

A Sneak Peak to the Future

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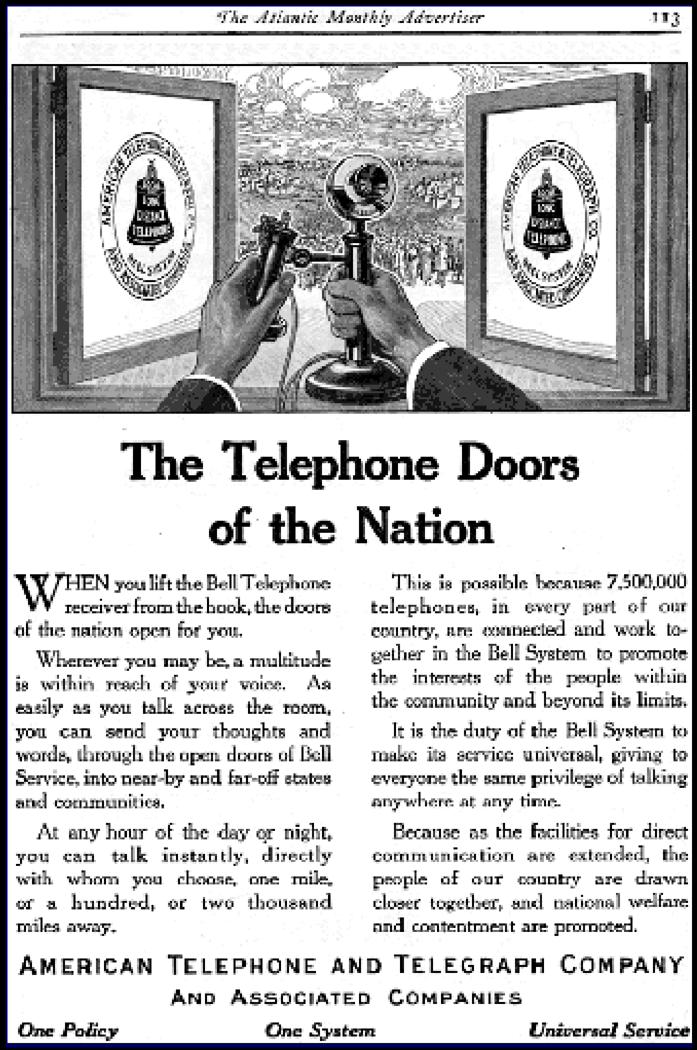
Should Our Expectations Change with Time



The Telephone Doors of the Nation

WHEN you lift the Bell Telephone receiver from the hook, the doors of the nation open for you.

Wherever you may be, a multitude is within reach of your voice. As easily as you talk across the room, you can send your thoughts and words, through the open doors of Bell Service, into near-by and far-off states and communities.

At any hour of the day or night, you can talk instantly, directly with whom you choose, one mile, or a hundred, or two thousand miles away.

This is possible because 7,500,000 telephones, in every part of our country, are connected and work together in the Bell System to promote the interests of the people within the community and beyond its limits.

It is the duty of the Bell System to make its service universal, giving to everyone the same privilege of talking anywhere at any time.

Because as the facilities for direct communication are extended, the people of our country are drawn closer together, and national welfare and contentment are promoted.

AMERICAN TELEPHONE AND TELEGRAPH COMPANY

AND ASSOCIATED COMPANIES

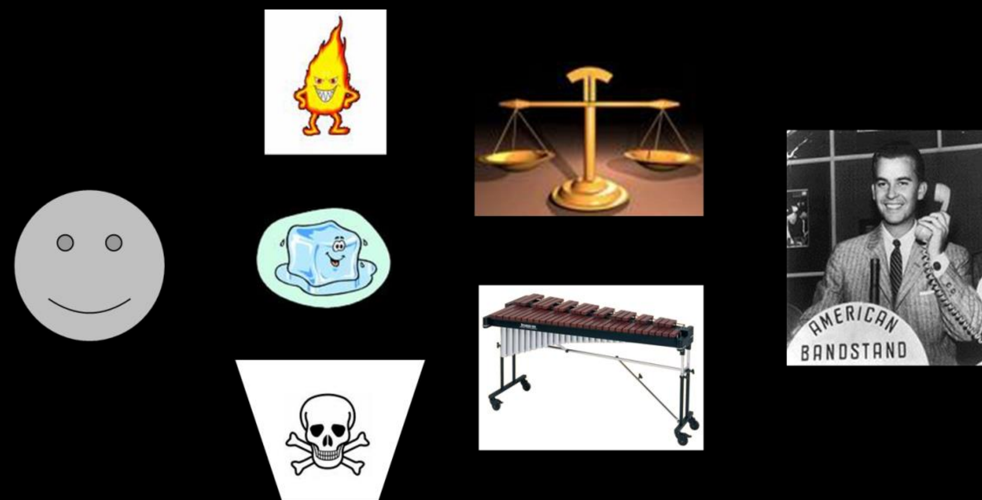
One Policy *One System* *Universal Service*

