Can Resistivity/Conductivity Measurements Really Capture Long-Term Chloride Resistance?

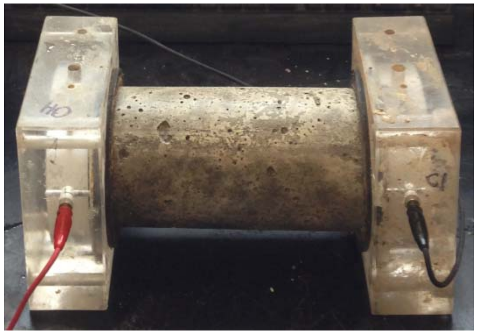
Michael Thomas

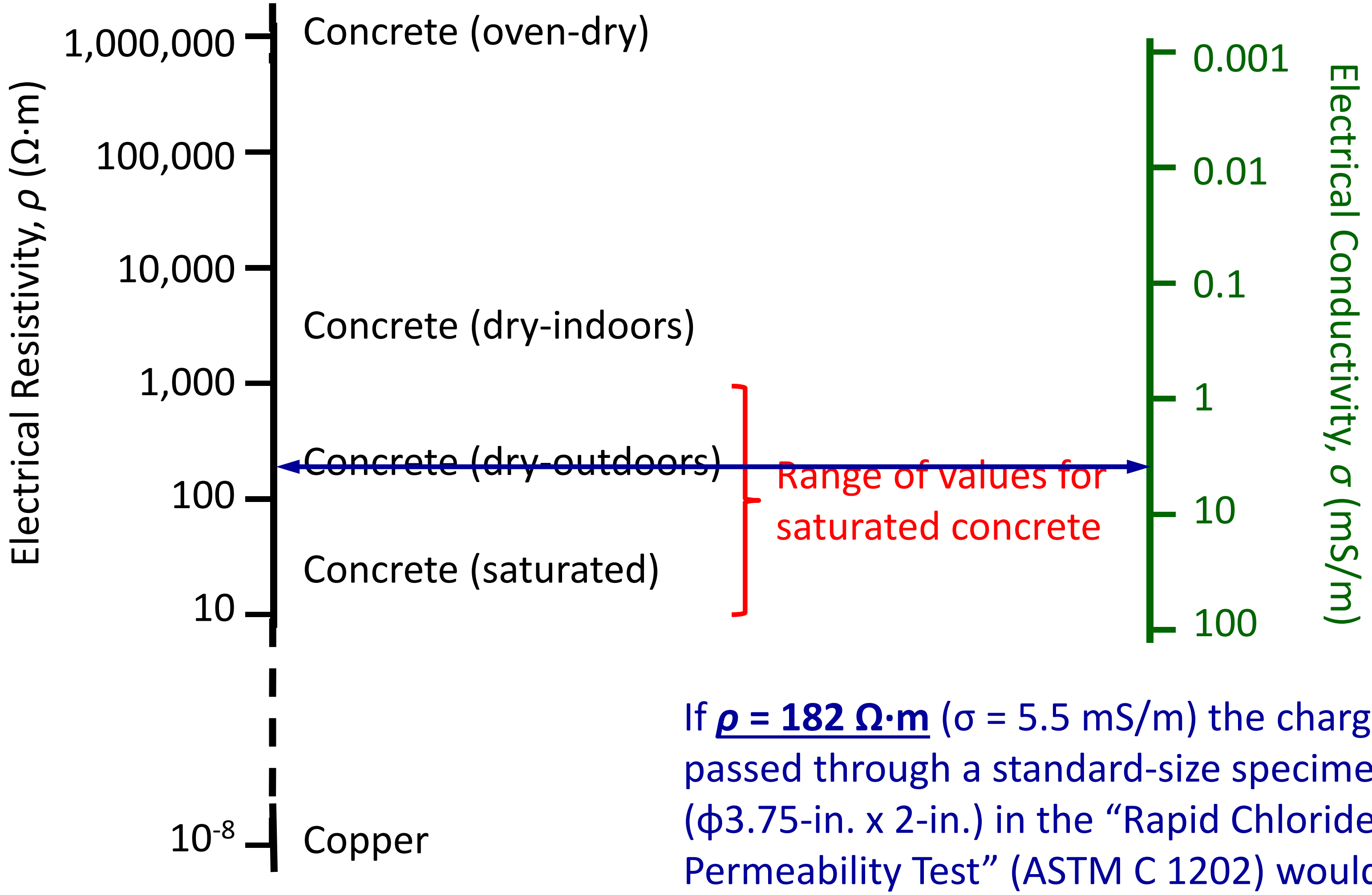
University of New Brunswick

Chloride Specifications in Concrete Construction: Part 1 Issues & Ideas

Anna Maria Workshop XVIII: Chemical Attack on Concrete, November 2017

ASTM C 1760 (2012)
“Bulk Conductivity”

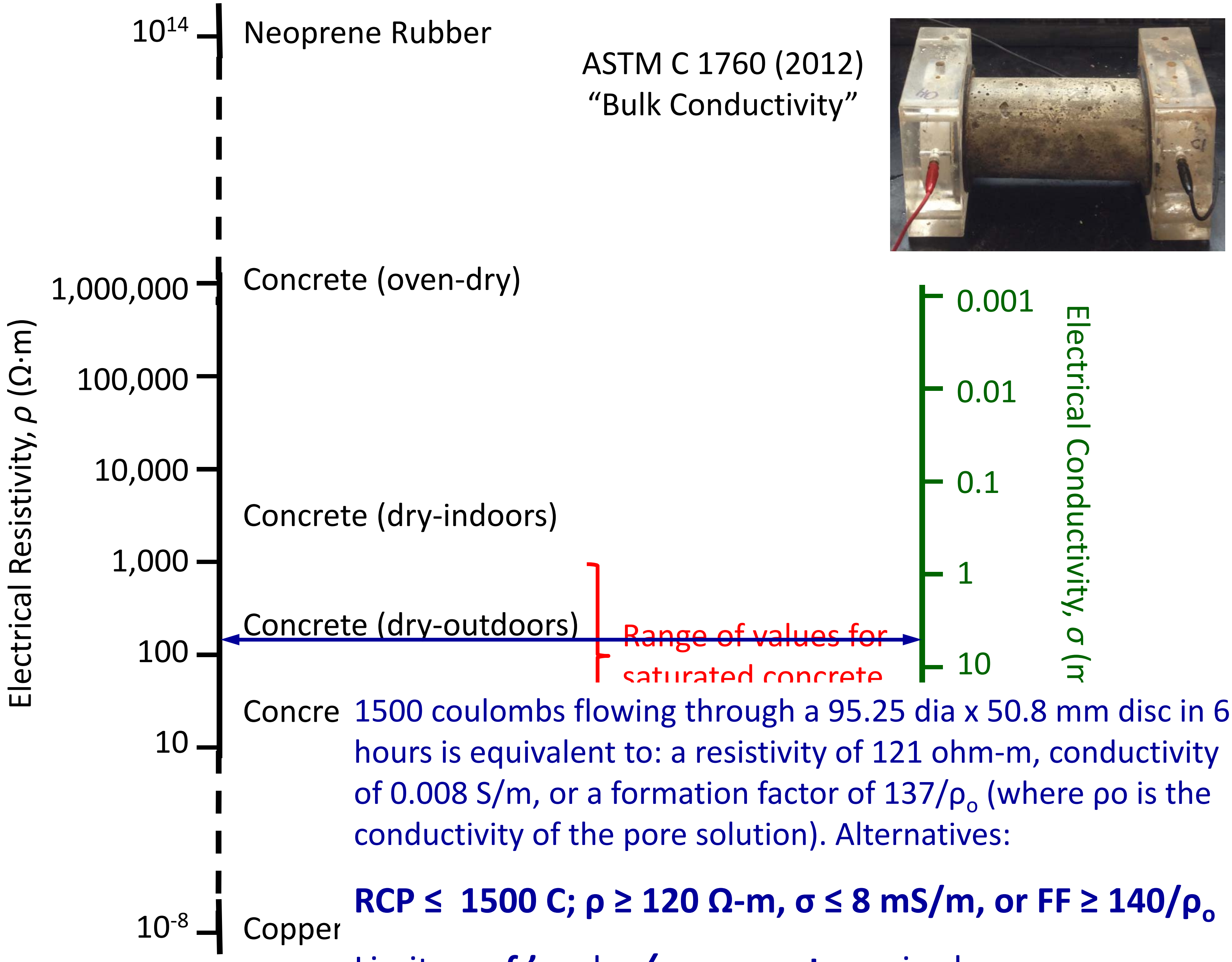




Range of values for saturated concrete

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)

Adapted from Whiting & Nagi, 2003



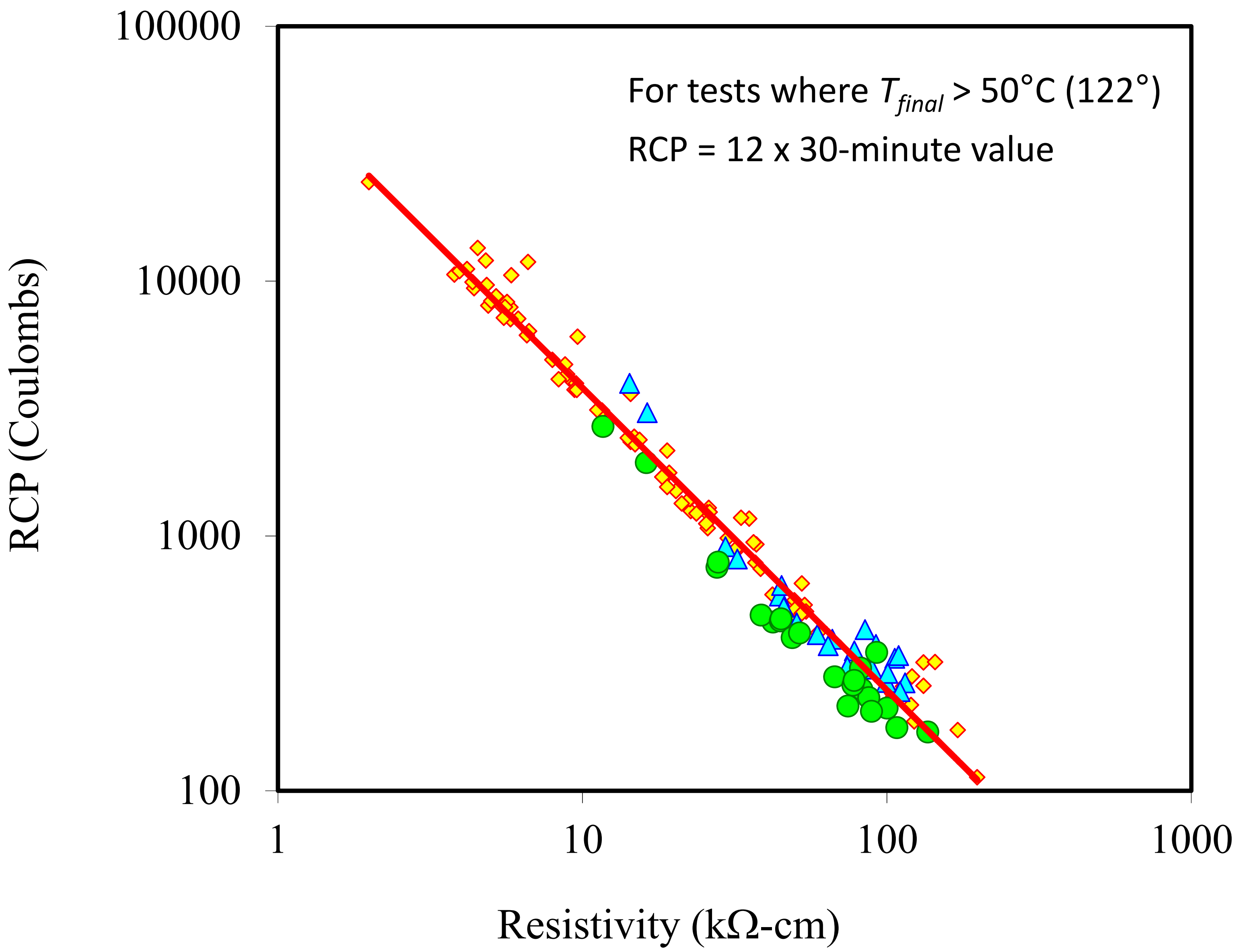
Adapted from Whiting & Nagi,

1500 coulombs flowing through a 95.25 dia x 50.8 mm disc in 6 hours is equivalent to: a resistivity of 121 ohm-m, conductivity of 0.008 S/m, or a formation factor of 137/ρ_o (where ρo is the conductivity of the pore solution). Alternatives:

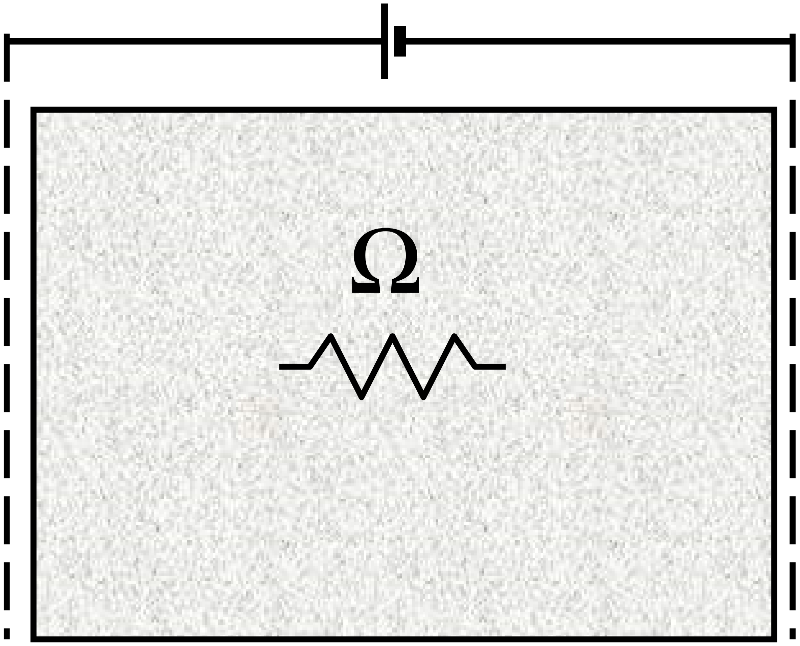
RCP ≤ 1500 C; ρ ≥ 120 Ω-m, σ ≤ 8 mS/m, or FF ≥ 140/ρ_o

