# Performance Evaluation and Specification of Fresh and Hardened Concrete Using Its Electrical Properties

**O. Burkan Isgor**

Professor and John and Jean Loosley Faculty Fellow

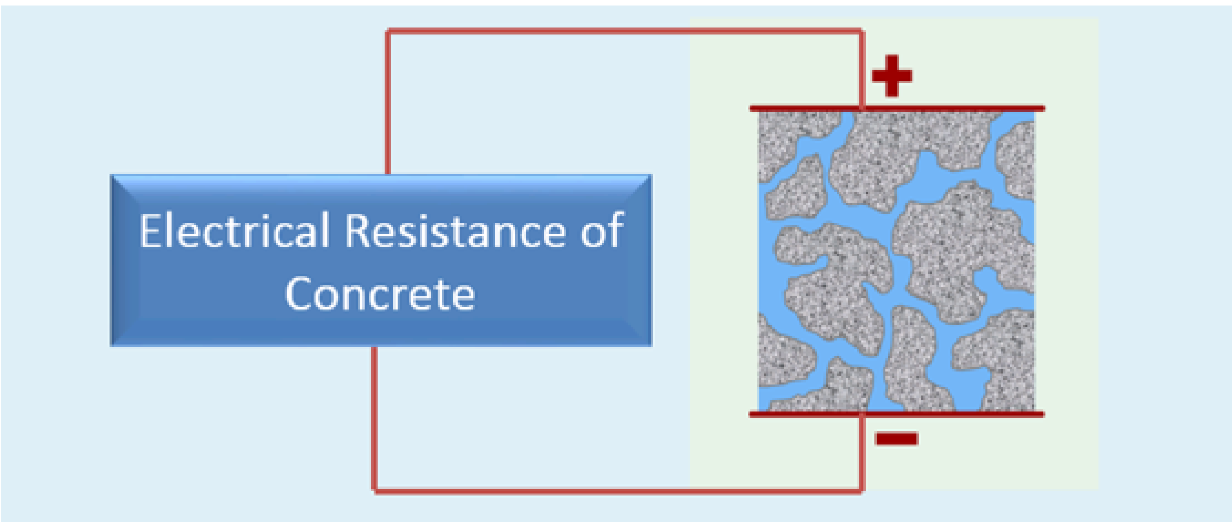
**W. Jason Weiss**

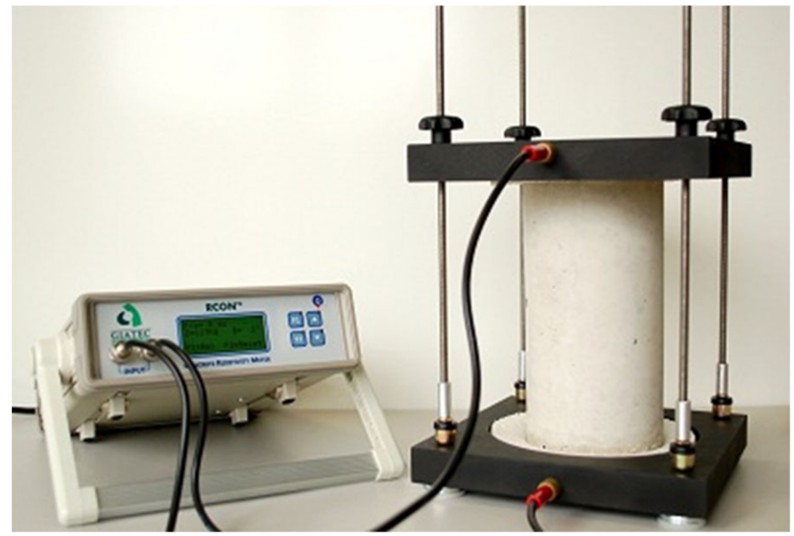
Professor and Miles Lowell and Margaret Watt Edwards Distinguished Chair in Engineering

# Background

# Electrical properties of concrete

## Resistance (R):



R = Applied voltage / measured current

$R = \Delta V / I$ [ohm]

# Electrical properties of concrete

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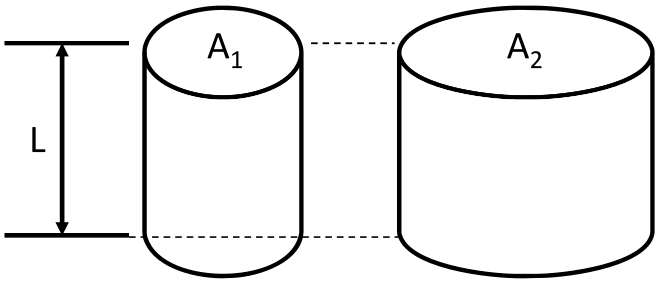
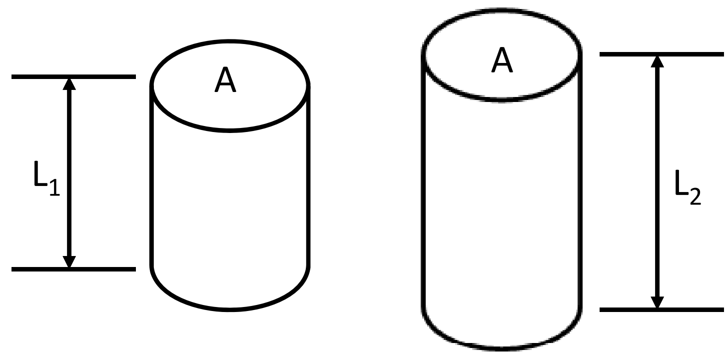
## Bulk resistivity ($\rho_{bulk}$):