Today We Ask More from Concrete

- Today we ask for more
- TRB's 2013 Theme is Smarter, Better, Faster
- But We Also Want:
  - More Economic to Build
  - Safer for Travelers
  - Longer Lasting
  - More Sustainable
  - Economic to Maintain

Changes On The Horizon

- Historically
  - Tested Materials in harsh conditions and given a “AB type of rating”

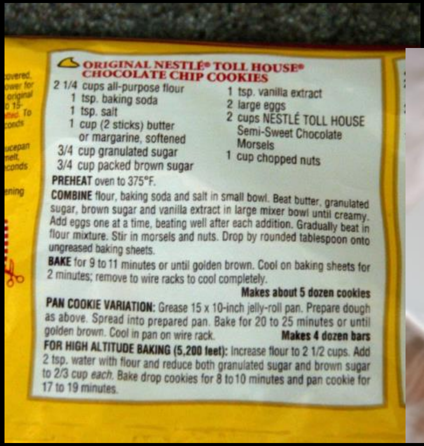


- Moving Forward
  - We will use material properties and exposure conditions to predict performance

http://www.colledun.com/gallery/albums/TowPlow/TowPlow.jpg

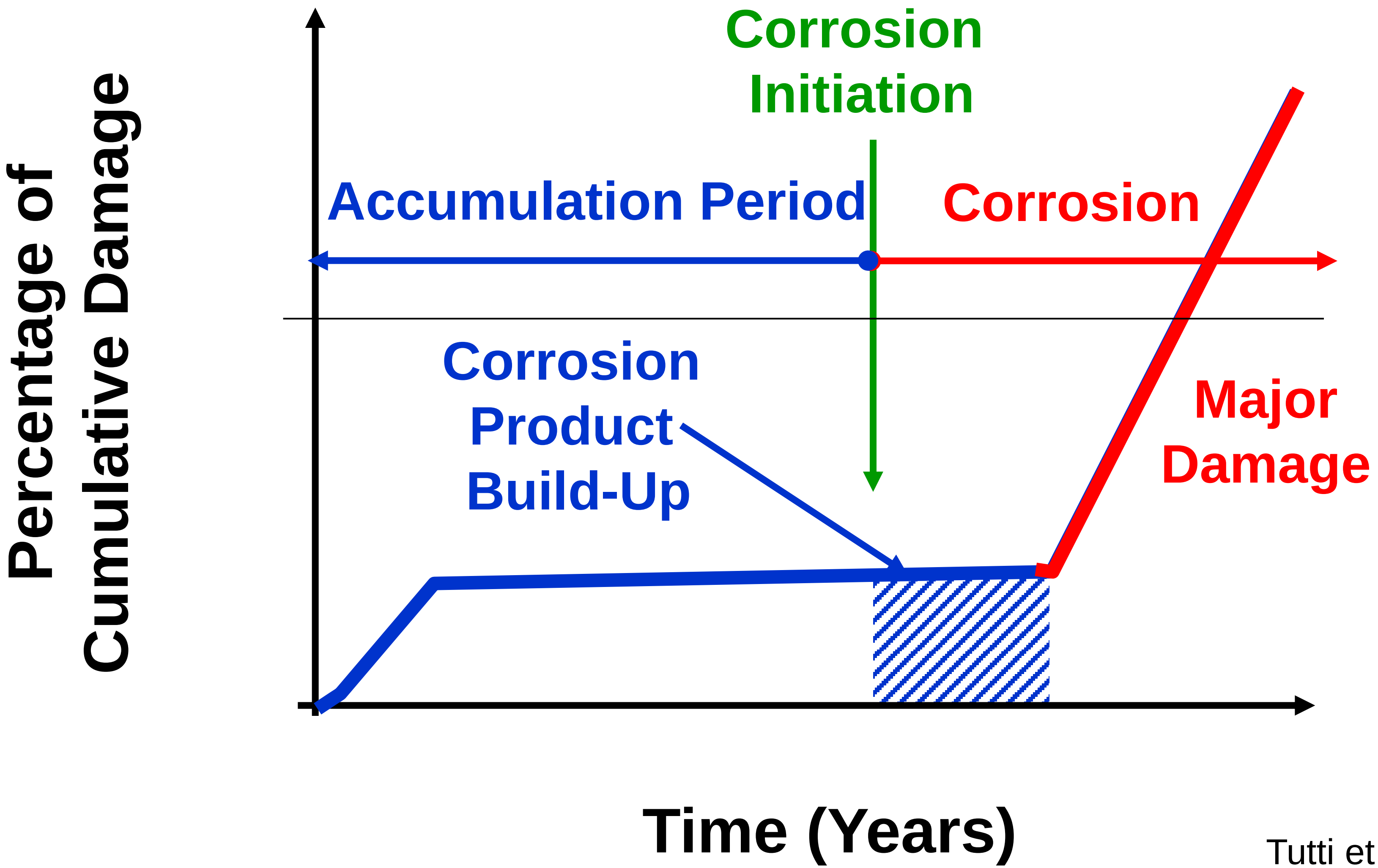
Recipe vs Performance Specifications

- Recipe
  - Developed over time
  - Items added to address specific concerns



  - Responsibility/risk borne by the agency
  - Agencies have workforce reduction – compliance?
- Performance Specifications
  - Encourage innovation, new materials
  - How do we evaluate performance without waiting 50 years – Simulations have value