Limits on ***f_c'*** and ***w/cm*** are **<u>not</u>** required

RCPT vs. Electrical Resistivity

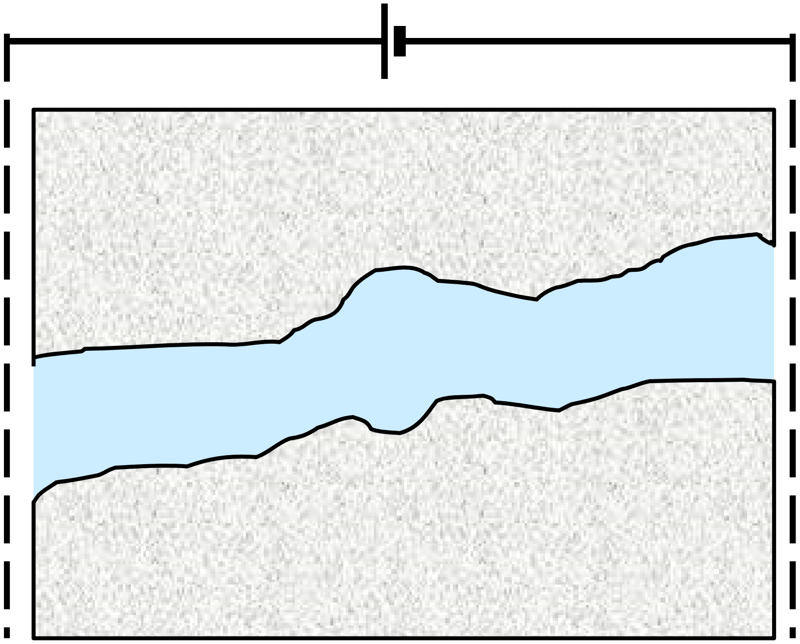


Electrical resistance of saturated concrete is primarily dependent on:



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:

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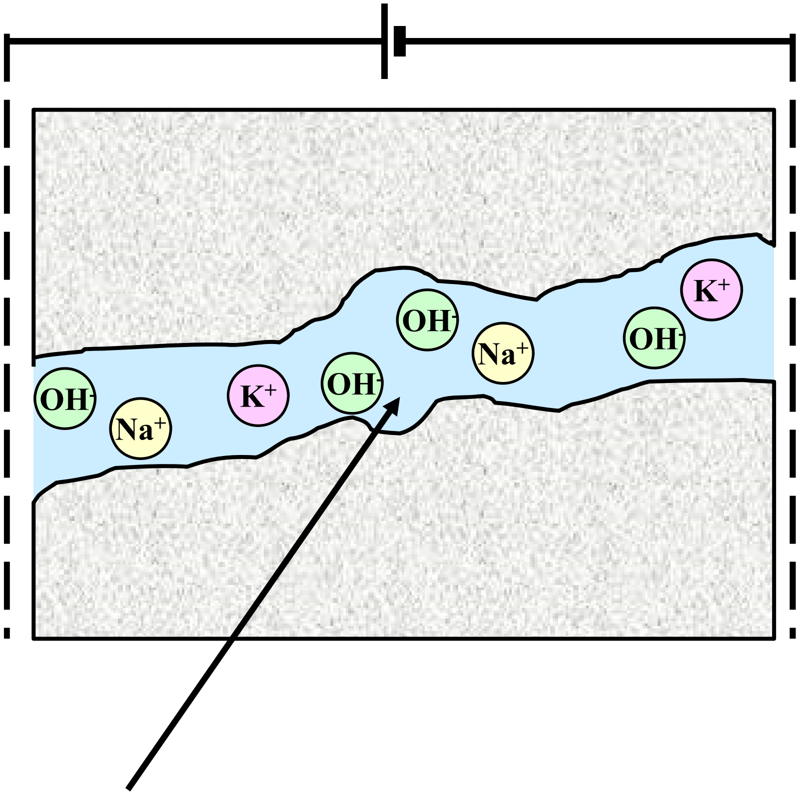
- Composition of **pore solution**
    - Concentration of ions



More **ions** in solution – increased electrical conductivity – i.e. reduced electrical resistance

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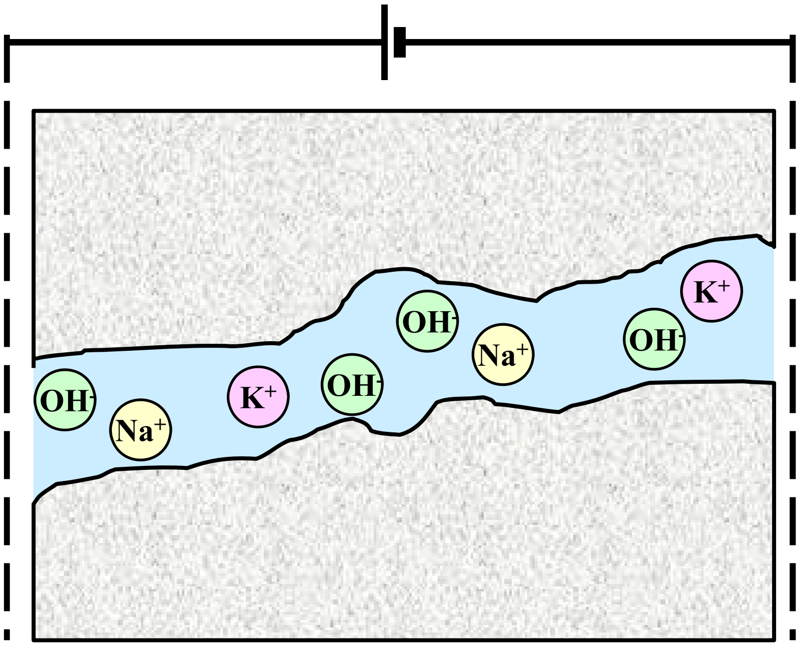

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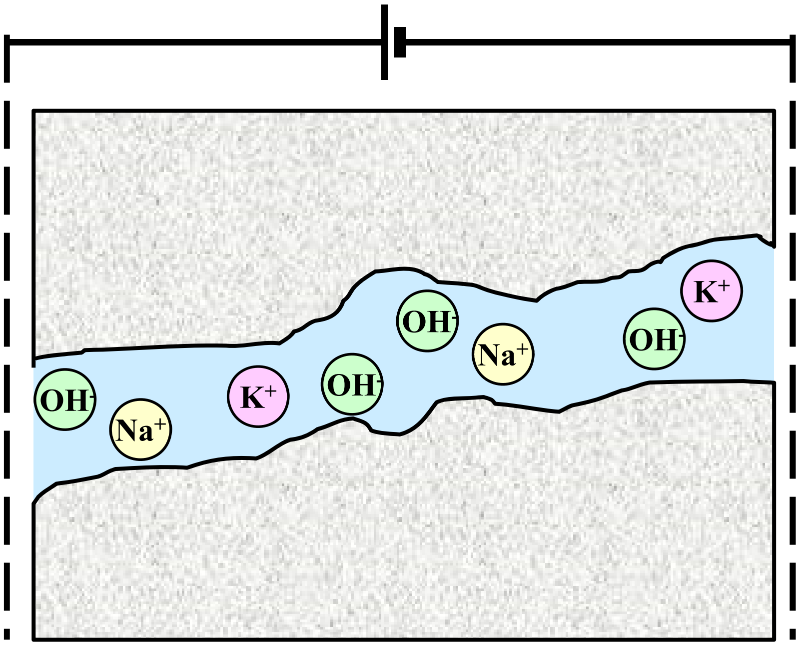

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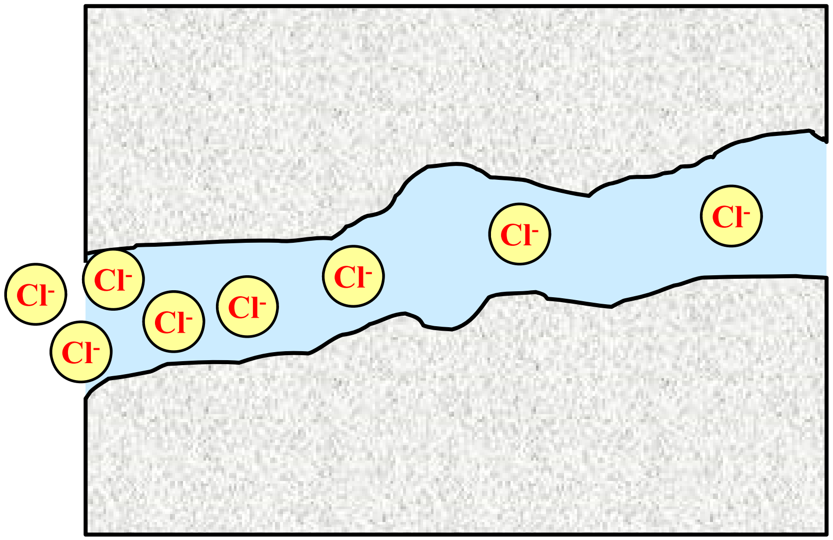

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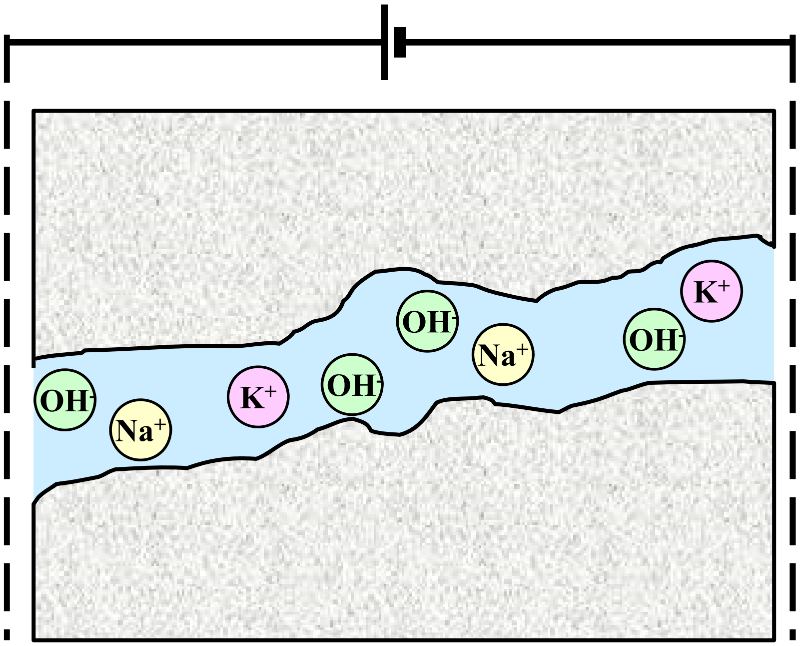

Chloride resistance of saturated concrete is primarily dependent on:

- Pore structure
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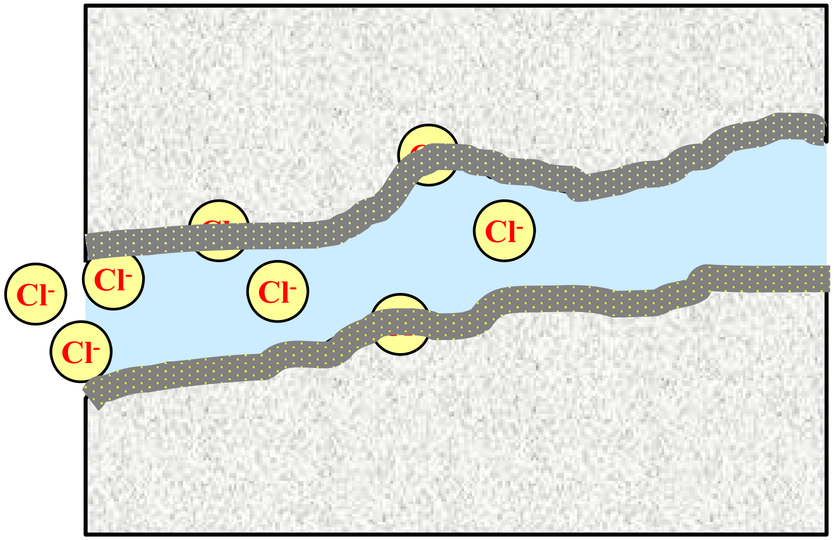
- Composition of **cement hydrates**
  - Ability of hydrates to bind chlorides



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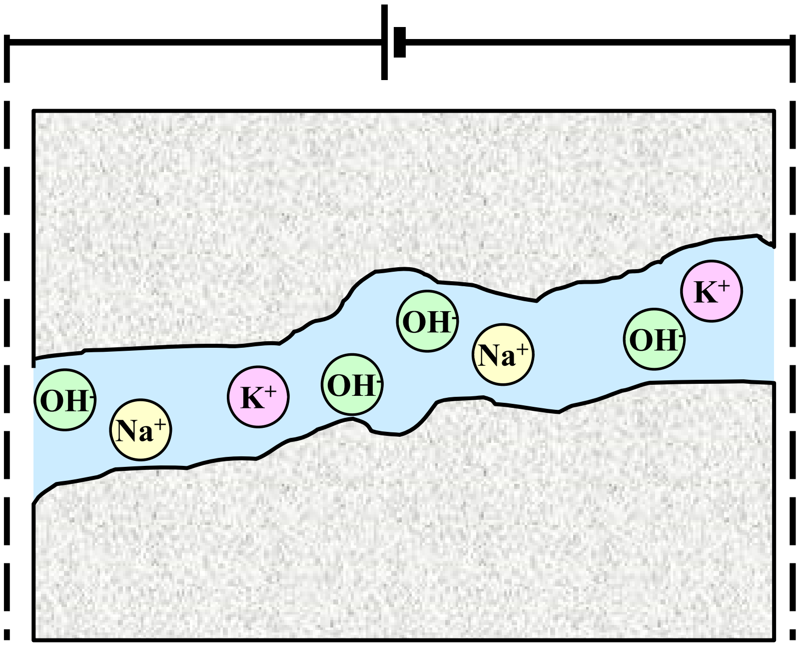