Area$_1$ ($A_1$) < Area$_2$ ($A_2$)
$R_1 > R_2$



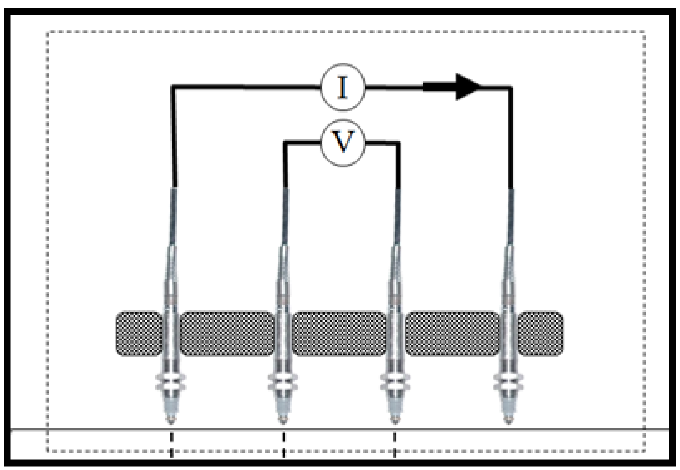

Length$_1$ ($L_1$) < Length$_2$ ($L_2$)
$R_1 < R_2$

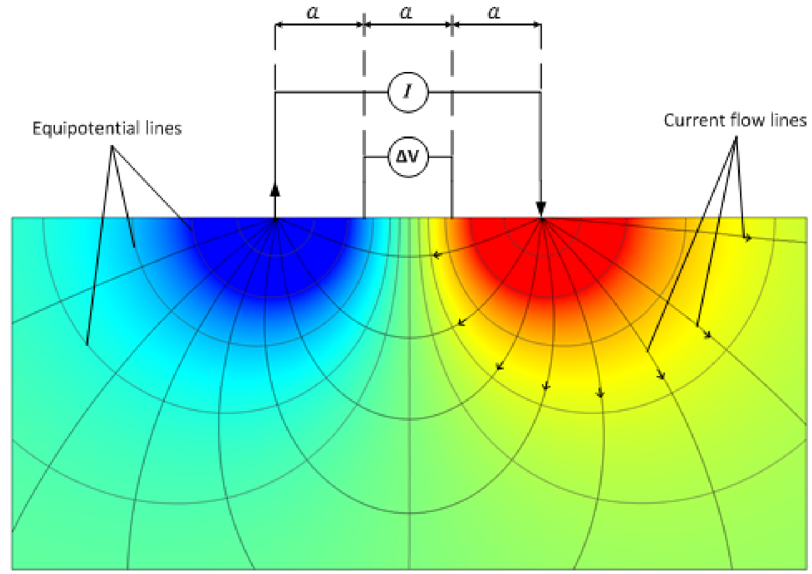
$$\rho_{bulk} = R\frac{A}{L} \quad \text{[ohm-m]}$$

Material-related parameter (no geometry effects)

# Electrical properties of concrete

## Surface resistivity ($\rho_{surf}$):

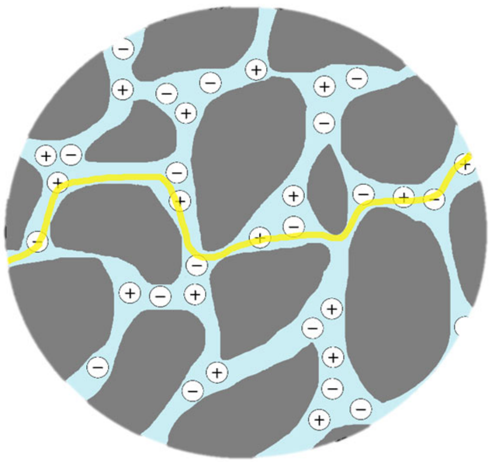




$$\rho_{surf} = 2\pi\, a \,\frac{\Delta V}{I}$$

# Electrical properties of concrete

## Pore solution resistivity ($\rho_o$):



- Liquid phase in concrete.
- Ionic-rich solution: sodium ($Na^+$), potassium ($K^+$), hydroxide ($OH^-$), calcium ($Ca^{2+}$), sulfate ($SO_4^{2-}$) ions, etc.

- Pore solution resistivity is highly dependent on ionic composition.

# Electrical properties of concrete

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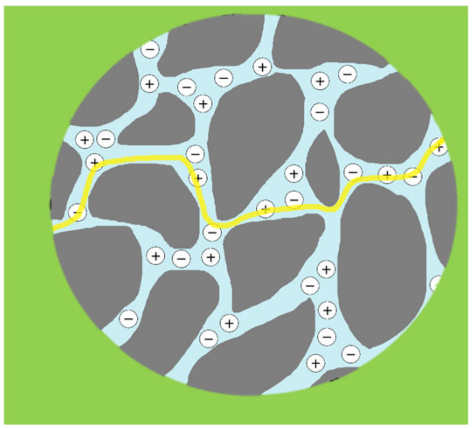
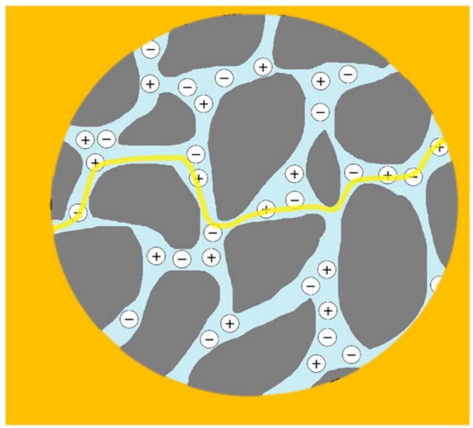
## Pore solution resistivity:



Concrete 1



Concrete 2

- Same pore structure (porosity, connectivity, tortuosity), but

$$\rho_{o,1} > \rho_{o,2}$$

- Therefore:

$$\rho_{\text{Concrete-1}} > \rho_{\text{Concrete-1}}$$

- Resistivity of concrete is not a fundamental material property.