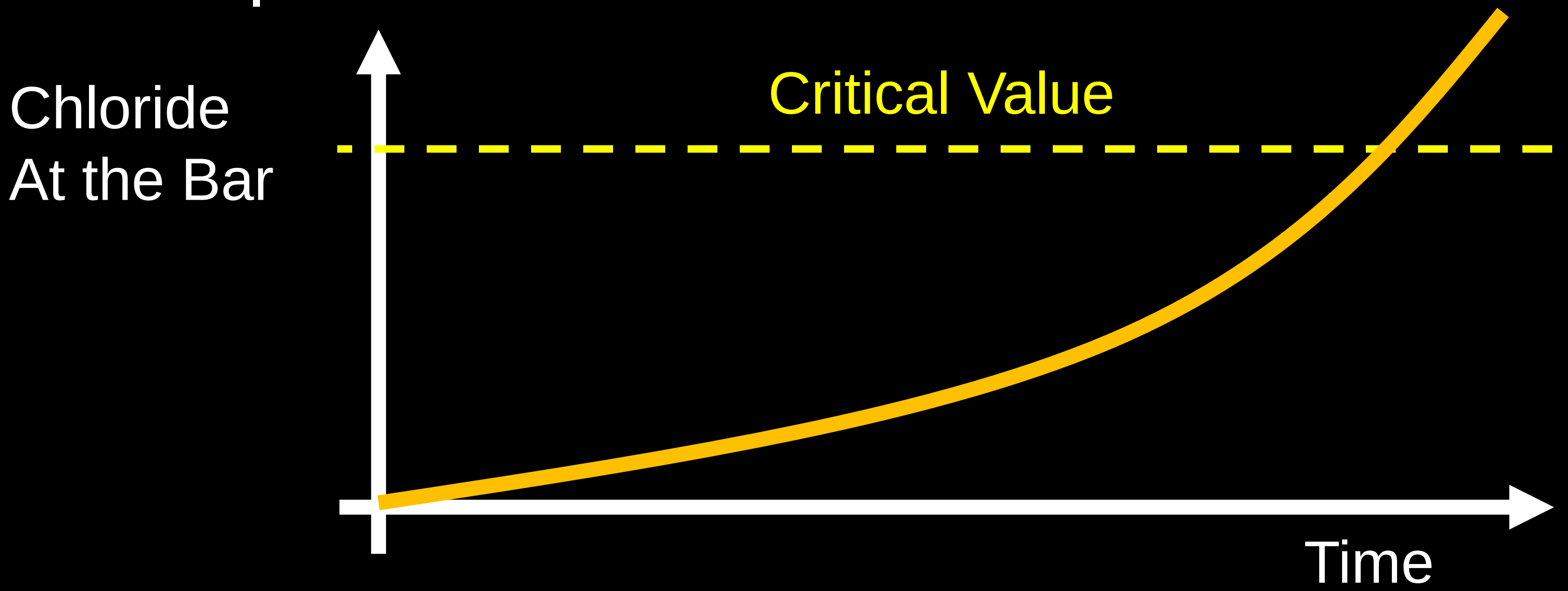
Distress Models (Example - Corrosion Initiation)



Tutti et al.

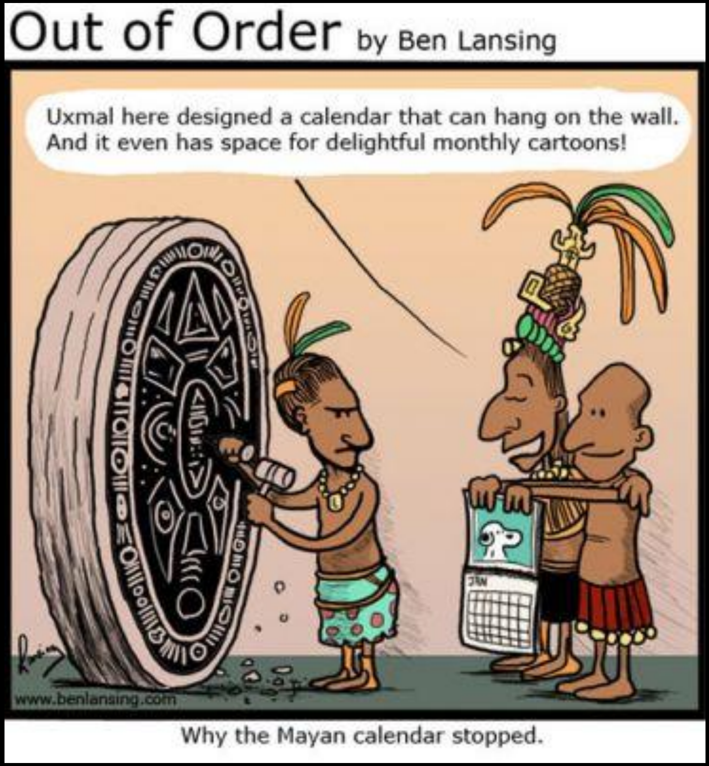
How Long Does for Corrosion to Start

- 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



What is service life and how is it predicted?