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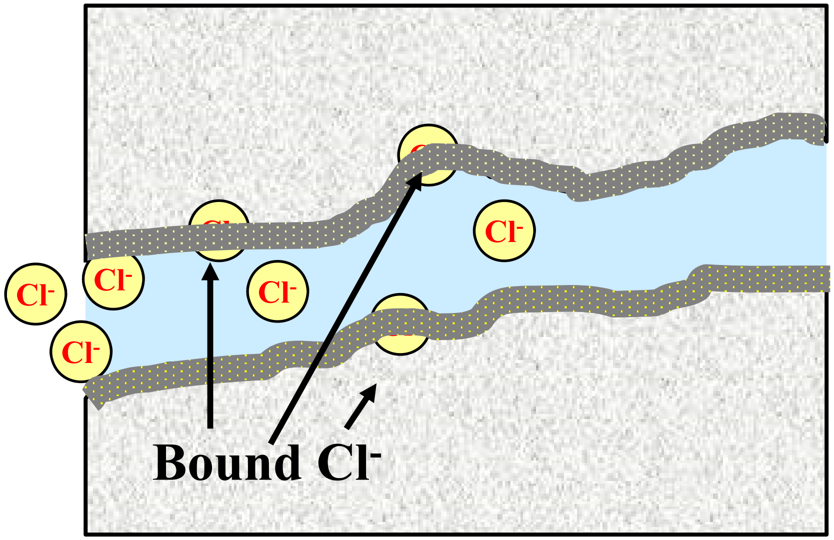

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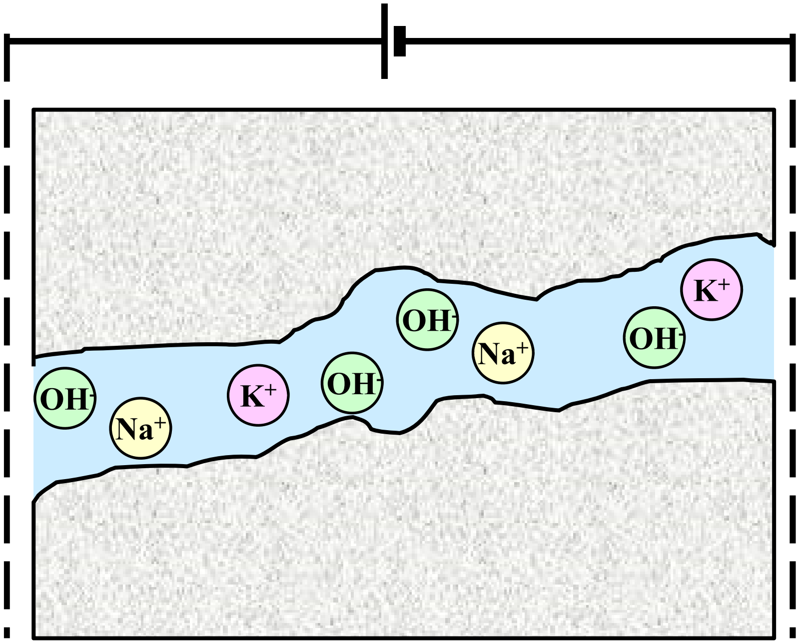
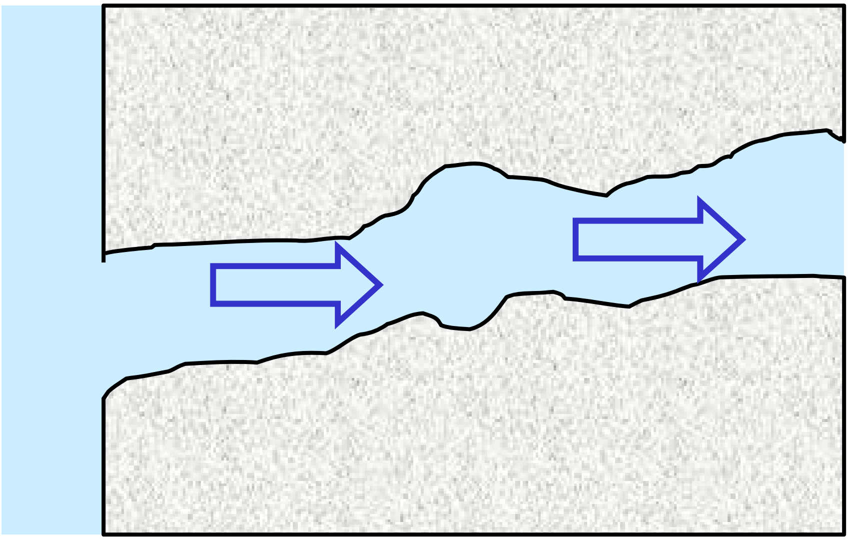


Hydraulic conductivity is primarily dependent on:

- Pore structure
  - Volume, size & connectivity of pores



ASTM C 1556 Test to Determine the Bulk Diffusion Coefficient of Concrete

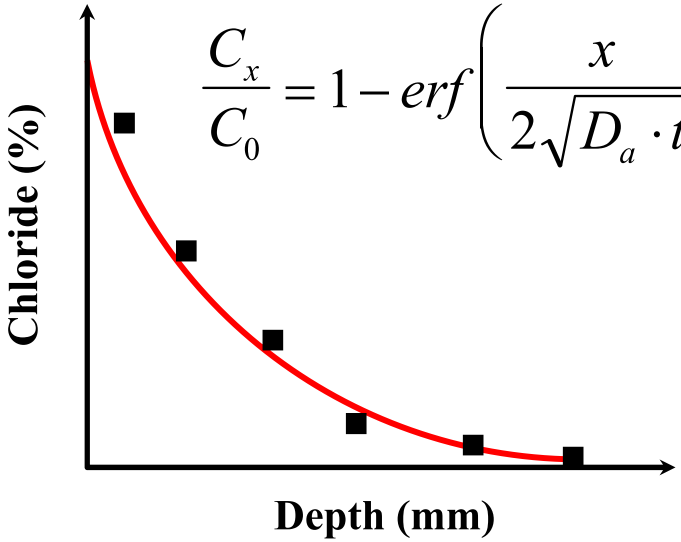
Concrete sample is immersed in NaCl solution for time t (minimum 35 days)

Sample then ground in approx. 1-mm depth increments

Dust samples analyzed for chlorides →

To produce chloride profile ↓

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

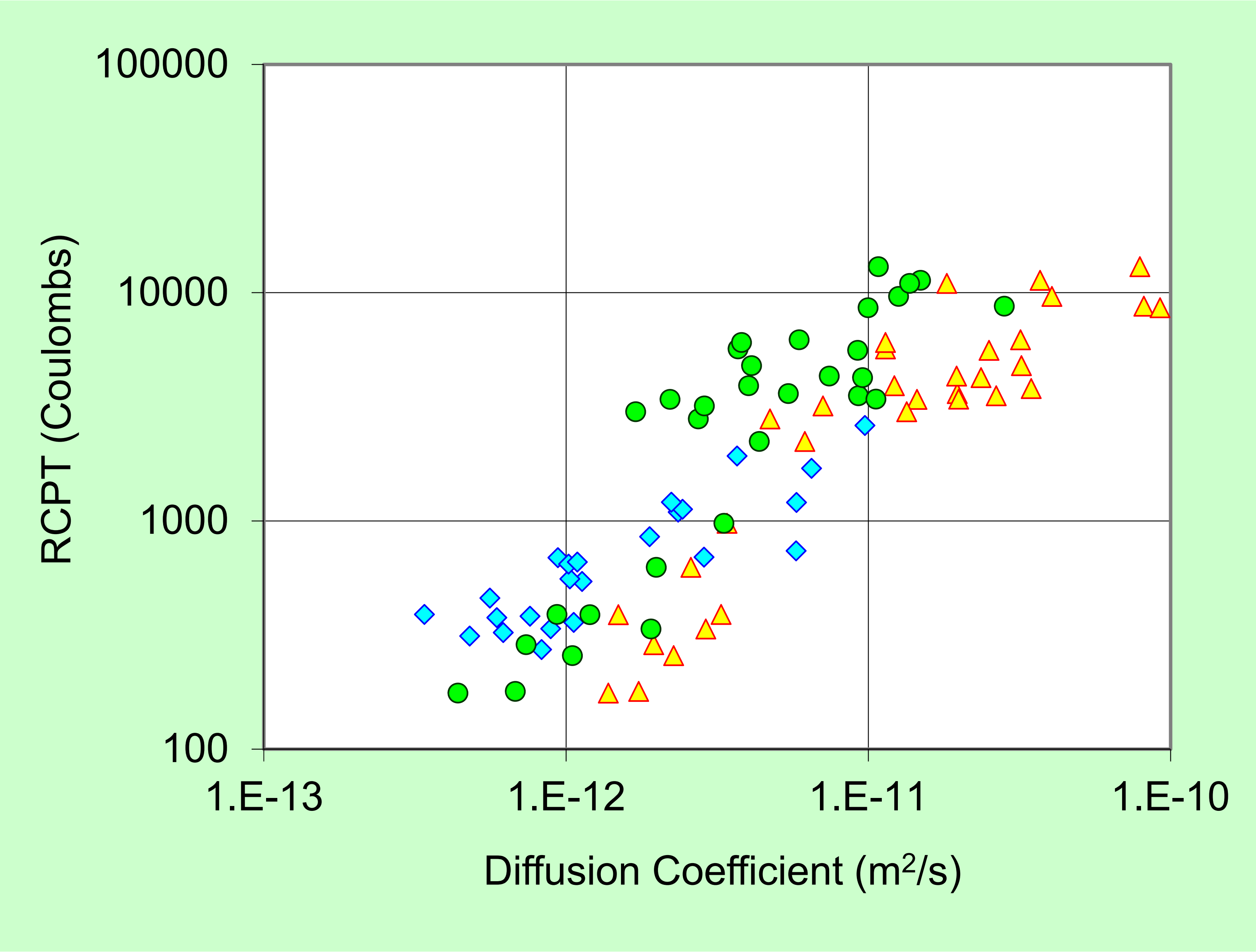


C_o and D_a found by fitting the equation shown to the measured profile.

Values of D_a typically in the range:

1×10^{-13} to 1×10^{-11} m^2/s

RCPT vs. Bulk Diffusion



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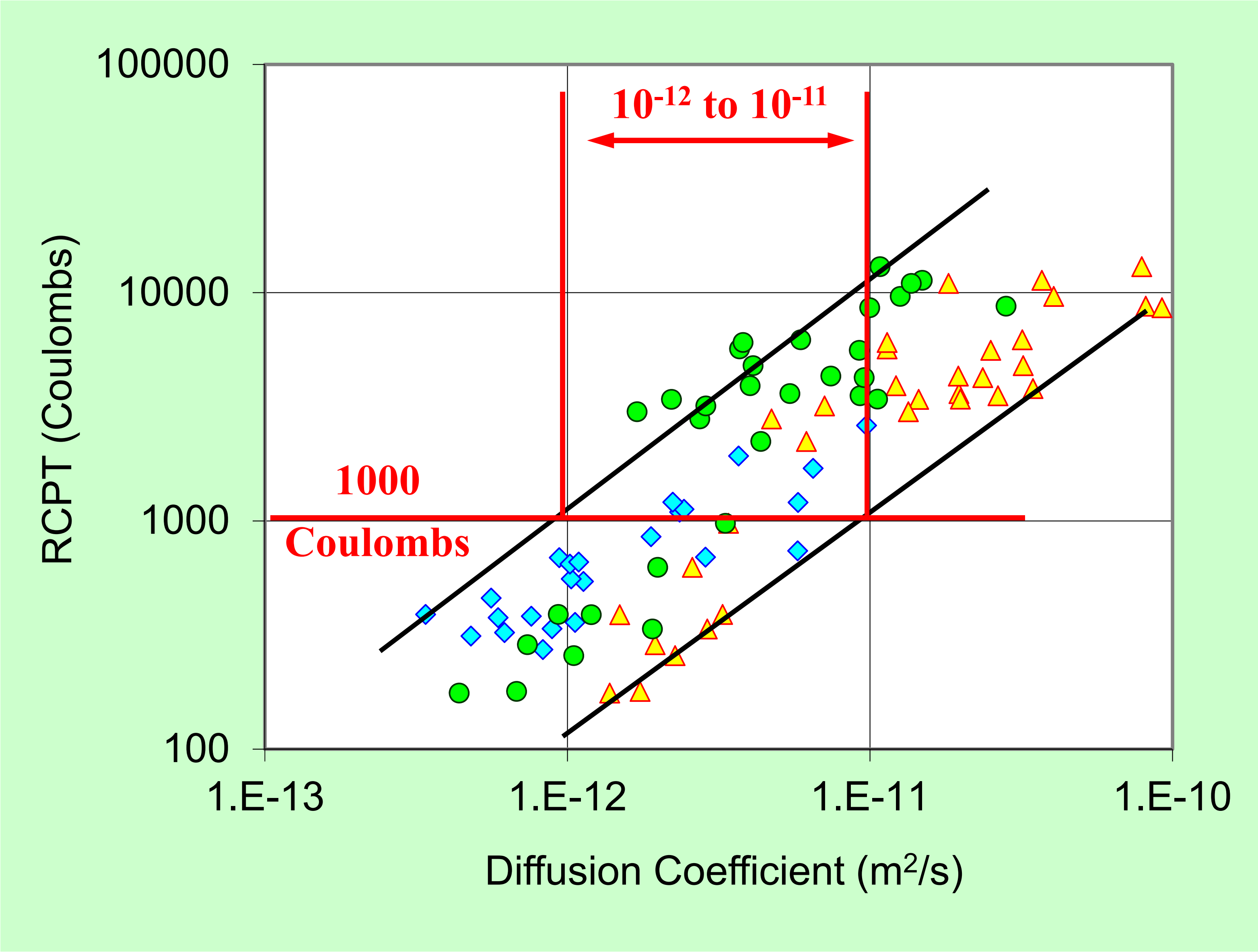
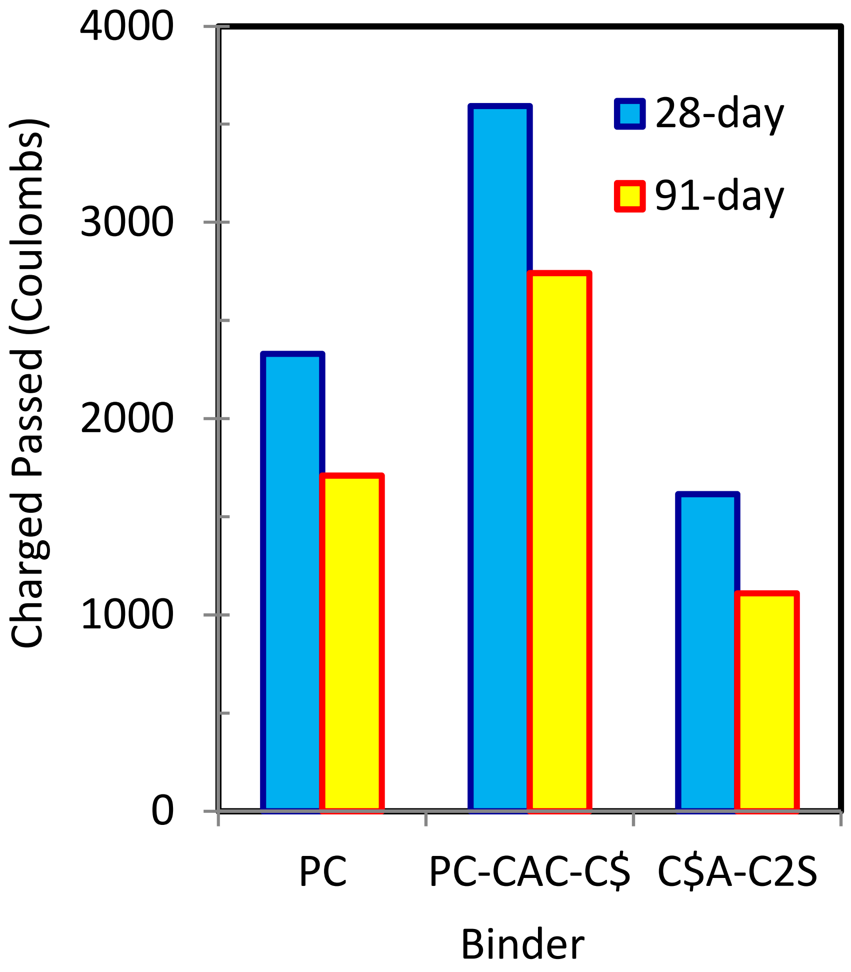