# Electrical properties of concrete

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## Formation factor:

$$F = \frac{\rho_c}{\rho_o}$$

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

- Pore solution effect is removed
- Fundamental property
- Inversely related to porosity (Φ) and pore connectivity (β)
- Known in petrophysics as Archie's law (after Gustavus Archie) who worked for Shell Oil Company

# Electrical properties of concrete

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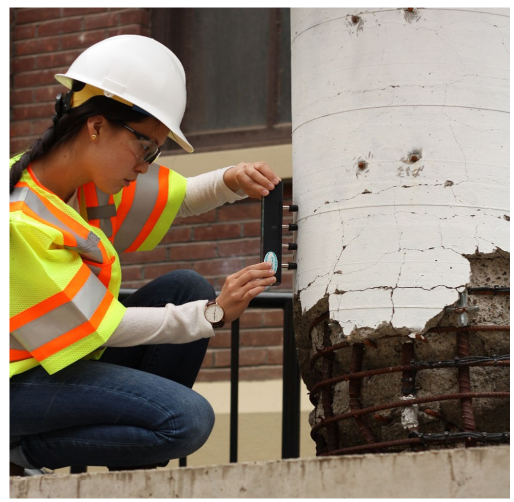
## Formation factor:

$$F = \frac{\rho_c}{\rho_o}$$



$\rho_c$ measurement is done in seconds

# Electrical properties of concrete

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## Formation factor:

$$F = \frac{\rho_c}{\rho_o}$$

- Assume a pore solution resistivity (0.04-0.12 ohm-m)
- Estimate from mill certs (NIST calculator)
- Estimate with thermodynamic modeling (GEMS software)
- Pore solution expression
- Other approaches that are in development

# Estimate from mill certs

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NIST  Search NIST  NIST MENU

Engineering Laboratory / Materials and Structural Systems Division

**INORGANIC MATERIALS GROUP**

## Estimation of Pore Solution Conductivity

**Mixture Proportions**

| Material | Mass (kg or lb) | $Na_2O$ content (mass %) | $K_2O$ content (mass %) | $SiO_2$ content (mass %) |
|---|---|---|---|---|
| Water | 160.0 | Not applicable | Not applicable | Not applicable |
| Cement | 400.0 | 0.2 | 1.0 | Not applicable |
| Silica fume | 20.0 | 0.2 | 0.2 | 99.0 |
| Fly ash | 0.0 | 0.2 | 0.2 | 50.0 |
| Slag | 0.0 | 0.2 | 0.5 | Not applicable |

Estimated system degree of hydration (%): 70

Hydrodynamic viscosity of pore solution relative to water: 1.0

Curing: Saturated ◉ Sealed ○

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

Snyder et al. (2003)

Compute **Estimated pore solution composition (M):**

K+: 0.0

Na+: 0.0

OH-: 0.0

**Estimated pore solution conductivity (S/m):** 0.0

Effective water-to-cement ratio: 0.5 Free alkali ion factor: 0.75

Reset all values to defaults

https://www.nist.gov/el/materials-and-structural-systems-division-73100/inorganic-materials-group-73103/estimation-pore

# Estimate using thermodynamics

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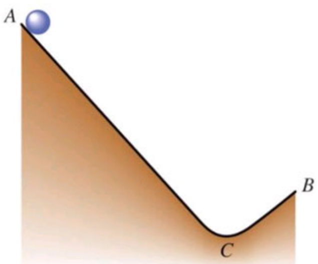
The equilibrium is obtained through minimization of the total Gibbs free energy;

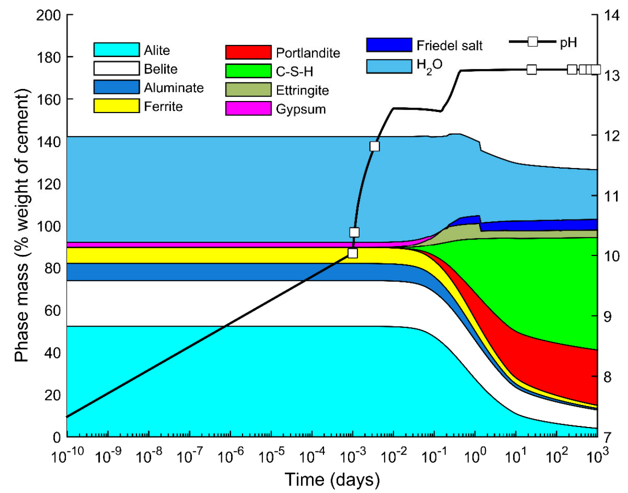
$$G = \sum_j n_j \, v_j$$

normalized chemical potential

mole amounts




The chemical system tends to minimize its energy




Pore solution: $c_{OH}^{-}$, $c_K^{+}$, $c_{Na}^{+}$, $c_{SO4}^{2-}$, etc.

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

Snyder et al. (2003)

# Measure from expressed solution

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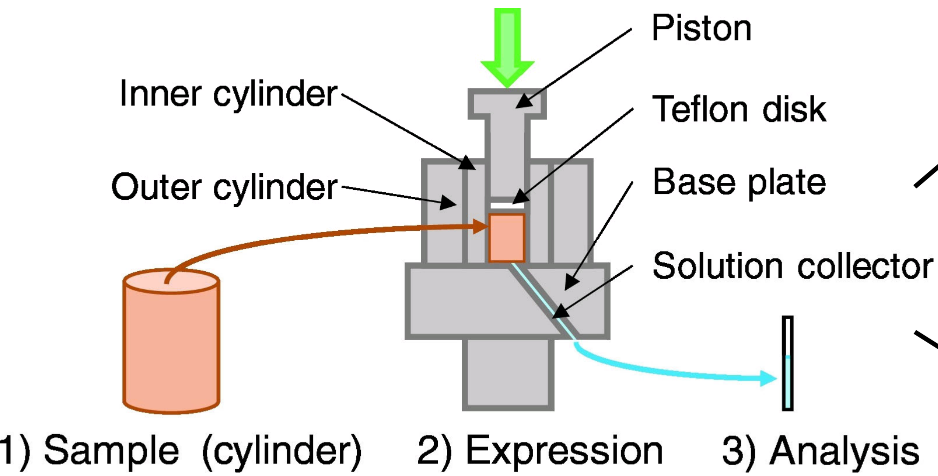
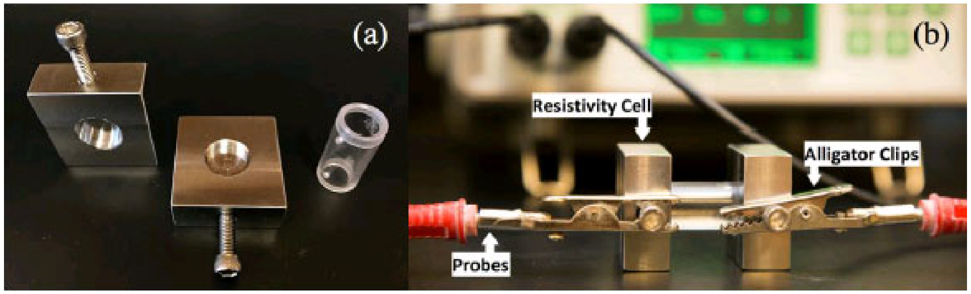