- AASHTO LRFD Bridge Design Specifications define service life as the period of time that the bridge is expected to be in operation.
- Design life - period of time on which the statistical derivation of transient loads (75 year)
- Silent on the extent of the expected service life. (Relation to Durability)

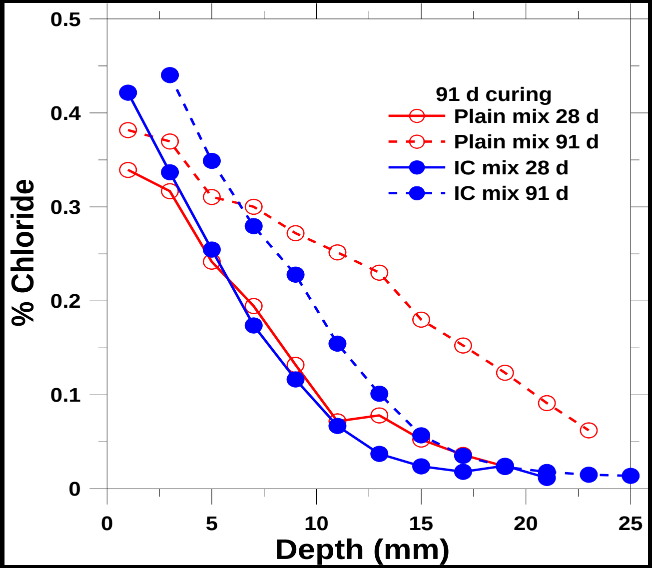


Sources of Degradation

- Major causes of degradation are high transient loads and severe environmental conditions.
- Environmental degradation: carbonation, sulfate attack, alkali-silica reaction, freeze-thaw, chloride ingress, and chemical attack.
- Water and ionic species invade the concrete's pore structure and initiate physical/chemical reactions causing expansive by-products.