Chloride Resistance: Rapid-Set Cements

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

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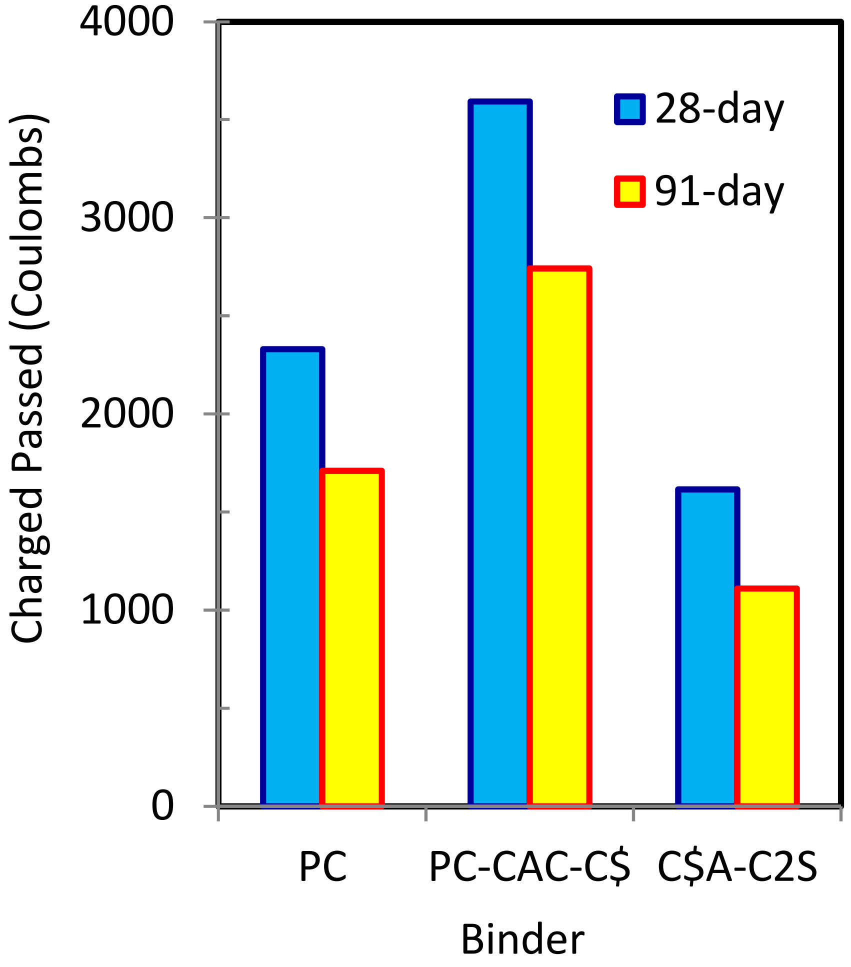
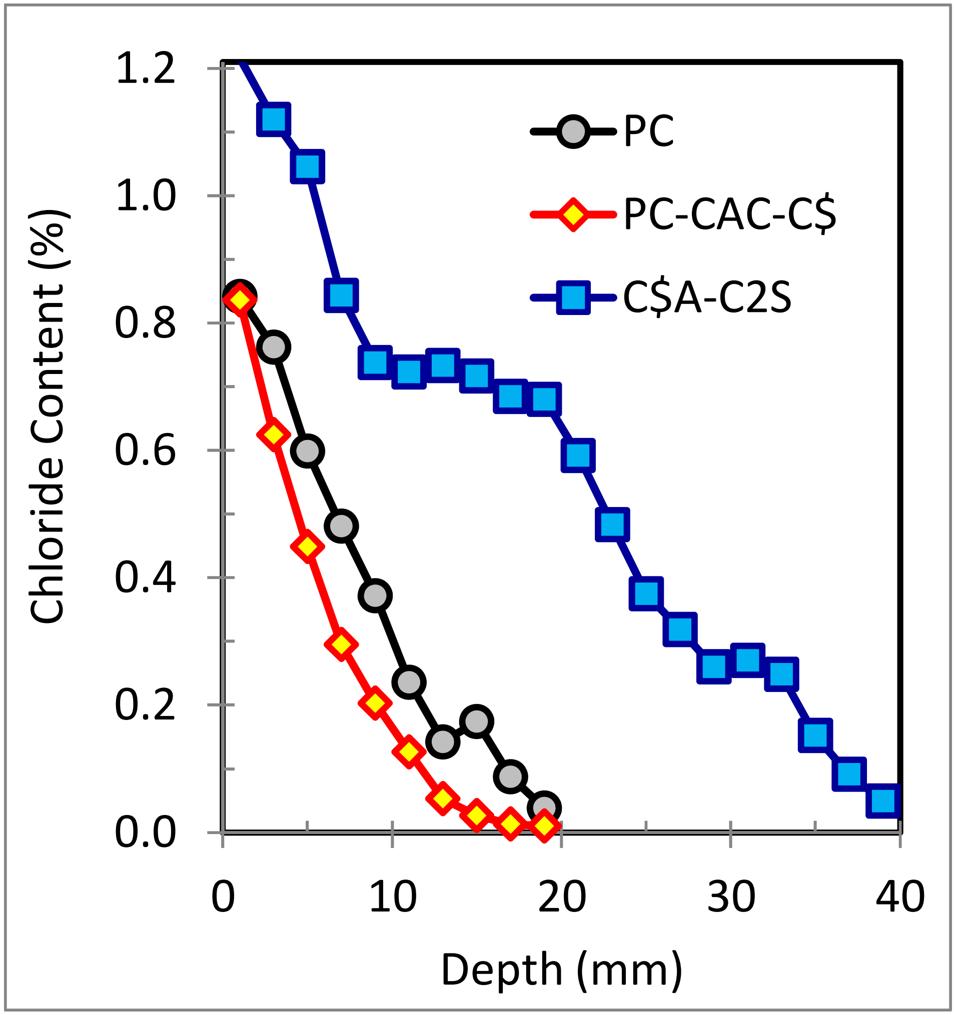
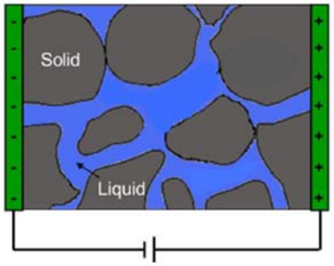


ASTM C 1567
“Chloride Diffusion”

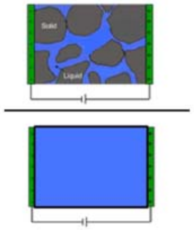


Formation Factor

Formation Factor is a fundamental material property



$$F = \frac{\rho}{\rho_O} =$$



$$F = \frac{1}{\phi\beta}$$

$$F = \frac{\rho}{\rho_0} = \frac{D}{D_i}$$

F = formation factor

ρ = resistivity of concrete

ρ_0 = resistivity of concrete pore solution

D = chloride diffusion coefficient

D_i = self diffusion coefficient for ion (= 2.032×10^{-9} m^2/s for Cl^-)

Φ = Porosity

β = Tortuosity of pore system

Courtesy Jason Weiss

Formation Factor

Resistivity of the pore solution can be

(i) assumed (e.g. $\rho_0 = 0.1\ \Omega\text{-m}\ [\sigma_0 = 10\ \text{S/m}]$ for PC mixes),

(ii) estimated (e.g. “NIST model”) – mill certs and mix proportions

(iii) measured (by pore-solution extraction)

then:

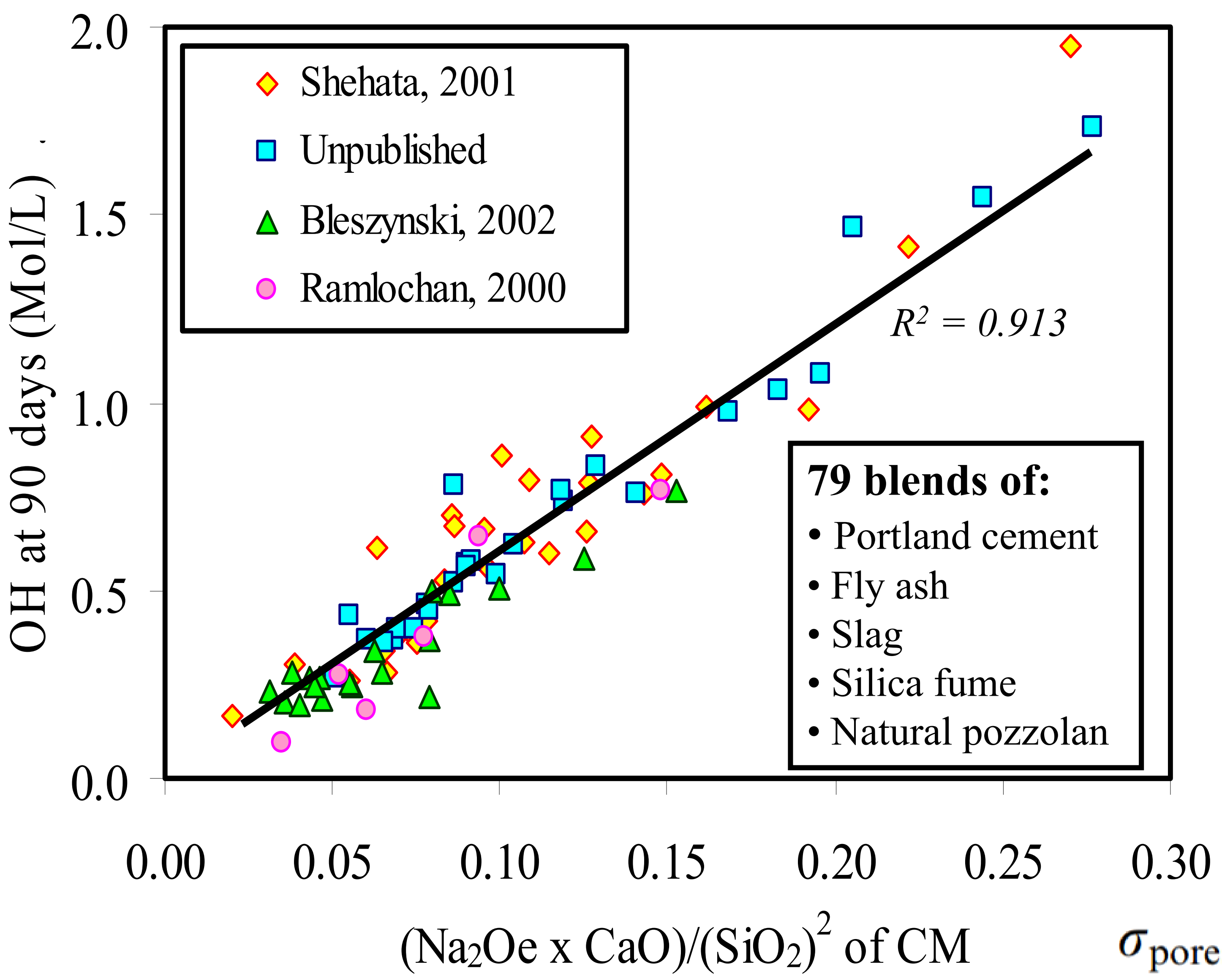
1. *F* could be used to specify concrete

   (correcting resistivity for pore solution effects)