Plusquellec et al. (2017)

**Direct measurement**




**Chemical analysis (XRF, ICP, etc.)**


$c_{OH}^{-}$, $c_{K}^{+}$, $c_{Na}^{+}$, $c_{SO4}^{2-}$, etc. → $\sigma_{\text{calc}} = \sum_i z_i c_i \lambda_i$

Marisol Tsui Chang (2017)

# Formation factor of fresh concrete

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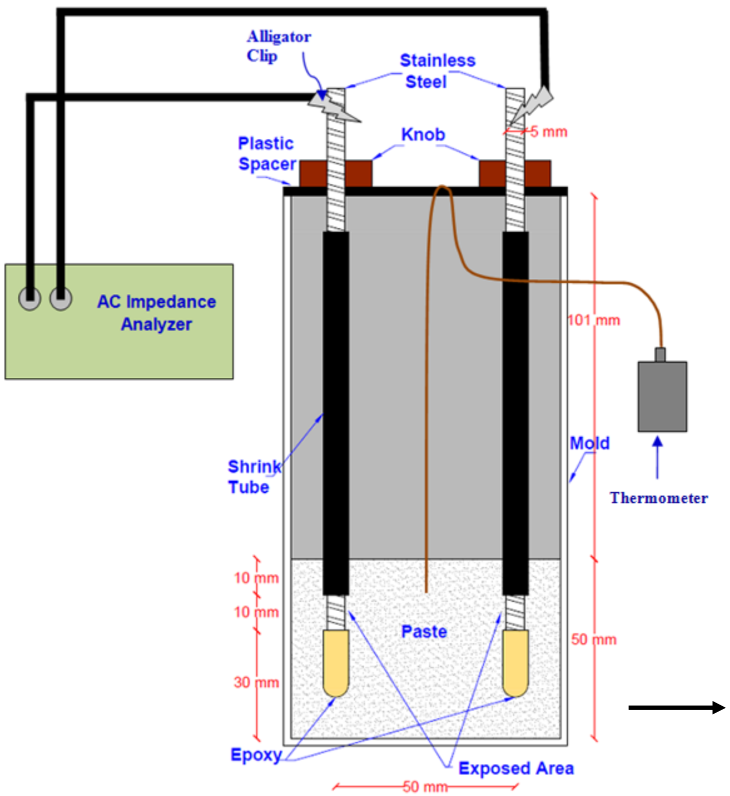


