity

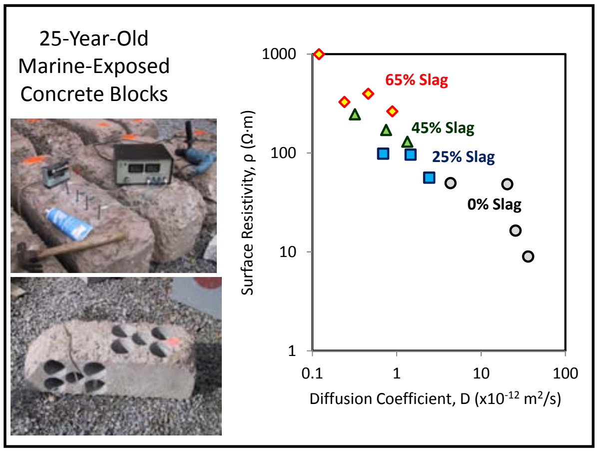


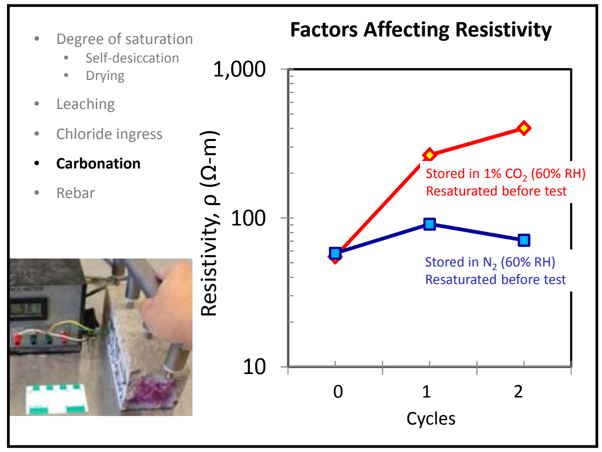
Superior performance of concrete with SCM at Treat Island has been confirmed for fly ash, slag and silica fume (and ternary cement blends with silica fume plus fly ash)

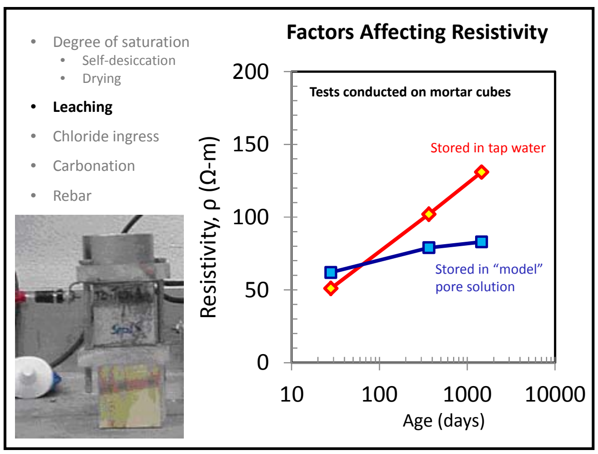
Phase	Year	w/cm	SCM replacement level, % of total cementitious material content	Other details
I(A)	1978	0.40 to 0.60	0, 25, 45, 65 SG	—
I(B)	1978	0.50	None	AE and non-AE
II	1979	0.40 to 0.60	0, 25 FA, 20/40 and 20/60 FA/SG	—
III	1980	0.40 to 0.60	0, 25, 45, 65 SG	LWA
IV	1981	0.40 to 0.60	0, 25 FA	—
V(A)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

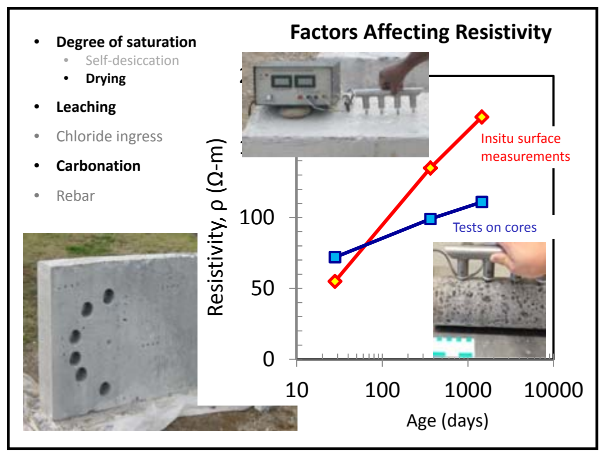
LWA is lightweight aggregate; AE is air-entrained concrete; SG is slag cement; FA is fly ash; and SF is silica fume