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



Tests – Entering Vernacular in Practice

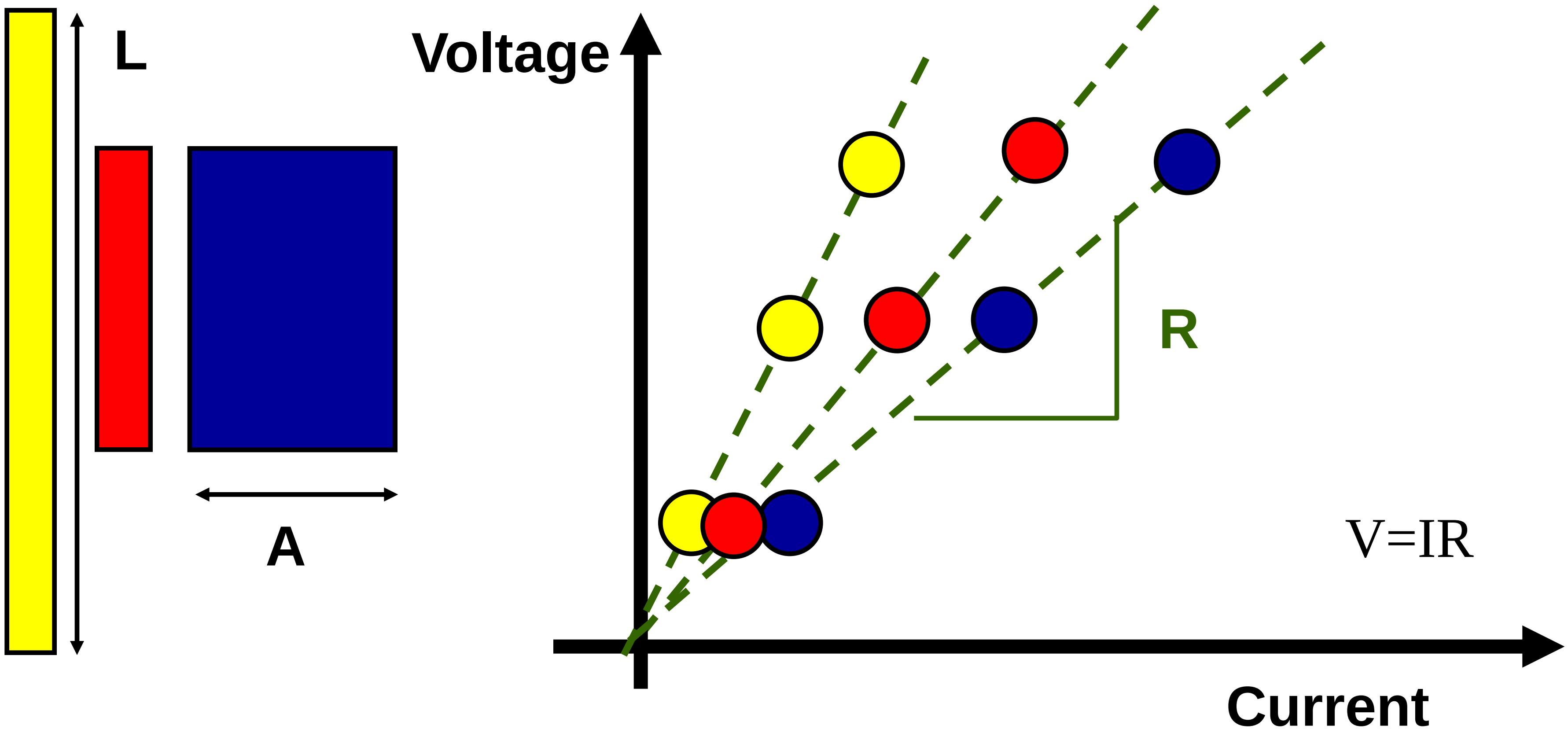
Can we Look At Alternative Tests

- 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)

Resistance



Resistivity Independent of Geometry

$$\frac{RA}{L} = \rho$$

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

Diffusion Coefficient

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

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

$$D = \sigma_{Sample} \frac{D_{ion}}{\sigma_{Fluid}} = \frac{1}{\rho_{Sample}} \rho_{Fluid} D_{ion}$$

$$D = \sigma_{Sample} * Constant$$

- Challenges how does D change over time, what if the solution differs, etc
- Opportunities for QC/QA

Review of the Impact of Geometry

Sample Geometry
Is Resistivity the Goal ?
Exposure
Formation Factor
Porosity/Tortuosity
Relate to SLM
Pore Solution
Variation Source
Curing
Saturation
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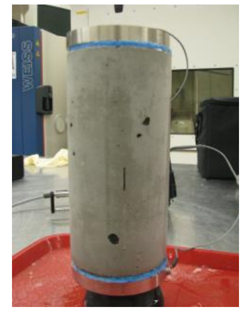
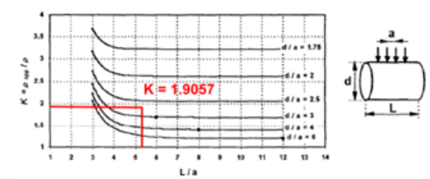
Summary

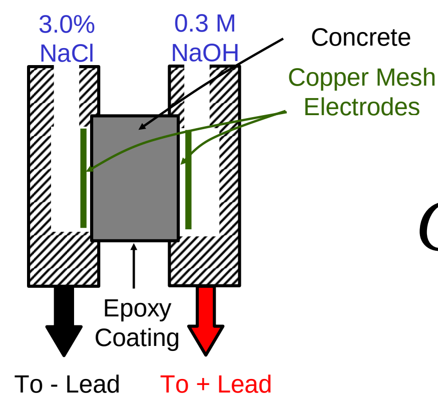
- Uniaxial, surface, embedded, and RCPT electrical measurements all yield results that can be directly compared if done properly
- Proper reporting is essential



$$\rho = \frac{V}{I}\frac{A}{L} = \frac{RA}{L}$$

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





$$Q = \int_{0h}^{6h} \frac{V}{\rho\kappa} dt$$

A thought as we begin

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- Can relate resistivity to RCPT (known value) - 1st principles

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- This results in a table
- However is this really what we want…….. think back to the gorilla

ASTM C1202 Classification[1]	Charge Passed (Coulombs)[1]	Resistivity (kOhm·cm)[2]
High	>4,000	< 5.2
Moderate	2,000 - 4,000	5.2 - 10.4
Low	1,000 - 2,000	10.4 - 20.8
Very Low	100 - 1,000	20.8 - 207
Negligible	< 100	> 207

[1] from ASTM C1202-12
[2] calculated using first principles

Spragg et al. 2010

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Archie's Law and The Formation Factor

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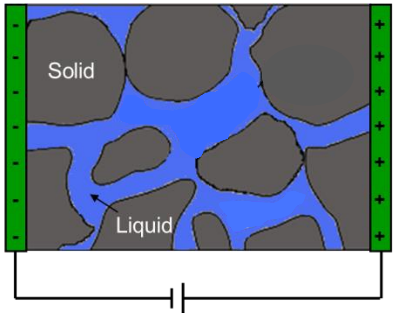
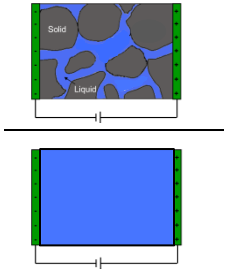
- Empirical relationship that is the ratio of the bulk resistivity (ρ) of a saturated medium and the fluid (ρ_O) that is in the medium



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



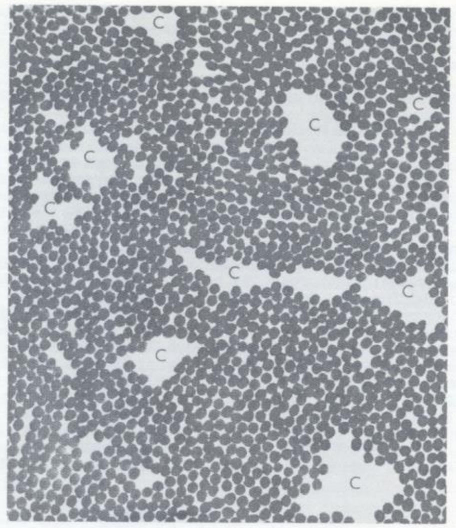
- This makes the assumption that it is only the fluid that is conductive (Weiss et al.)
- There are solutions for other cases; but this works most of the time