2. *F* could be used to determine *D* from measurement of ρ

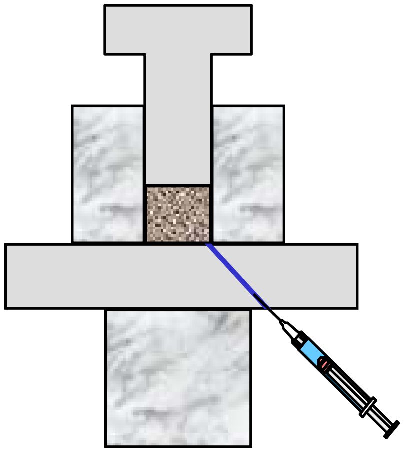
$$D = D_i \frac{\rho}{\rho_0}$$

Cement Composition & Pore Solution Alkalinity



79 blends of:

- Portland cement
- Fly ash
- Slag
- Silica fume
- Natural pozzolan



Results for cement pastes:

w/cm = 0.50

OH^- by titration

Na^+ & K^+ by flame photometry, atomic absorption or ICP

$OH^- \sim Na^+ + K^+$

$$\sigma_{\text{poresoln}} = \sum_i z_i c_i \lambda_i$$

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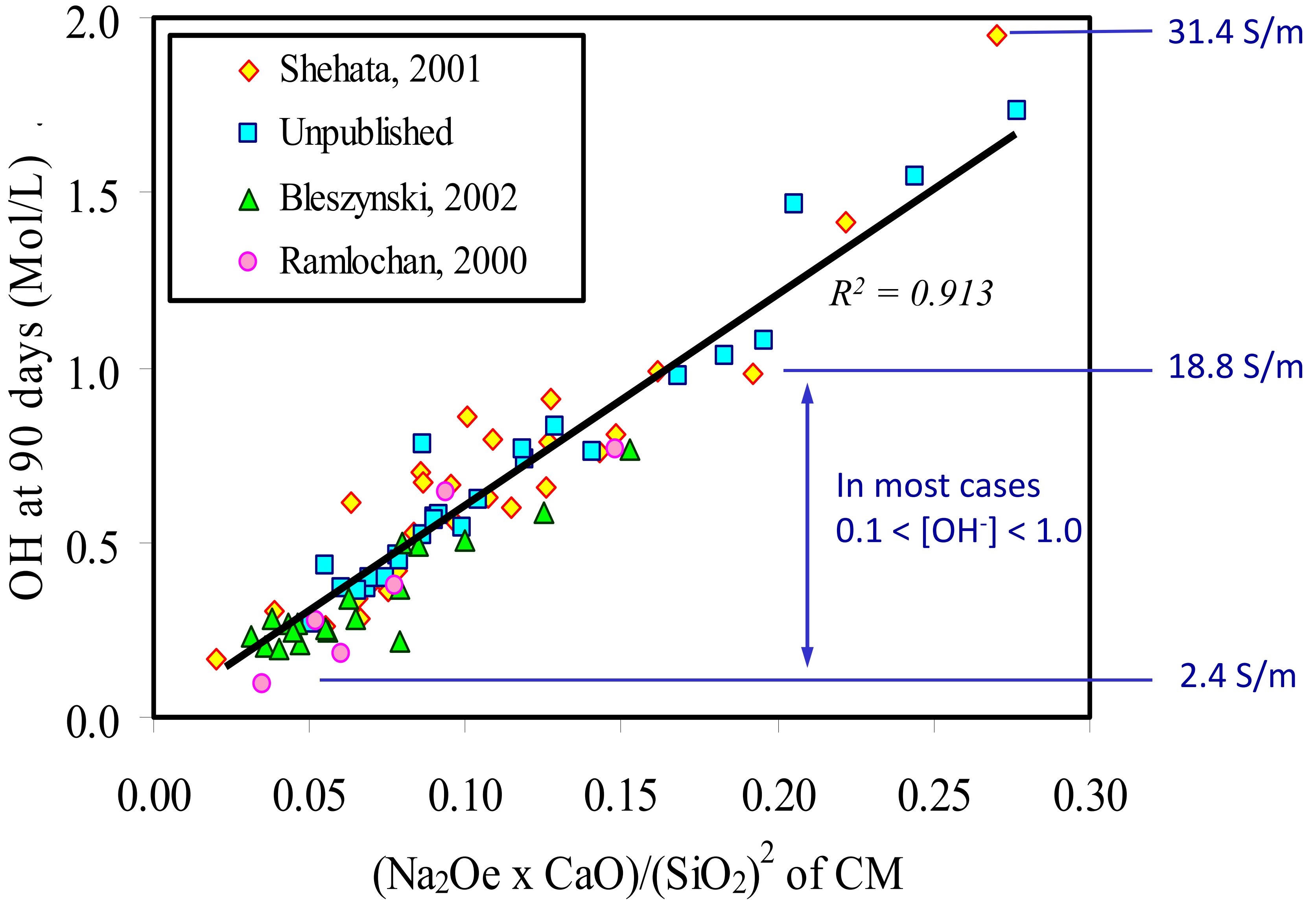
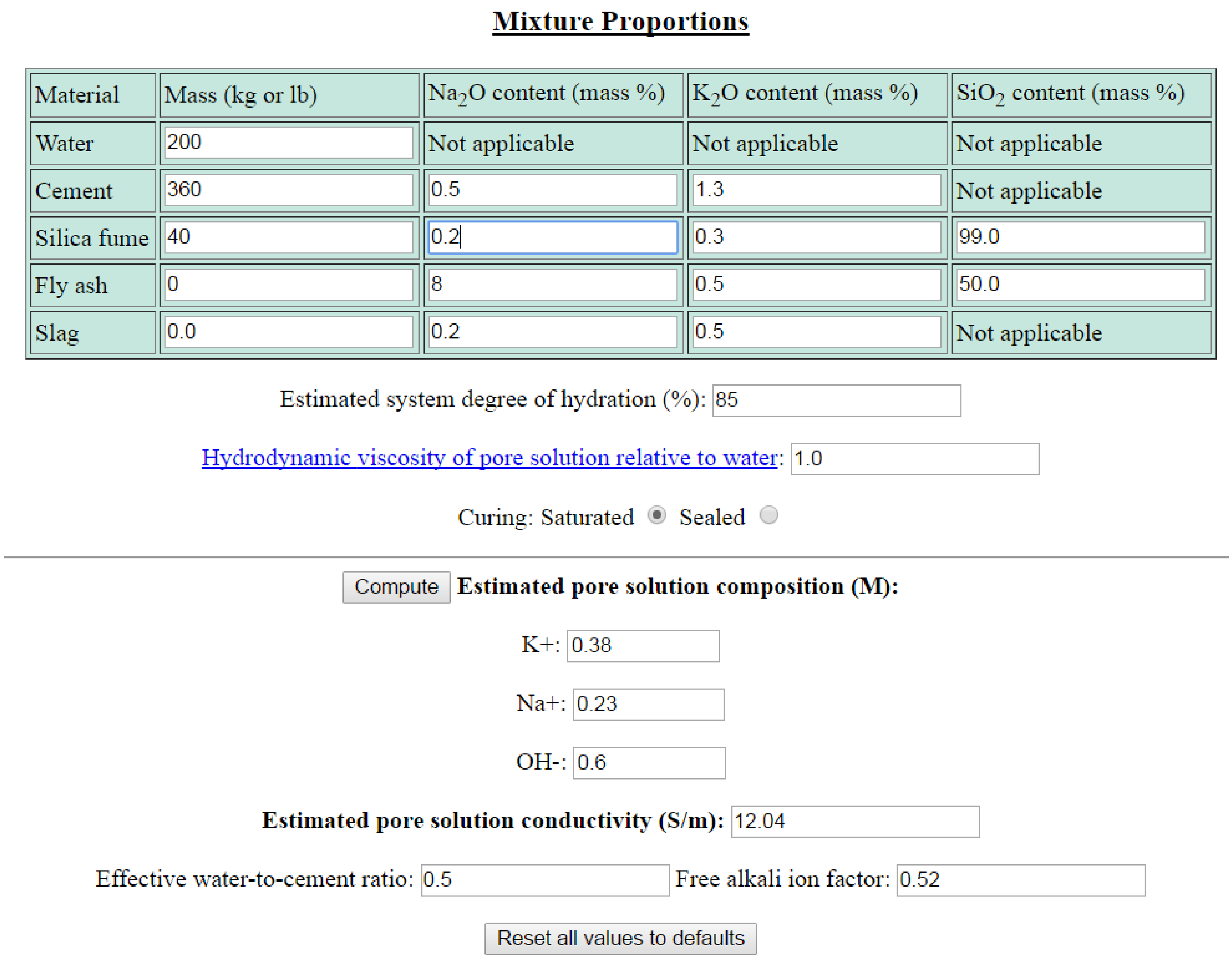


31.4 S/m

18.8 S/m

In most cases
$0.1 < [OH^-] < 1.0$

2.4 S/m



Mixture Proportions

Material	Mass (kg or lb)	Na_2O content (mass %)	K_2O content (mass %)	SiO_2 content (mass %)
Water	200	Not applicable	Not applicable	Not applicable
Cement	360	0.5	1.3	Not applicable
Silica fume	40	0.2	0.3	99.0
Fly ash	0	8	0.5	50.0
Slag	0.0	0.2	0.5	Not applicable

Estimated system degree of hydration (%): 85

Hydrodynamic viscosity of pore solution relative to water: 1.0

Curing: Saturated ● Sealed ○

Estimated pore solution composition (M):

K+: 0.38

Na+: 0.23

OH-: 0.6

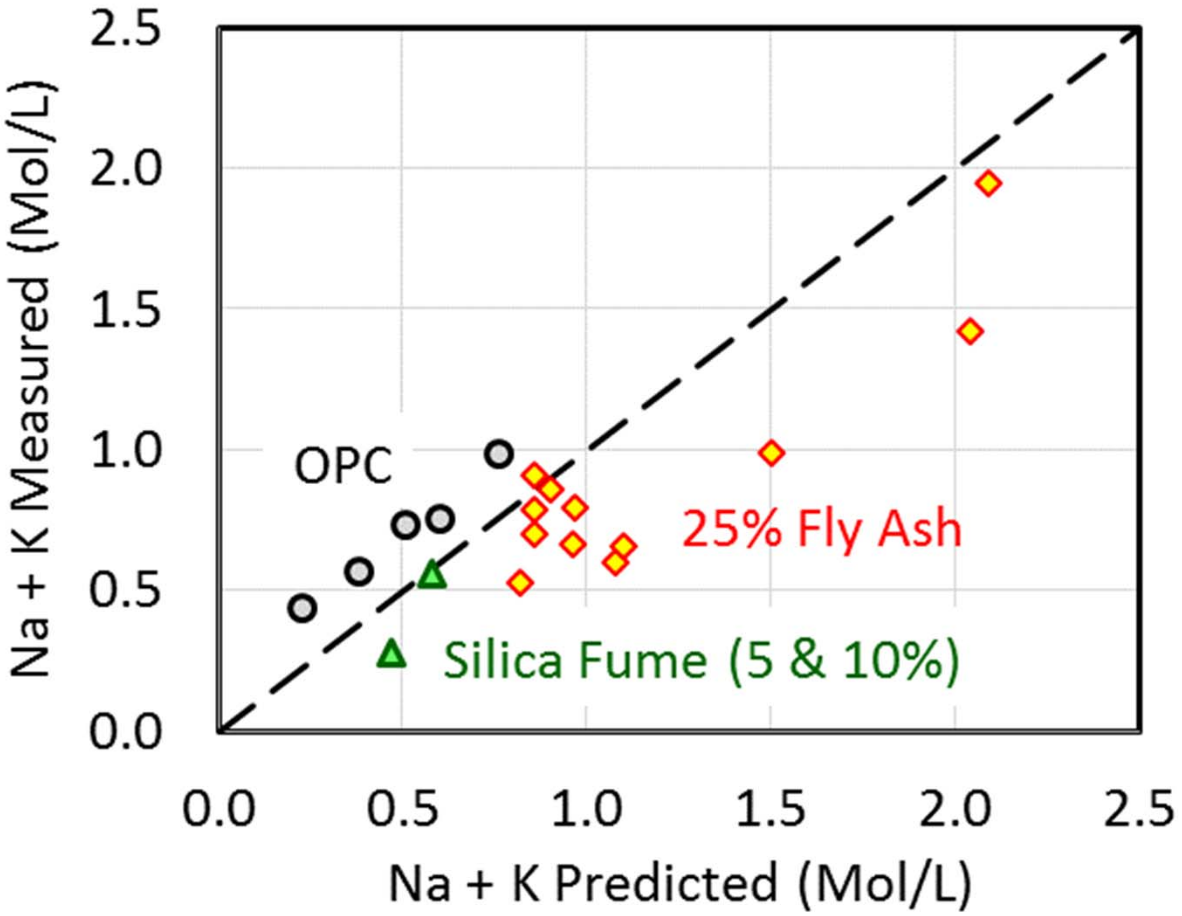
Estimated pore solution conductivity (S/m): 12.04

Effective water-to-cement ratio: 0.5 Free alkali ion factor: 0.52

https://ciks.cbt.nist.gov/poresolncalc.html

Comparison of Predicted vs Measured Values

- Measurements made on pore solution pressed from hardened paste samples at 90 days
- Predictions made using NIST - *https://ciks.cbt.nist.gov/poresolncalc.html*