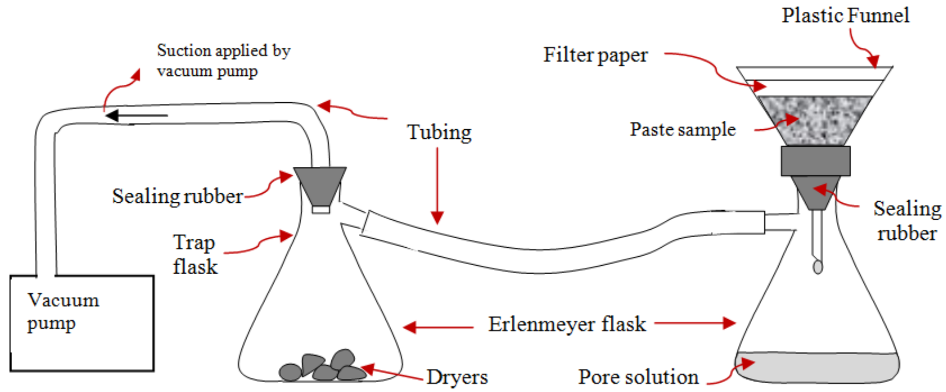


→ Fresh concrete resistivity → **Formation factor of fresh concrete**

Solution resistivity → **Formation factor of fresh concrete**

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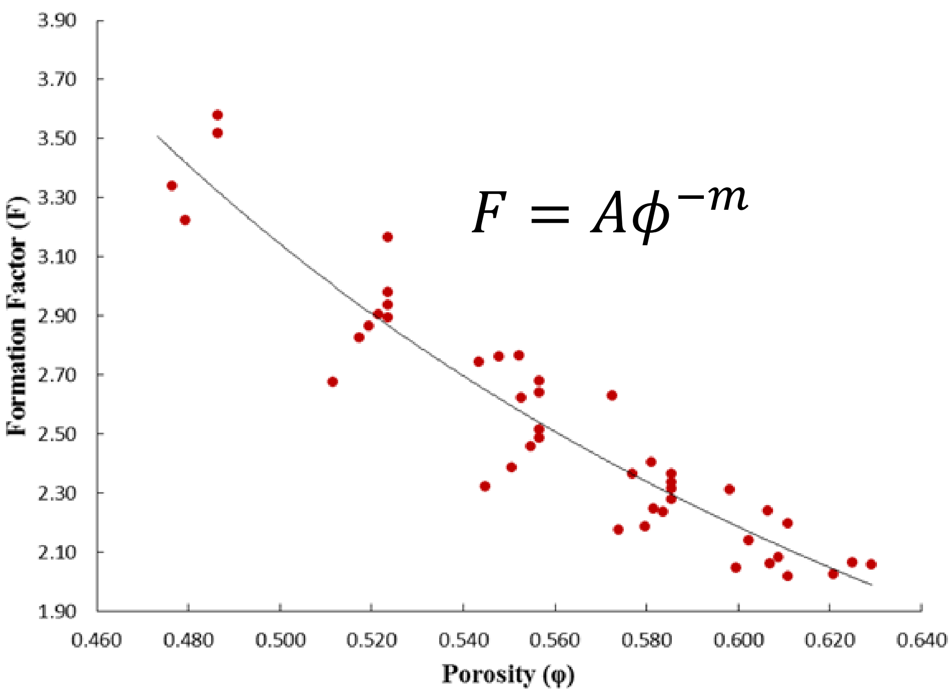
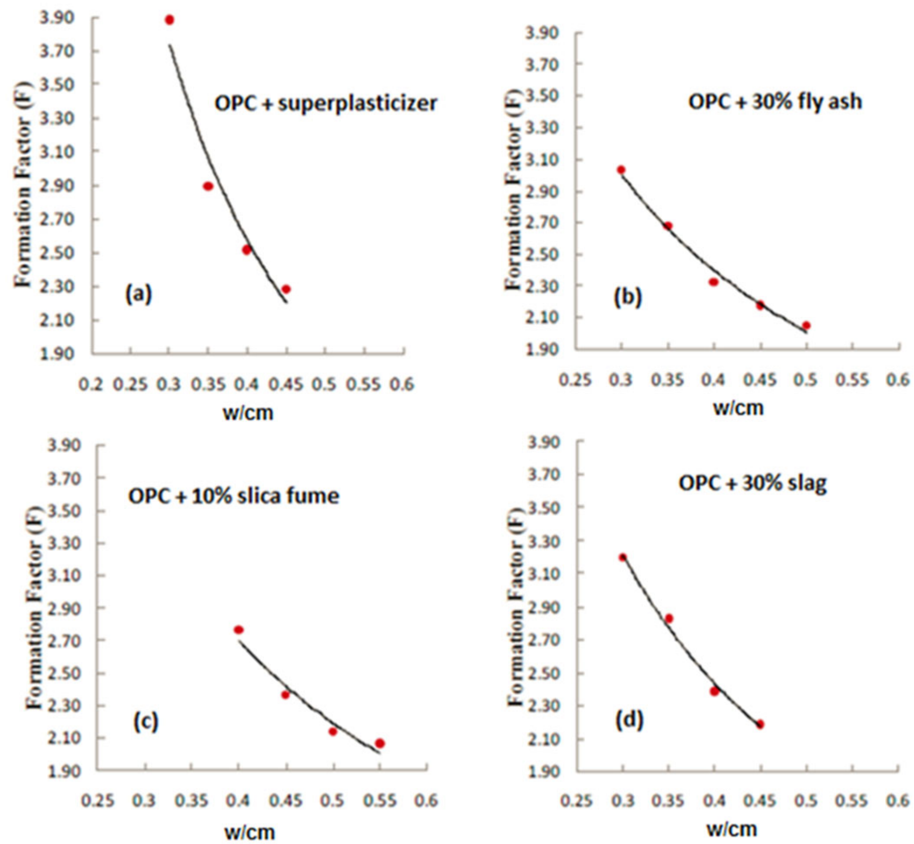
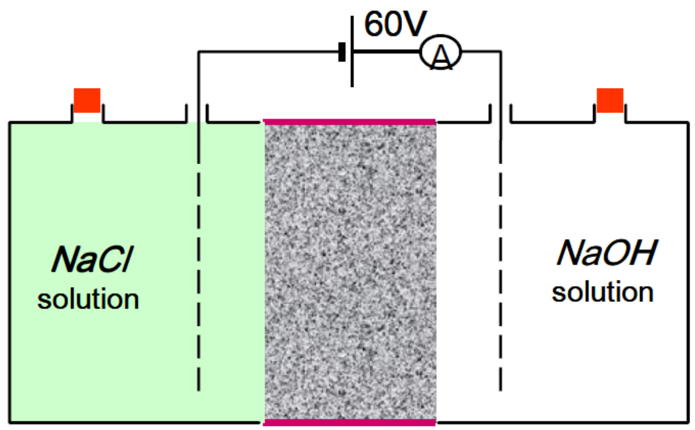
# Performance Evaluation and Specification using the F-Factor

# Fresh Properties and F-Factor

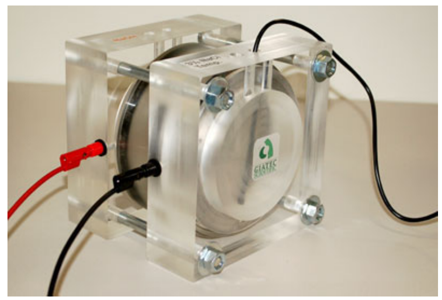


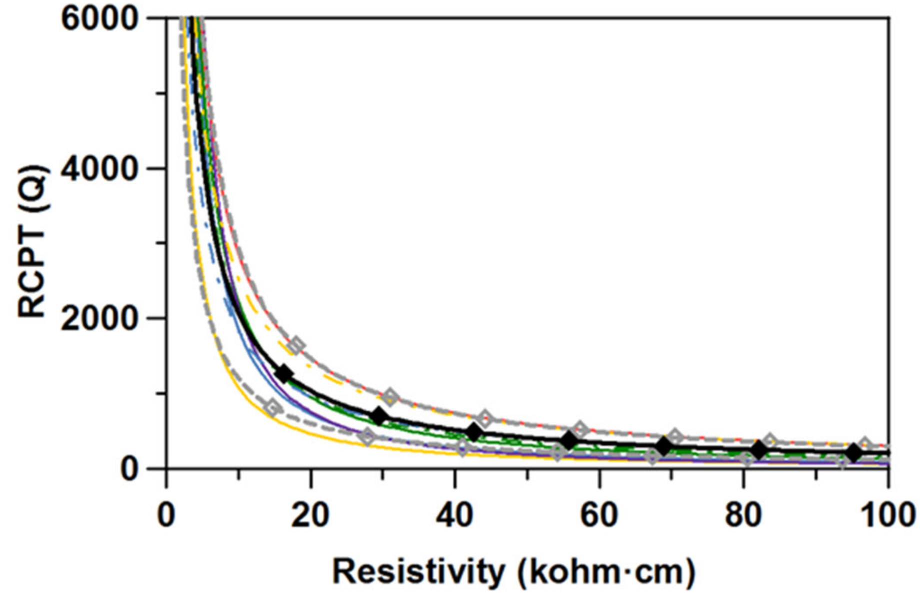
# RCPT and F-Factor




**ASTM C1202**



Spragg et al. 2015




- Takes 24+ hours with sample preparation and conditioning.
- Results are affected by conductivity of the pore solution, leaching, degree of saturation, and heat generation.
- We can fundamentally relate RCPT and resistivity:

$$Q = \int_{0\,hr}^{6\,hr} I\,dt = \int_{0\,hr}^{6\,hr} \frac{V}{R}\,dt = \int_{0\,hr}^{6\,hr} \frac{V}{\rho}\frac{A}{L}\,dt = \mathrm{Q} = V\,\frac{A}{L}\,t\,\frac{1}{\rho} = 60V\,\frac{8107\,mm^2}{50.8\,mm}\,21{,}600\,s\,\frac{1}{\rho} = \frac{206{,}830\,V\,m\,s}{\rho}$$