What is the Formation Factor Really Describing

Gel Pores (2-5 nm) – small, independent of w/c, increase in volume with hydration

Capillary Pores (5nm-10 μm) – large pores, very dependent on w/c, decrease in volume with hydration, what we control

Entrained/Entrapped Air – Largest pores from mixing, stabilizing bubbles



Formation Factor is all about Total Porosity (ϕ) and Tortuosity (β)

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

<u>**What Do We Need to Remember ?**</u>

Transport mainly in large pores
Capillary pores are large/connected
W/C, SCM and Curing

Maybe We Should Look at the Formation Factor

- Maybe it makes sense to look at the formation factor instead for specifications

ASTM C1202 Classification[1]	Charge Passed (Coulombs)[1]	Resistivity (kOhm·cm)[2]	Formation Factor
High	>4,000	< 5.2	520 ?
Moderate	2,000 - 4,000	5.2 - 10.4	520-1040 ?
Low	1,000 - 2,000	10.4 - 20.8	1040-2080 ?
Very Low	100 - 1,000	20.8 - 207	2080-20700 ?
Negligible	< 100	> 207	20700 ?

[1] from ASTM C1202-12
[2] calculated using first principles

- These numbers are just place holders however they illustrate how to get to the most fundamental value
- With this one can to go in two directions
  - 1) This relates to service life
  - 2) This enables various constituents

1) Direct Relation to Service Life

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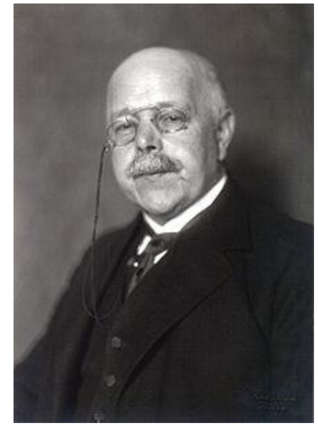
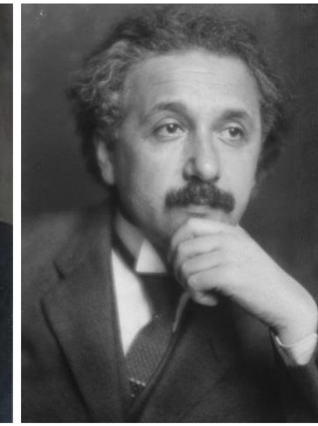
- Walther Nernst (1864-1941)
- German physical chemist/physicist
- Won 1920 Nobel Prize





$$F = \frac{\rho_{Bulk}}{\rho_{Soln}}$$

Table 1 – Diffusion coefficient of various species in free water

Species	D_i^{μ} (10^{-9} m^2/s)
OH^-	5.273
Na^+	1.334
K^+	1.957
SO_4^{2-}	1.065
Ca^{2+}	0.792
Cl^-	2.032
Mg^{2+}	0.706

$$D_i = D_i^{\mu} \cdot \frac{1}{F} = D_i^{\mu} \cdot \frac{\rho_{Soln}}{\rho_{Bulk}}$$

2) Enables Various Constituents

- Conduction requires an electrolyte
- Free ions making solution electrically conductive
- Na^{+}, K^{+}, $Ca^{2+,}$ Mg^{2+}, Cl^{-}, HPO_4^{2-}, HCO_3
- Heavily influenced by SCM

Three approaches to obtain ρ_O (for const.)

1) Extraction – Doable
2) Sensor –Promising (Rajabipour et al)
3) Calculation http://ciks.cbt.nist.gov/poresolncalc.html

Lets Take a Second to Review

- Geometry correction is key (κ)
- Many want a table for RCPT vs ρ
- Easy to do but is it the best thing

A Possible Thought

F is the way to go for a specification

ρ is the way to go for QC/QA

Requires ρ_O to be stated using a procedure in specification (much easier) or determined experimentally (harder)

Nothing Left to Worry About Right ?

- We may think that resistivity is fast and easy so what can go wrong with it

- We have been involved in two ‘round robin studies’
- National study samples were prepared and sent to different labs