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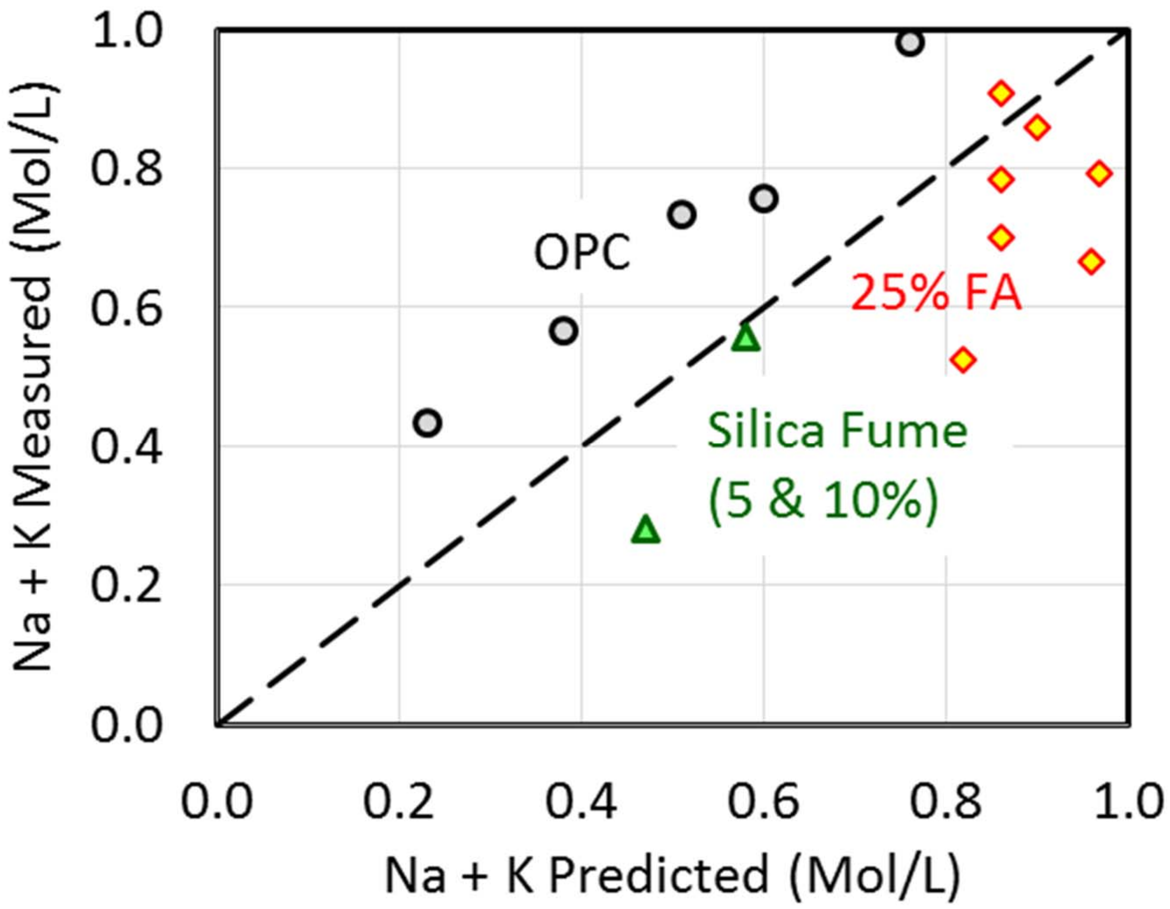
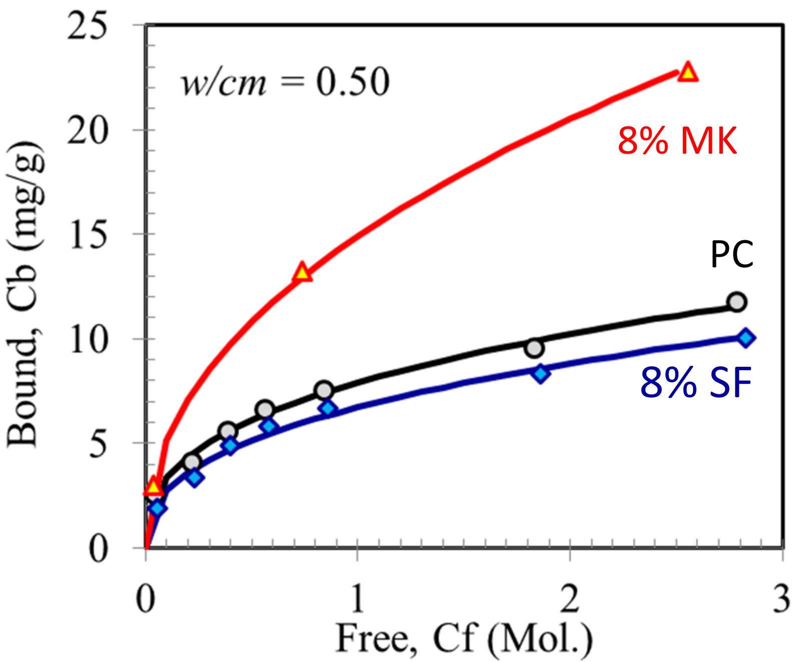
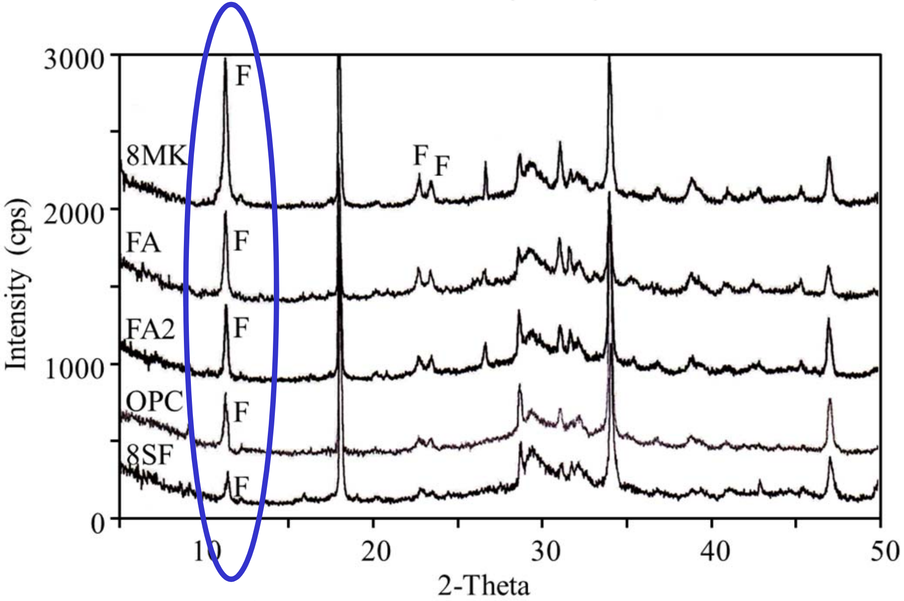


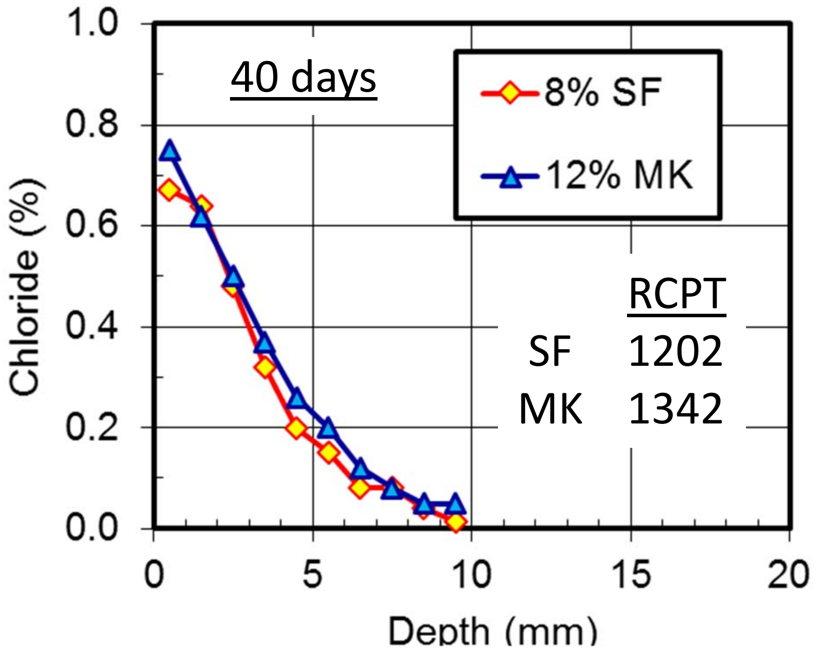
Metakaolin vs. Silica Fume



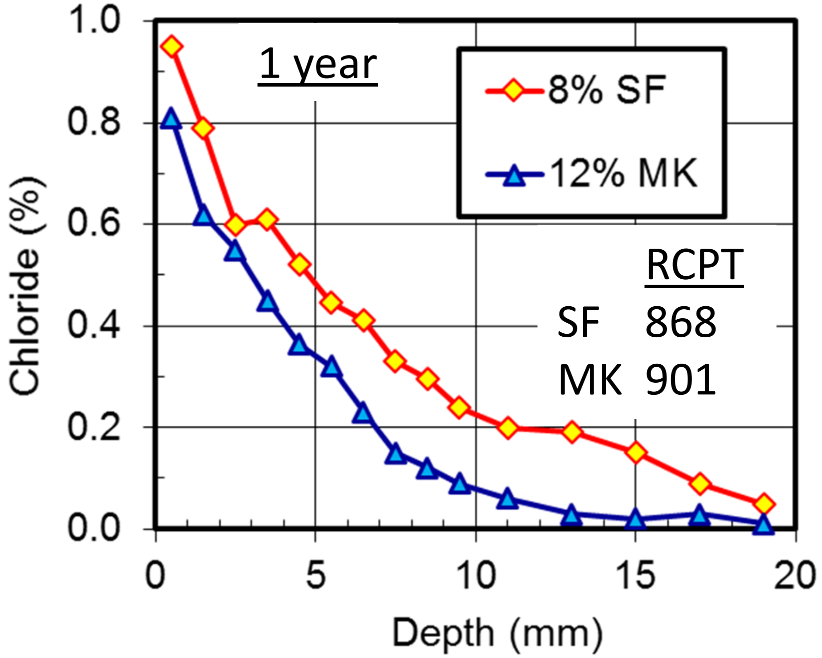


Friedel's Salt

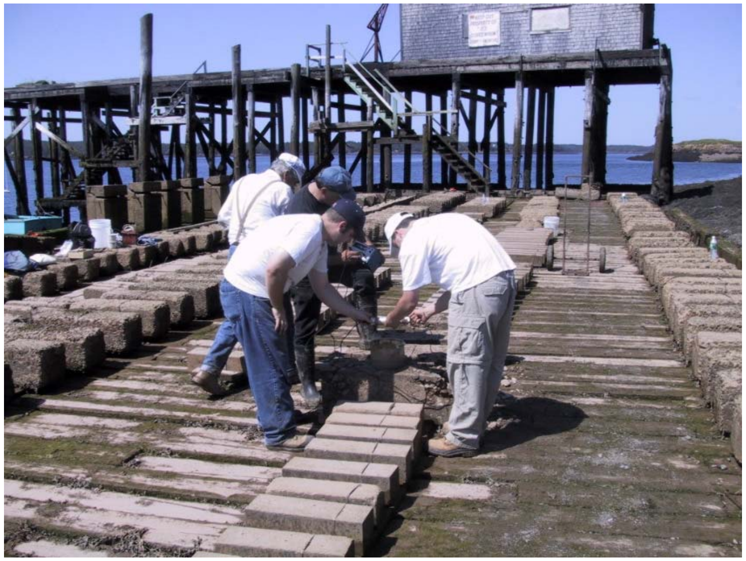
Bulk Diffusion Tests (C 1556)



	RCPT
SF	1202
MK	1342

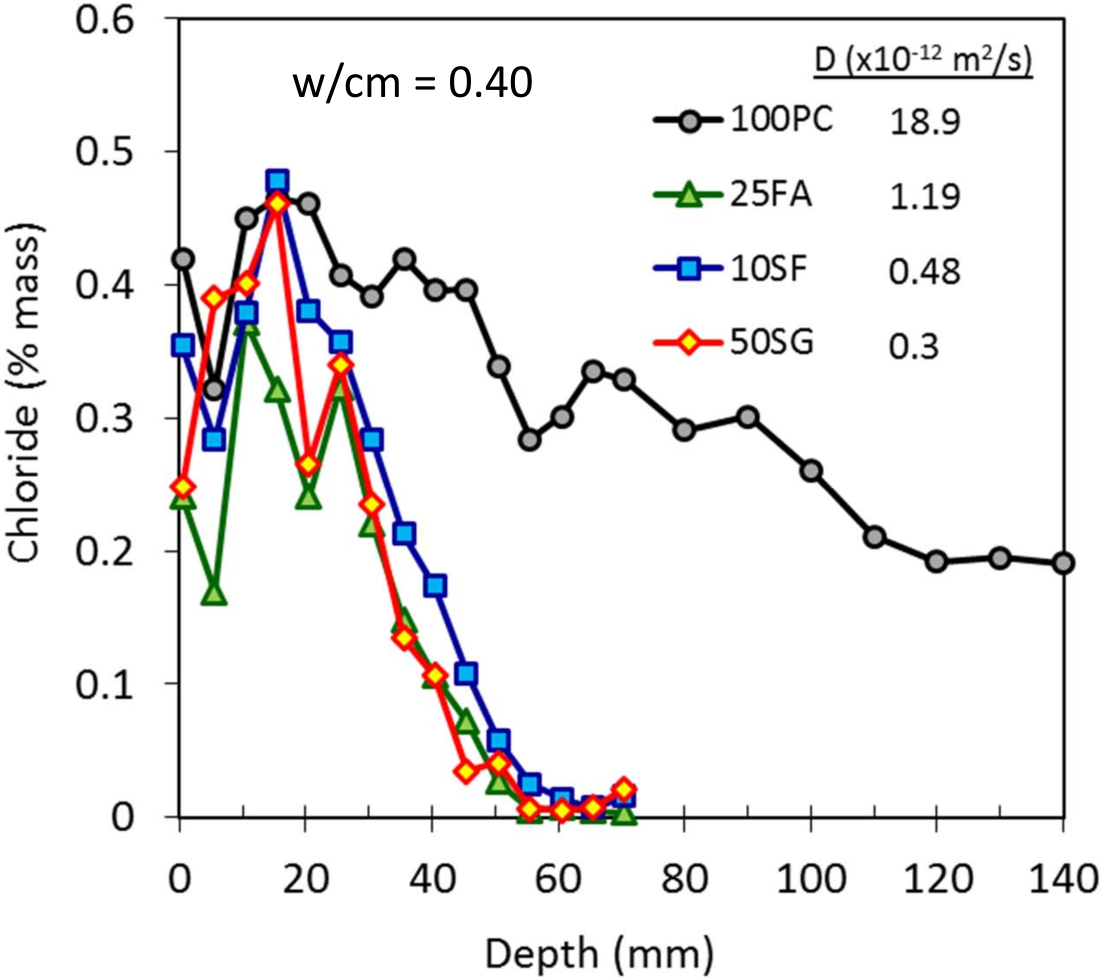


	RCPT
SF	868
MK	901



Mix	Bulk ρ (KΩ.cm)	RCPT (Coulomb)
100PC	8.4	3050
25FA	23.2	1230
10SF	16.9	1630
50SG	29.7	905