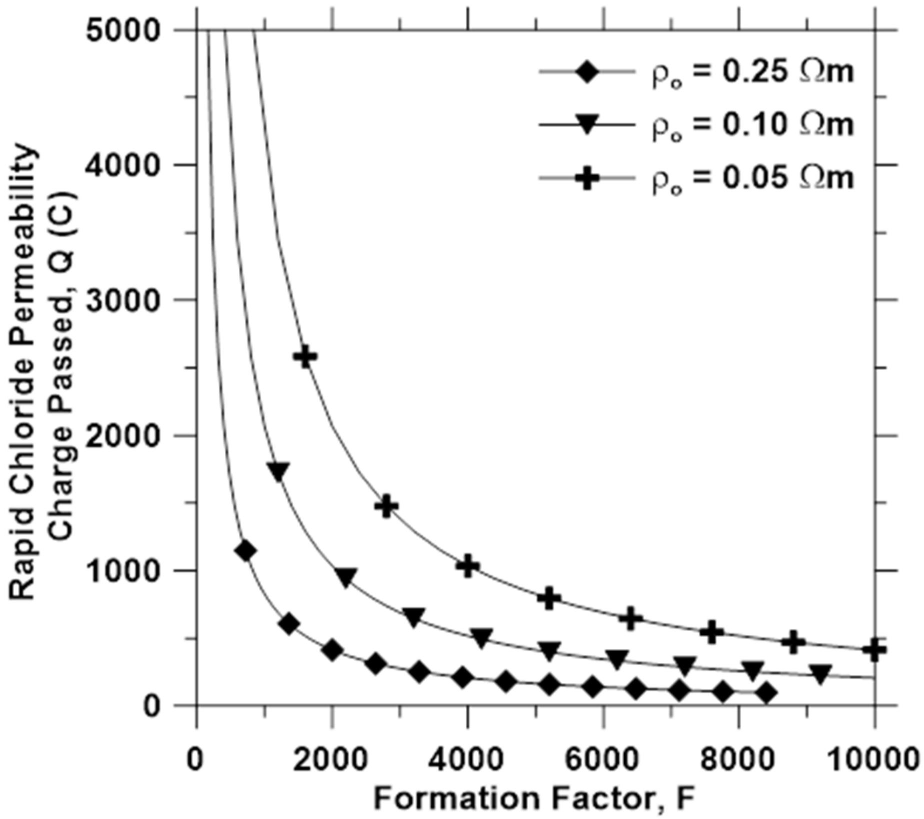
# RCPT and F-Factor

- More importantly, the F-Factor can be related with the pore solution conductivity and RCPT:

$$Q = V \frac{A}{L} t \frac{1}{\rho_0} \frac{1}{F}$$

$$Q = 60V \frac{8107\, mm^2}{50.8\, mm} 21{,}600\, s \frac{1}{\rho_o} \frac{1}{F}$$

$$Q = \frac{206{,}830\, V\, m\, s}{\rho_o} \frac{1}{F}$$




Weiss et al. 2016

# Ionic transport and F-Factor

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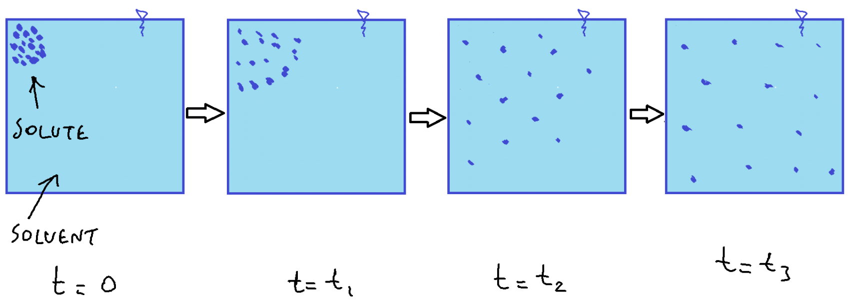
## Ionic diffusion in water:




**Example:**

Ions in water at 25°C

| Species | Mobility, $u_i$ ($10^{-8}$ $m^2 \cdot s^{-1} \cdot V^{-1}$) | Diffusion coefficient, $D_i$ ($m^2/s$) |
|---|---|---|
| $OH^-$ | 20.56 | $5.28 \times 10^{-9}$ |
| $Fe^{2+}$ | 5.60 | $0.72 \times 10^{-9}$ |
| $Ca^{2+}$ | 6.17 | $0.79 \times 10^{-9}$ |
| $Cl^-$ | 7.92 | $2.03 \times 10^{-9}$ |
| $Na^+$ | 5.19 | $1.33 \times 10^{-9}$ |
| $K^+$ | 7.62 | $1.96 \times 10^{-9}$ |
| $O_2$ | - | $2.20 \times 10^{-9}$ |

## Einstein's Equation

$$D_i = \frac{RTu_i}{z_i F}$$

- R: (Universal gas constant, 8.3143 J/mol-K))
- T: (Temperature, K)
- $u_i$: (Mobility of the ion at 25°C)
- $z_i$: (Valance # of the ion)
- F: (Faraday's constant, 96,488 C/mol)