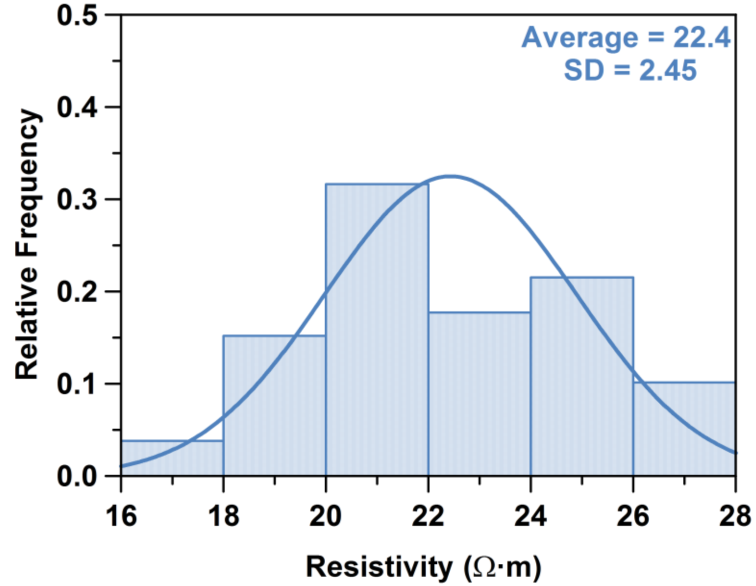
Testing Age [d]	Within-laboratory	Multi-laboratory
Uniaxial Resistivity	12 %	37 %
Surface Resistivity	13 %	35 %

- State study where we prepared all the samples, trained and distributed samples

Components of Variation

$$\sigma_{total} = \sqrt{\sigma^2_{machine} + \sigma^2_{operator} + \sigma^2_{material} + \sigma^2_{production} + \sigma^2_{curing}}$$

- Machine/Operator/Material
  - Traditionally estimated in a single lab as
  - 3-4% (Purdue, LaDOT)
- Production
  - Important when used as a QC/QA tool
  - Dependent on contractor quality
  - 10% is a typical value

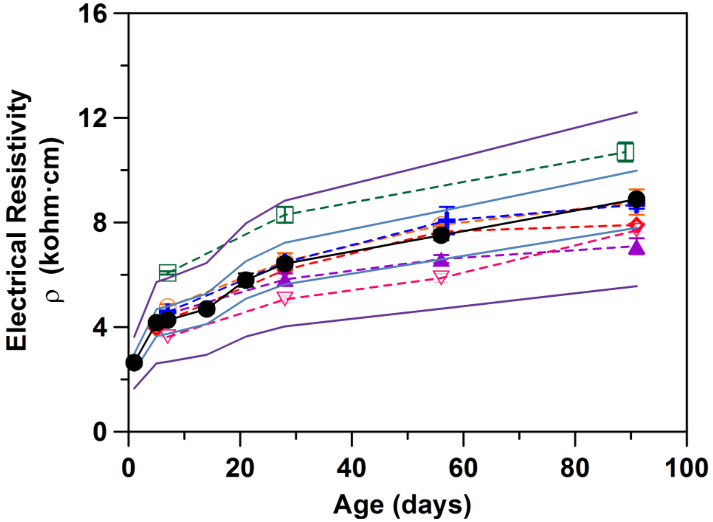


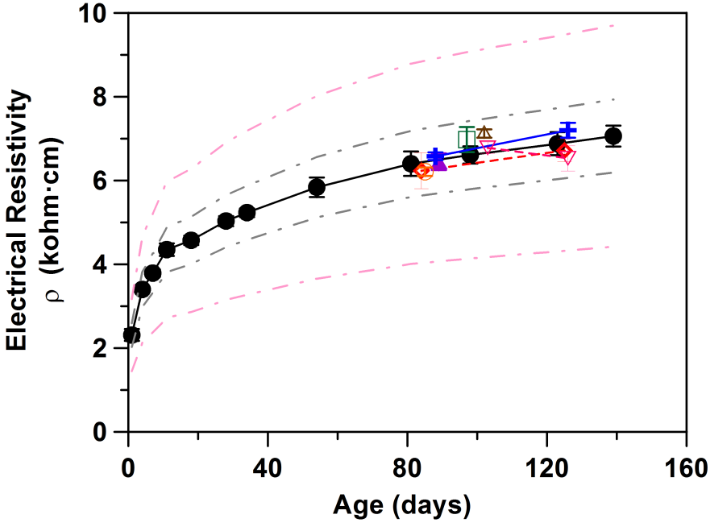
- Data shown is from a central mix plant with one mixture run frequently, low variation

Spragg et al. 2012

Components of Variation
Attention to Curing is Critical

- State Study
- Within-lab: 4.36%
  - Machine/Operator/ Material
- Multi-lab: 13.22%
  - Machine/Operator/ Material and curing
  - Believed Curing Variation: 12.5%
- State Variation Shown (top young, bottom old samples)