Concrete Blocks (1 x 1 x 3 ft) at Treat Island in Tidal Zone for 25 years



A study of the effect of chloride binding on service life predictions

B. Martín-Pérez[a,*], H. Zibara[b], R.D. Hooton[b], M.D.A. Thomas[b]

Cement and Concrete Research 30 (2000) 1215–1223

No binding:

$$C_{\mathrm{b}} = 0 \qquad \frac{\partial C_{\mathrm{b}}}{\partial C_{\mathrm{f}}} = 0 \qquad D_{\mathrm{c}}^{*} = D_{\mathrm{c}}$$

Linear isotherm:

$$C_{\mathrm{b}} = \alpha C_{\mathrm{f}} \qquad \frac{\partial C_{\mathrm{b}}}{\partial C_{\mathrm{f}}} = \alpha \qquad D_{\mathrm{c}}^{*} = \frac{D_{\mathrm{c}}}{1 + \frac{\alpha}{\omega_{\mathrm{e}}}}$$

Langmuir isotherm:

$$C_{\mathrm{b}} = \frac{\alpha C_{\mathrm{f}}}{1 + \beta C_{\mathrm{f}}} \qquad \frac{\alpha C_{\mathrm{b}}}{\alpha C_{\mathrm{f}}} = \frac{\alpha}{(1 + \beta C_{\mathrm{f}})^{2}} \qquad D_{\mathrm{c}}^{*} = \frac{D_{\mathrm{c}}}{1 + \frac{\alpha}{\omega_{\mathrm{e}}(1 + \beta C_{\mathrm{f}})^{2}}}$$

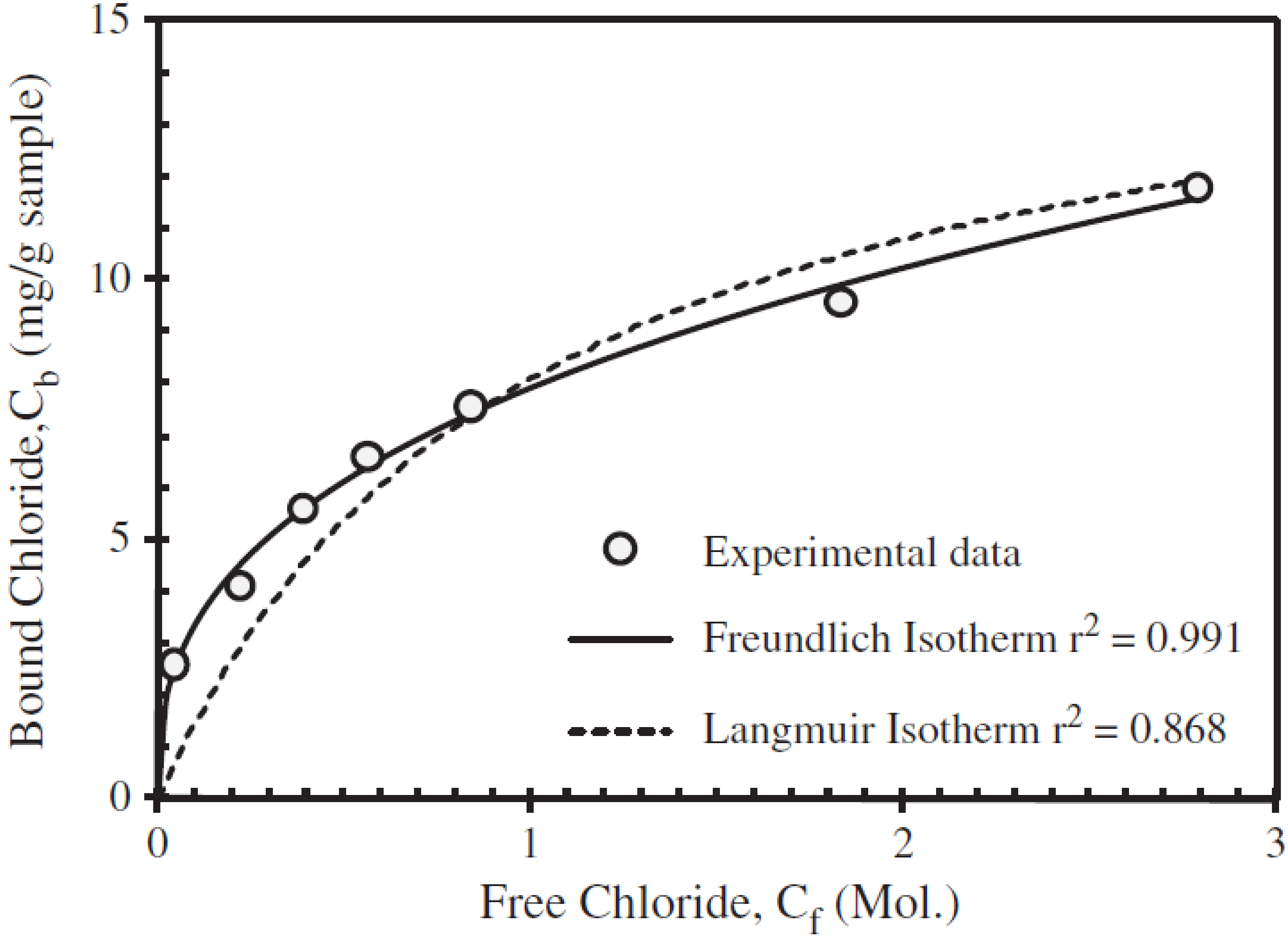
Freundlich isotherm:

$$C_{\mathrm{b}} = \alpha C_{\mathrm{f}}^{\beta} \qquad \frac{\partial C_{\mathrm{b}}}{\partial C_{\mathrm{f}}} = \alpha \beta C_{\mathrm{f}}^{\beta - t} \qquad D_{\mathrm{c}}^{*} \; \frac{D_{\mathrm{c}}}{1 + \frac{1}{\omega_{\mathrm{e}}} \alpha \beta C_{\mathrm{f}}^{\beta - 1}}$$

The effect of supplementary cementitious materials on chloride binding in hardened cement paste

Cement and Concrete Research 42 (2012) 1–7

M.D.A. Thomas [a,*], R.D. Hooton [b], A. Scott [c], H. Zibara [b]



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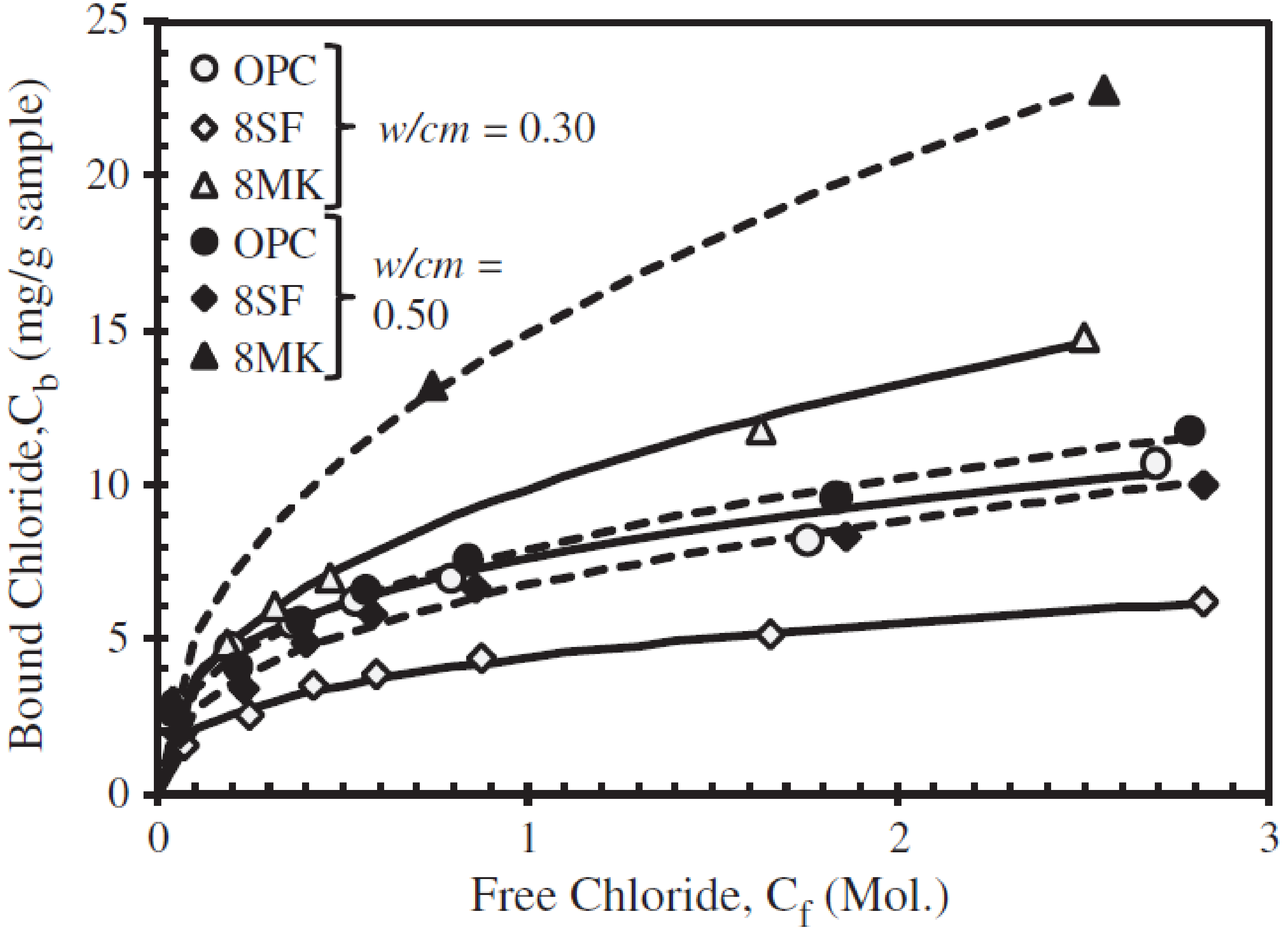
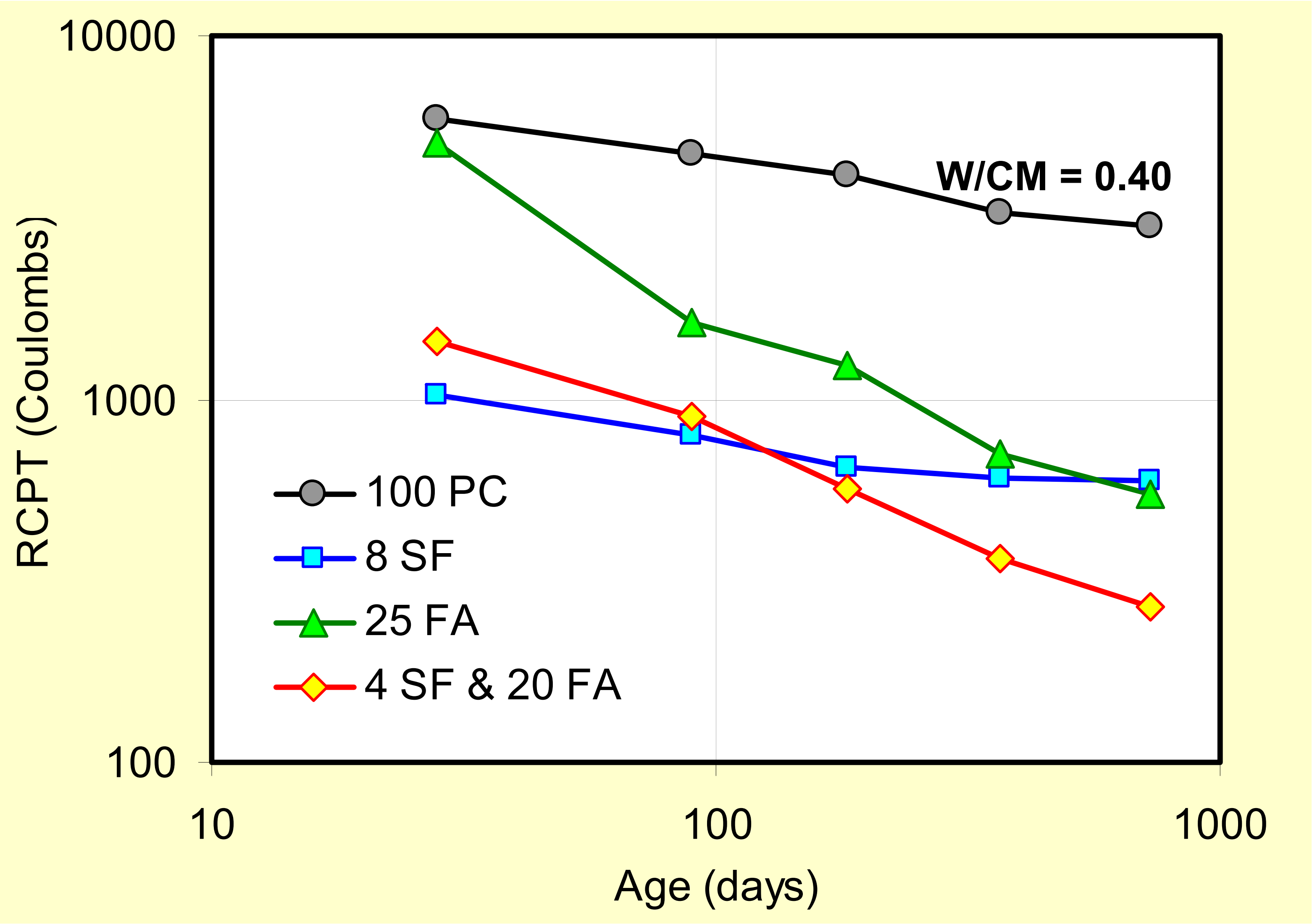
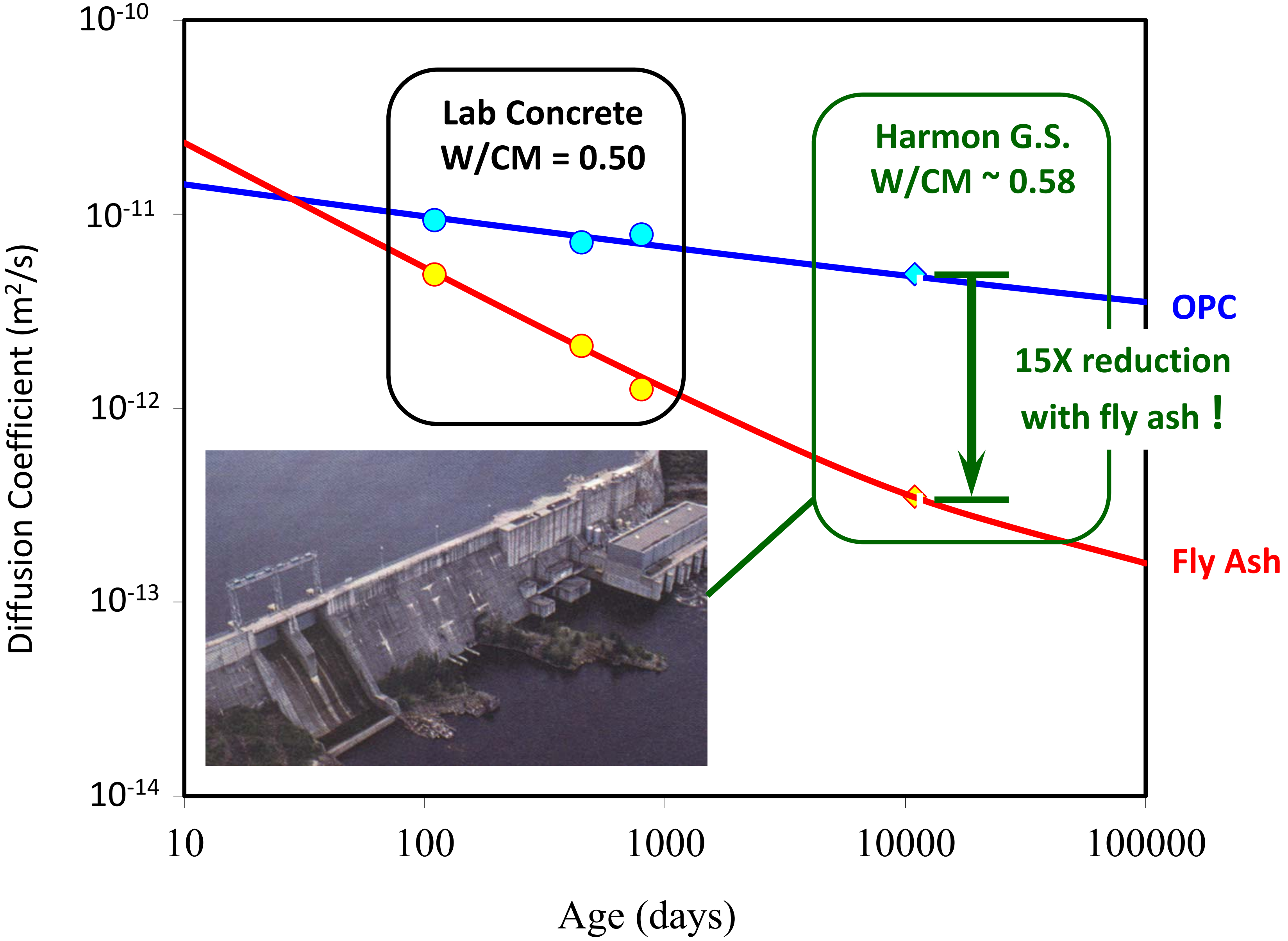