Concrete International, Nov 2011

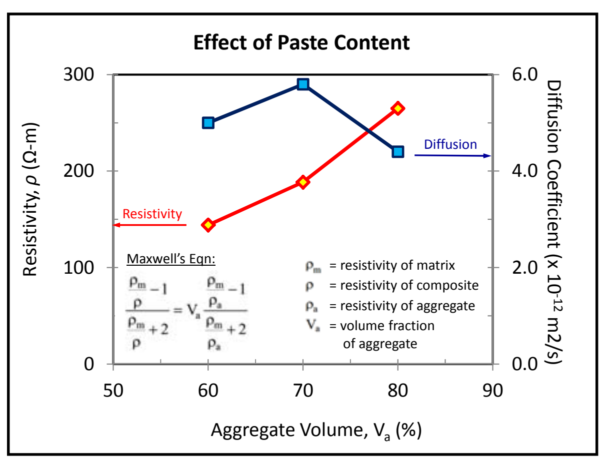

25-Year-Old
Marine-Exposed
Concrete Blocks
Surface Resistivity, ρ (Ω·m)
1000
100
10
1
0.1
1
10
100
Diffusion Coefficient, D (x10^-12 m²/s)
65% Slag
45% Slag
25% Slag
0% Slag


Degree of saturation
Self-desiccation
Drying
Leaching
Chloride ingress
Carbonation
Rebar
Factors Affecting Resistivity
Resistivity, ρ (Ω-m)
1,000
100
10
0
1
2
Cycles
Stored in 1% CO2 (60% RH)
Resaturated before test
Stored in N2 (60% RH)
Resaturated before test


Degree of saturation
Self-desiccation
Drying
Leaching
Chloride ingress
Carbonation
Rebar
Factors Affecting Resistivity
Tests conducted on mortar cubes
Resistivity, ρ (Ω-m)
200
150
100
50
0
10
100
1000
10000
Age (days)
Stored in tap water
Stored in "model"
pore solution

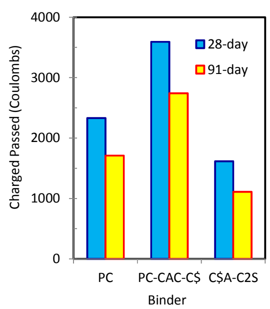

Degree of saturation
Self-desiccation
Drying
Leaching
Chloride ingress
Carbonation
Rebar
Factors Affecting Resistivity
Resistivity, ρ (Ω-m)
100
50
0
10
100
1000
10000
Age (days)
Insitu surface
measurements
Tests on cores


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


Effect of Paste Content
Resistivity, ρ (Ω-m)
300
200
100
0
6.0
4.0
2.0
0.0
Diffusion Coefficient (x 10^-12 m2/s)
50
60
70
80
90
Aggregate Volume, Va (%)
Diffusion
Resistivity
Maxwell's Eqn:
ρm = resistivity of matrix
ρ = resistivity of composite
ρa = resistivity of aggregate
Va = volume fraction
of aggregate

Chloride Resistance: Rapid-Set Cements

ASTM C 1202
"Rapid Chloride Permeability"

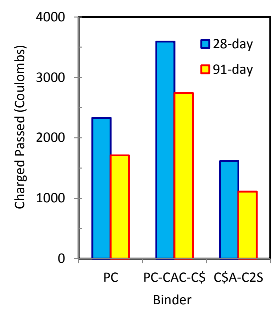


PC-CAC-C$ is a ternary blend of:
- Portland cement
- Calcium-aluminate cement
- Gypsum

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

Chloride Resistance: Rapid-Set Cements

ASTM C 1202
"Rapid Chloride Permeability"



ASTM C 1567
"Chloride Diffusion"

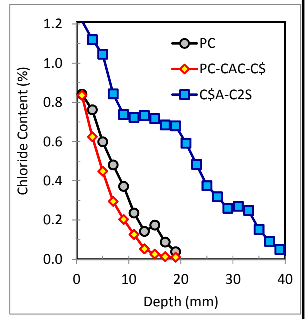


Table 5.5: Recommended Chloride Ion Penetrability Based on Resistivity

Risk	RCPT (Coulombs)	Wenner (Ω-m)	//Plate – 200mm (Ω-m)	//Plate – 50mm (Ω-m)	AC-Cell (Ω-m)	DC-Cell (Ω-m_
High	>4000	<50	<70	<50	<50	<50
Moderate	2000-4000	100-50	130-70	100-50	80-50	100-50
Low	1000-2000	200-100	250-130	200-100	170-80	200-100
Very Low	100-1000	2300-200	2300-250	2600-200	2000-170	2000-200
Negligible	<100	>2300	>2300	>2600	>2000	>2000

Smith, D. 2004. "The Development of a Rapid Test for Determining the Transport Properties of Concrete." M.Sc.E. Thesis, University of New Brunswick