Spragg et al. 2013

Testing Temperature

w/c	Eac (KJ/mole)
0.36	9.39
0.42	10.19
0.45	10.06
0.50	9.69
STD DEV	0.365

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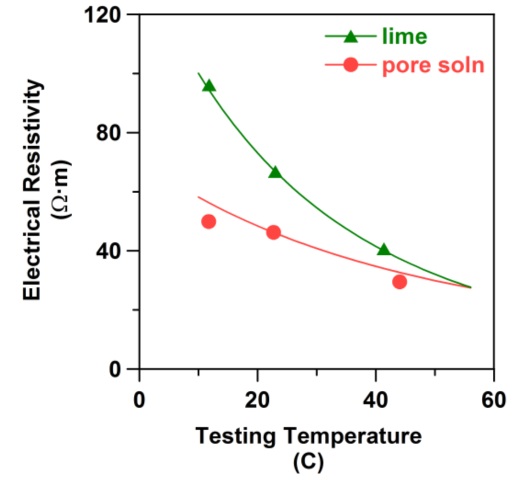
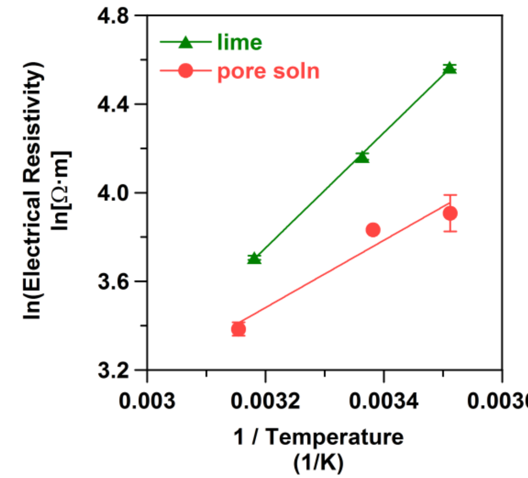
- Activation Energy of Conduction (test temp)

Rajabipour et al. 2007, Sant et al.2007

$$\frac{\rho_{T_{ref}}}{\rho} = exp\left[\frac{E_{a-con}}{R}\left(\frac{1}{T} - \frac{1}{T_o}\right)\right]$$

- In the past we noticed differences between
- Varied the solutions
  - Pore Solution: 9-12 kJ/mol
  - Bulk Sample: 20-25 kJ/mol



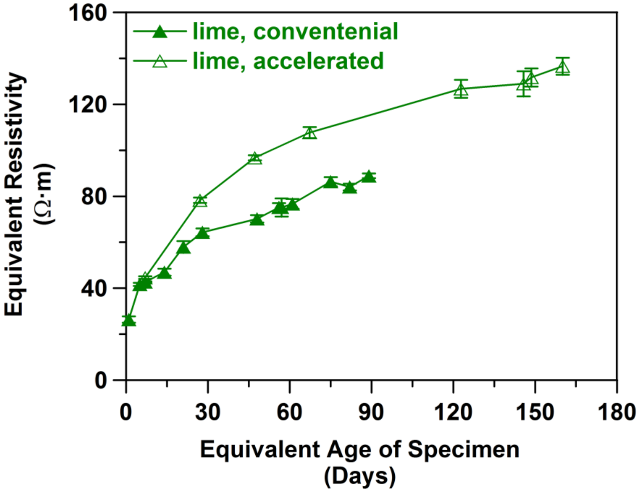


Spragg et al. 2013

$$\rho = \rho_o^* \cdot F \cdot f(S) \cdot f\left(T_{Testing}\right) \cdot f(Leach) \text{ at } t_{equivalent}$$

Accelerating Curing Time

- Many materials we test take a long time to show benefits (91 d)
- We frequently want to speed this time up
- VTRC/NRMCA method
- Lime water 7d, 23C followed by 21d, 38C
- T equivalent 56d
- Application on the right shows difference ~25%



Bu et al. 2014

Accelerated Curing Effects

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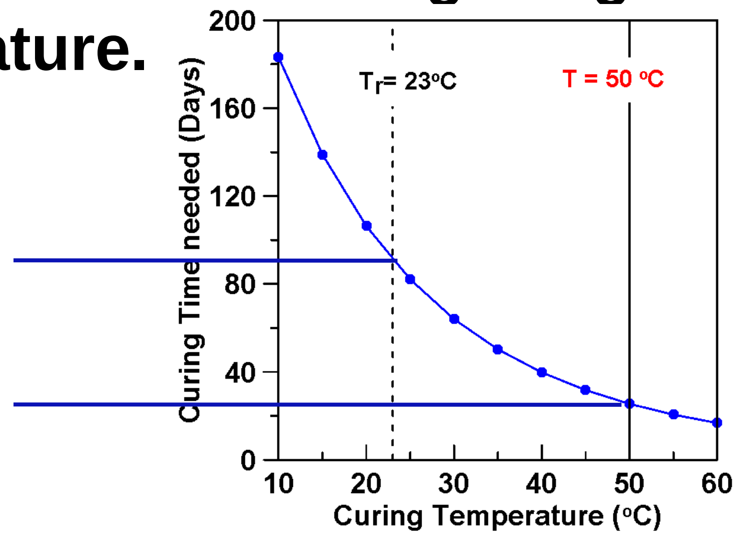
Transport testing and service life prediction usually performed on specimens of later age (91 days).

$$t_e = e^{-\frac{E_a}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)} t$$

Same maturity (DOH) could be achieved with shorter time using a higher curing temperature.

91 days

23 days



E_a = 37 kJ/mol

Bu et al. 2014

Summary

- Geometry correction is key (κ)
- Many want a table for RCPT vs ρ
- Formation factor is the way to go (IMHO)
- Electrical Properties are dependent on
  - Degree of Saturation
  - Test Temperature
  - Ionic Leaching
- Accelerated curing possible but expansion of water needs to be considered
- Training necessary - sensitive in ways that slump and compressive strength are not