Fig. 3. Chloride binding isotherms for pastes with silica fume and metakaolin (w/cm = 0.30 and 0.50, T = 23 °C).

Time-Dependent Changes in Electrical and Transport Properties



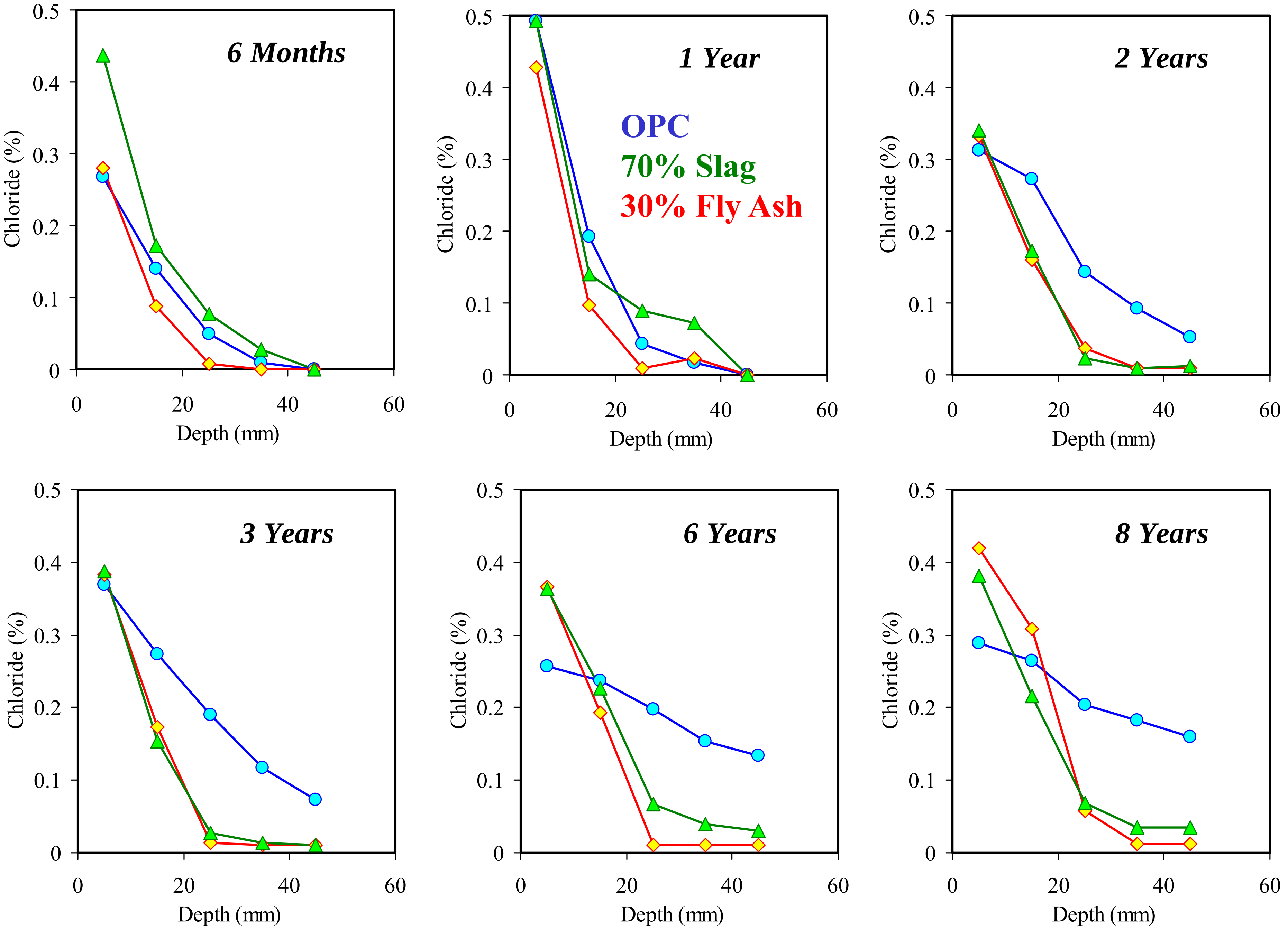
Bulk Diffusion (ASTM C 1556) Results for Lab & Field Concretes



M.D.A. Thomas, P.B. Bamforth/Cement and Concrete Research 29 (1999) 487–495

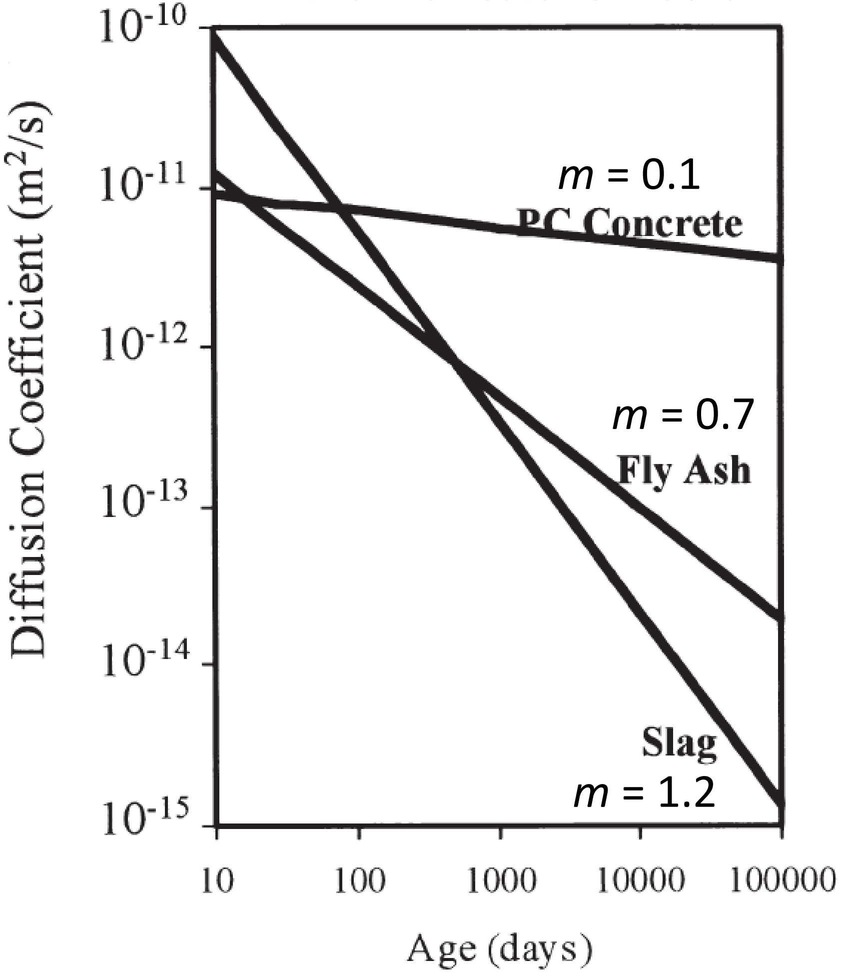
Taywood Blocks nr. Folkestone

Thomas & Bamforth, 1999

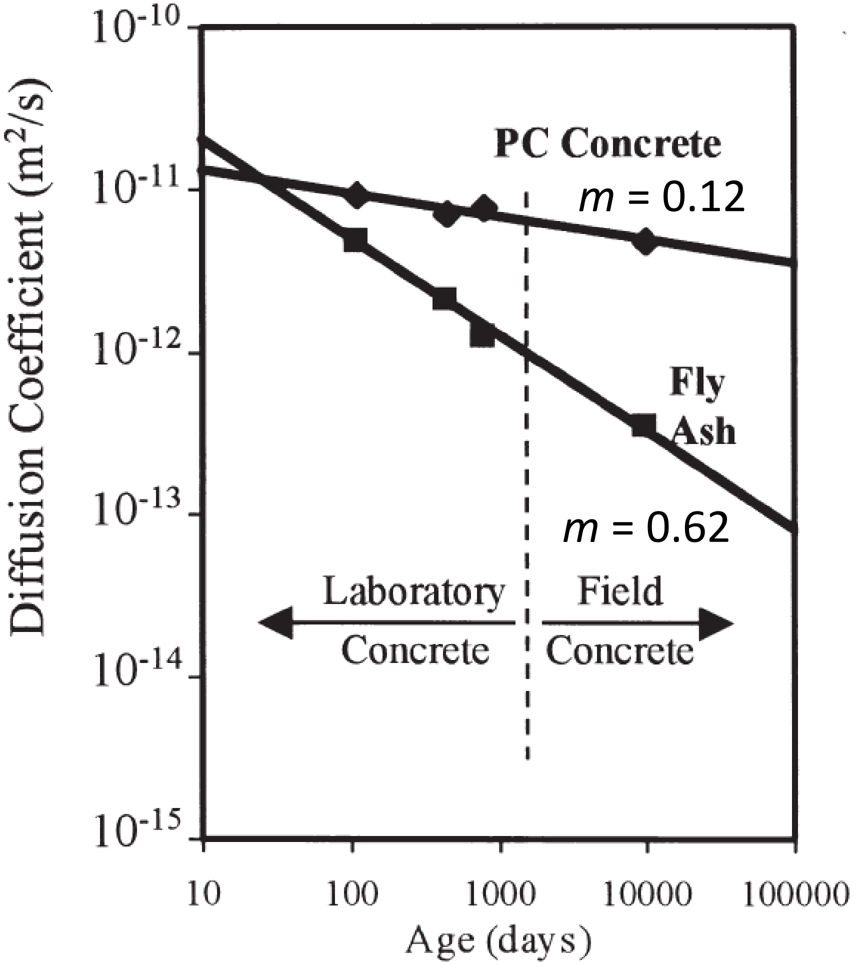


Thomas & Bamforth, 1999

D v t for Folkestone Blocks



D v t for Lab & Field Concrete



M.D.A. Thomas, P.B. Bamforth/Cement and Concrete Research 29 (1999) 487–495

Conclusions

- Electrical resistivity/conductivity provides a good indication of the mass-transport properties of Portland-cement concrete
- The relationship between electrical and mass-transport properties of concrete is strongly influenced by a number of parameters including pore-solution conductivity
- Predicting or measuring the pore-solution conductivity is **not** trivial
- Electrical properties do **not** account for the interaction between chlorides and the hydrates (binding) and this can be a **very** significant factor for some binders
- Early-age measurements of either electrical or mass-transport properties do **not** capture the substantial changes that may occur with high replacement levels of pozzolans or slag

Questions?