# Ionic transport and F-Factor

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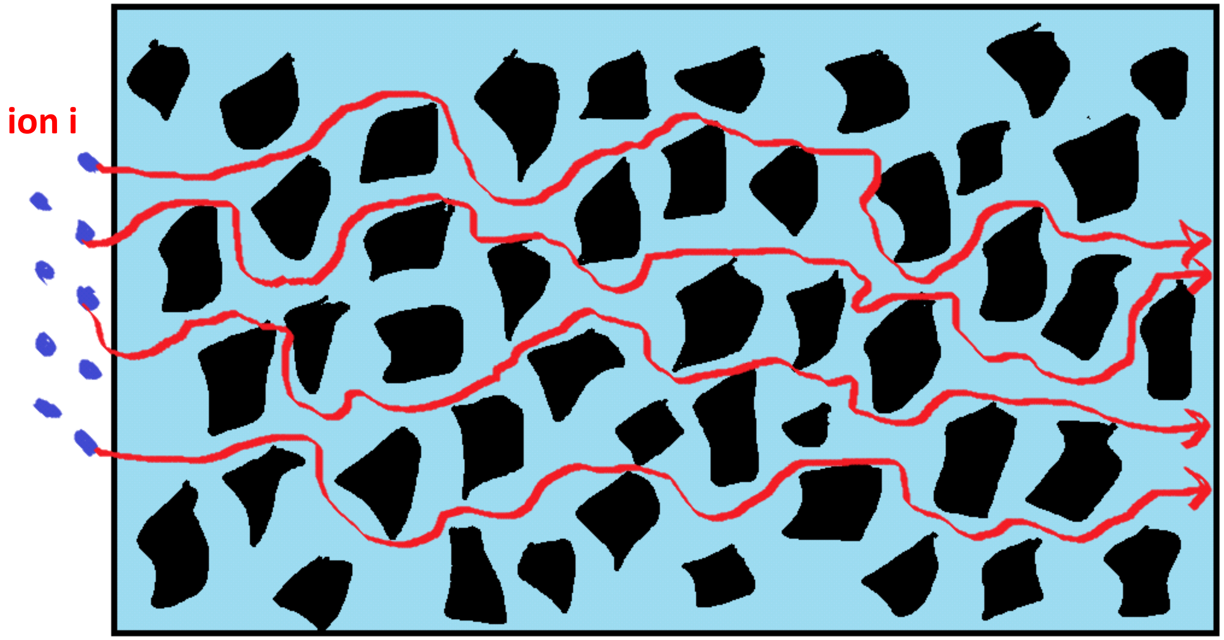
## Ionic transport in concrete:



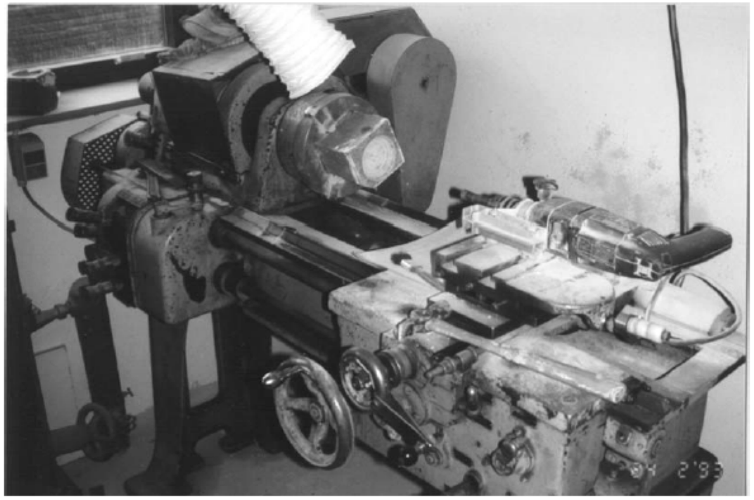

$$\frac{D_{i,concrete}}{D_i} = \frac{\rho_o}{\rho_c}$$

$$D_{i,concrete} = \frac{D_i}{F}$$

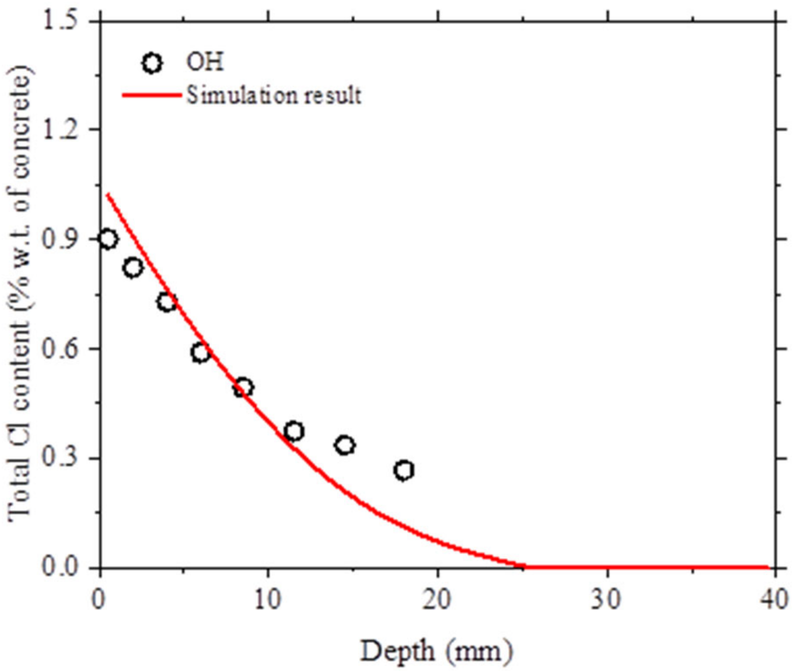
# Ionic transport and F-Factor

## Apparent chloride diffusion coefficient ($D_a$):

**ASTM C1556**

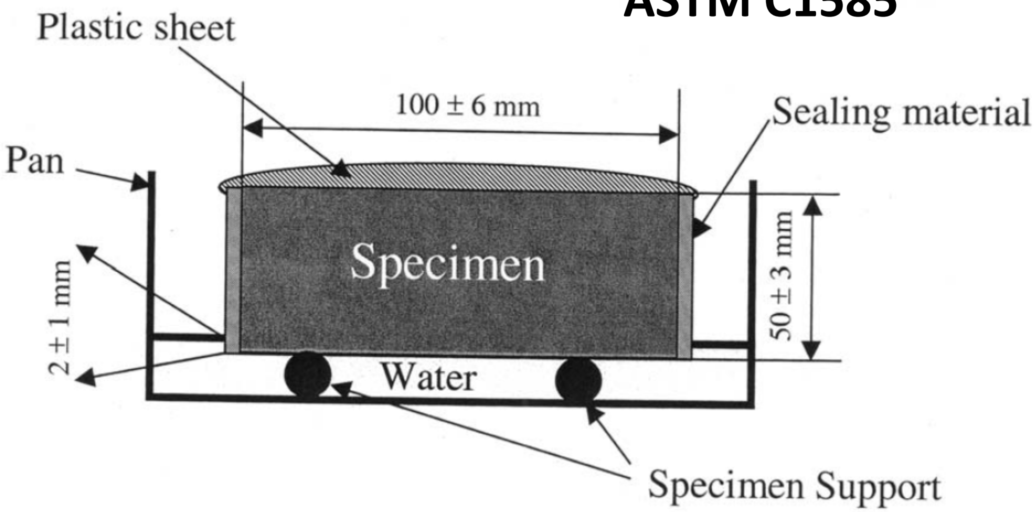


$D_a$= ∫(F-Factor)



# Absorption and F-Factor

**ASTM C1585**




- Condition the samples (18 days)
- Absorption test (weeks)
- Record mass change over time

**M(t) vs. F**

$$M(t) = \frac{A\rho R_i}{2}\sqrt{\frac{\varepsilon P_{cap}}{\mu}}\sqrt{\frac{1}{F}}\sqrt{t}$$

**(Derived from first principles)**

# Absorption and F-Factor

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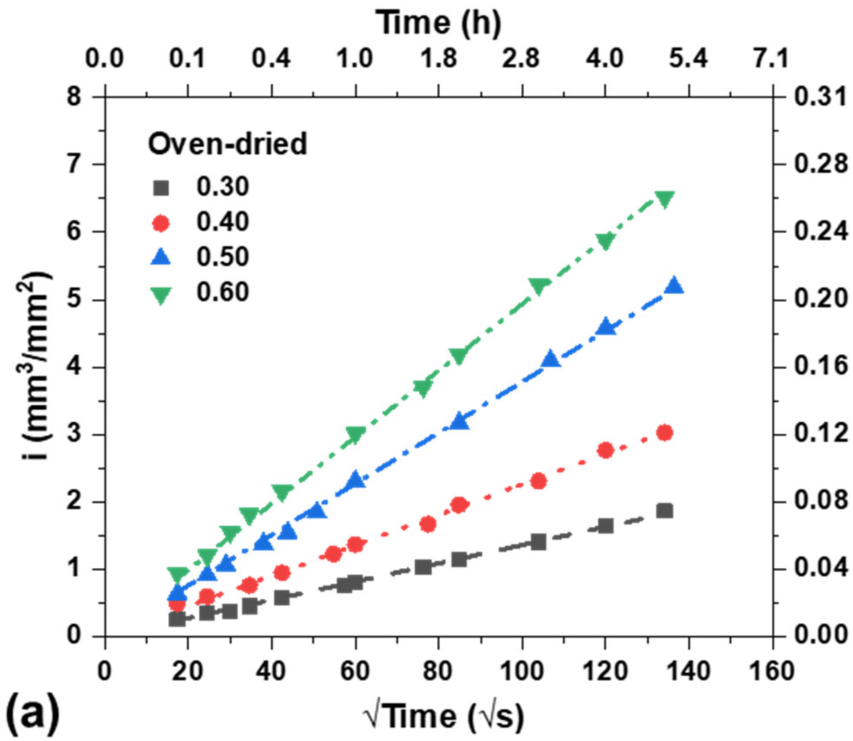


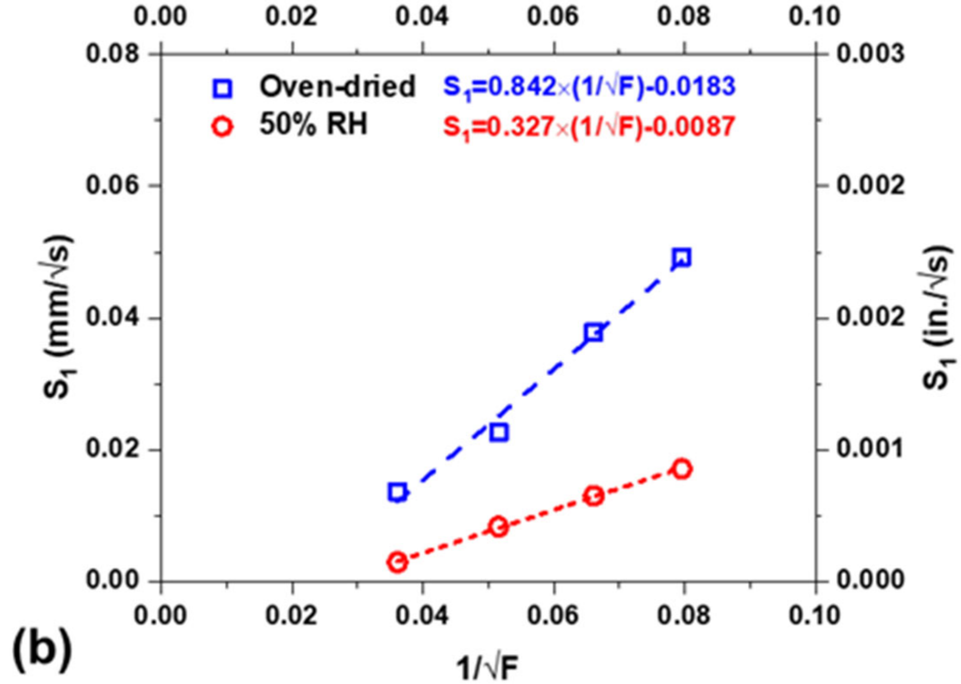


Moradllo et al. submitted

# Conclusions

# Conclusions

- **F–Factor** is a physical representation of the pore structure
- **F–Factor** is the ratio of resistivities (Bulk/Solution)
- **F–Factor** can be determined easily and rapidly
- **F–Factor** is not affected by chemical composition of pore solution, temperature, degree of saturation, other chemical admixtures
- **F–Factor** is related to many existing standard tests that are time-consuming, expensive, and error-prone.

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# Thank you
# Are There Any Questions?

**O. Burkan Isgor**
Burkan.Isgor@oregonstate.edu
**W. Jason Weiss**
Jason.Weiss@oregonstate.edu