Longer-Life Reinforced Concrete Structures through Supplementary Cementitious Materials

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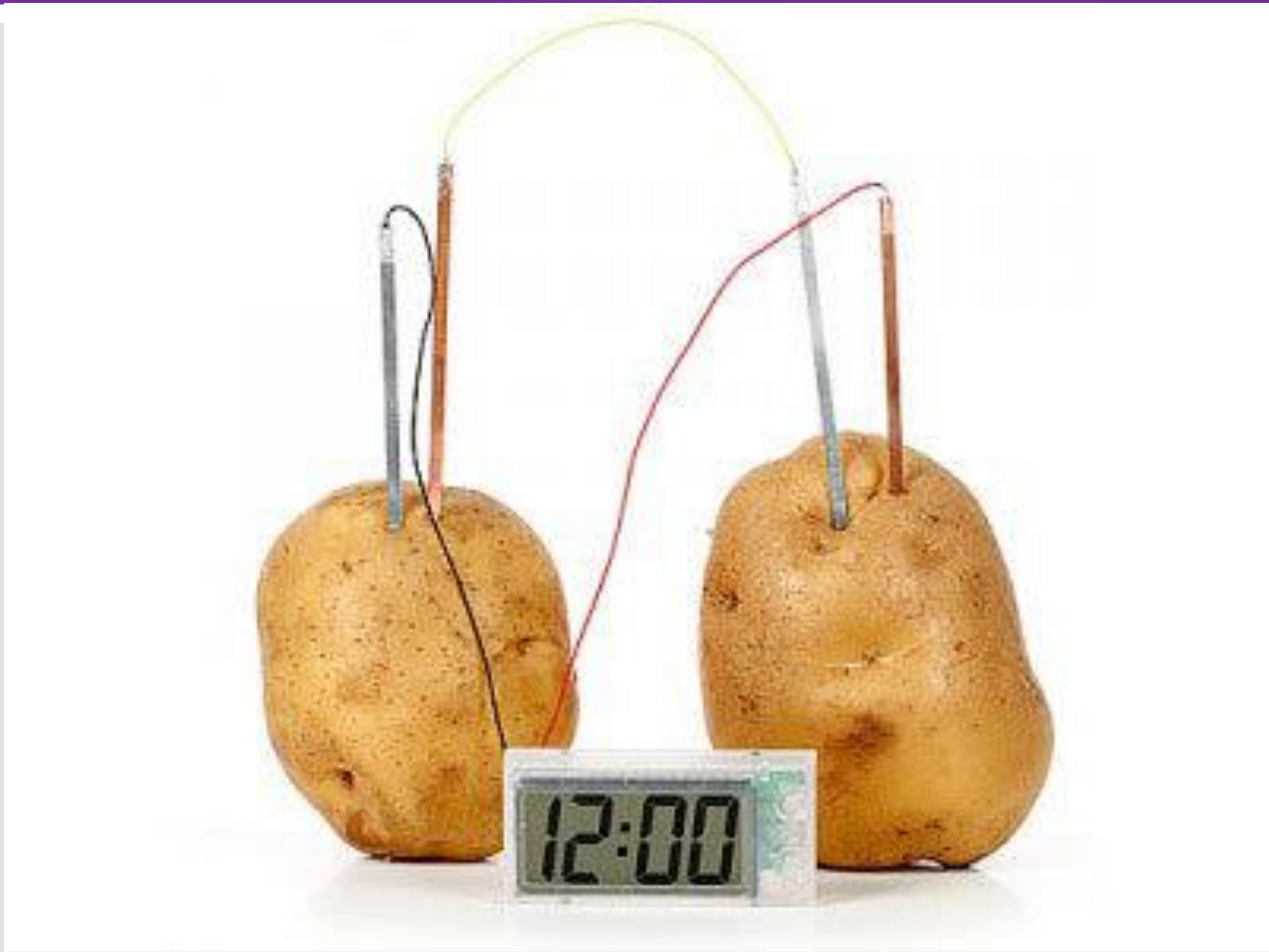
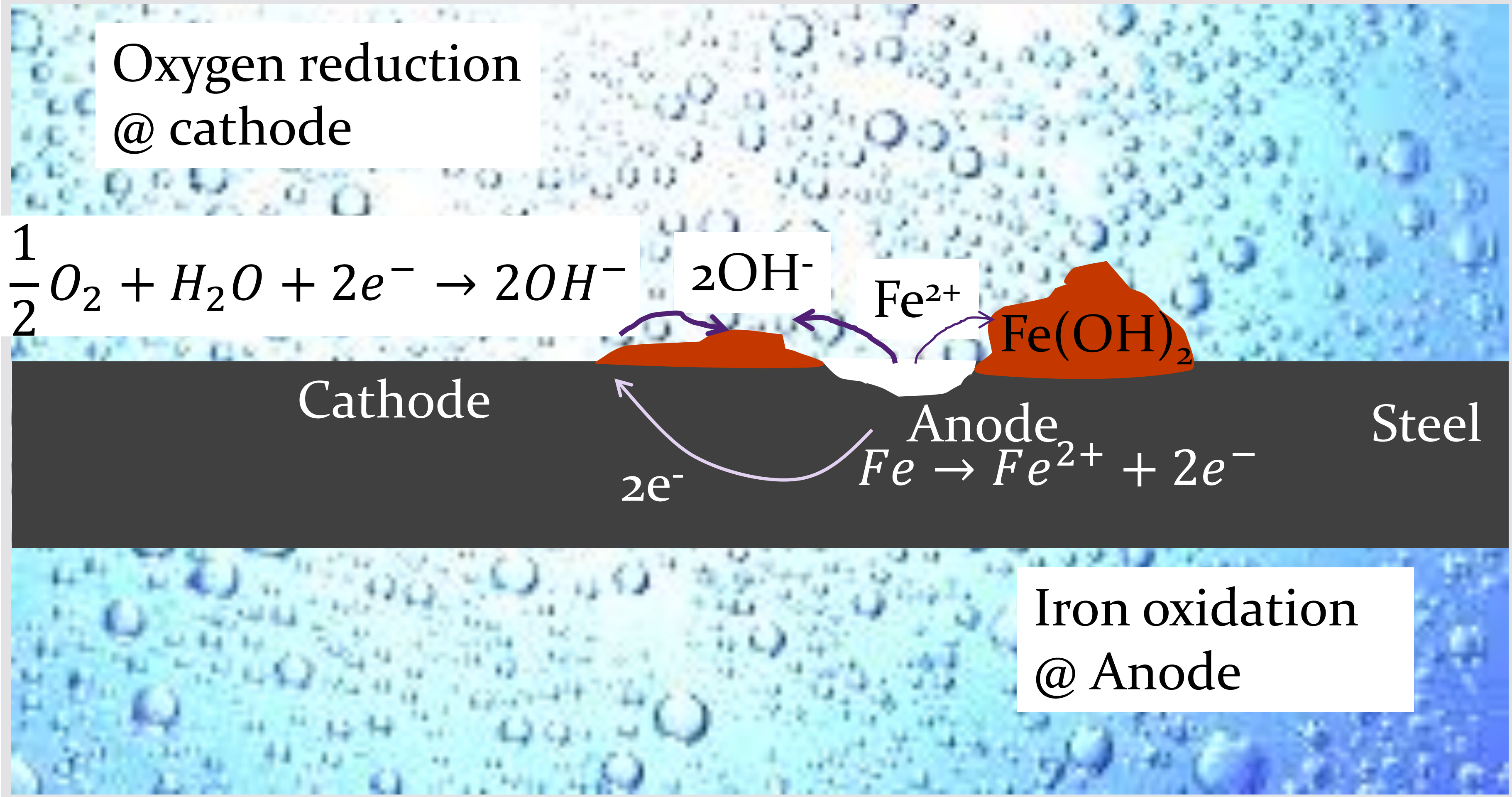
Objectives

- Explain corrosion mechanism in concrete
- Validate service-life models for concrete mixture design
- Quantify benefits of supplementary cementitious material (SCM) use in extending concrete service life

Battery

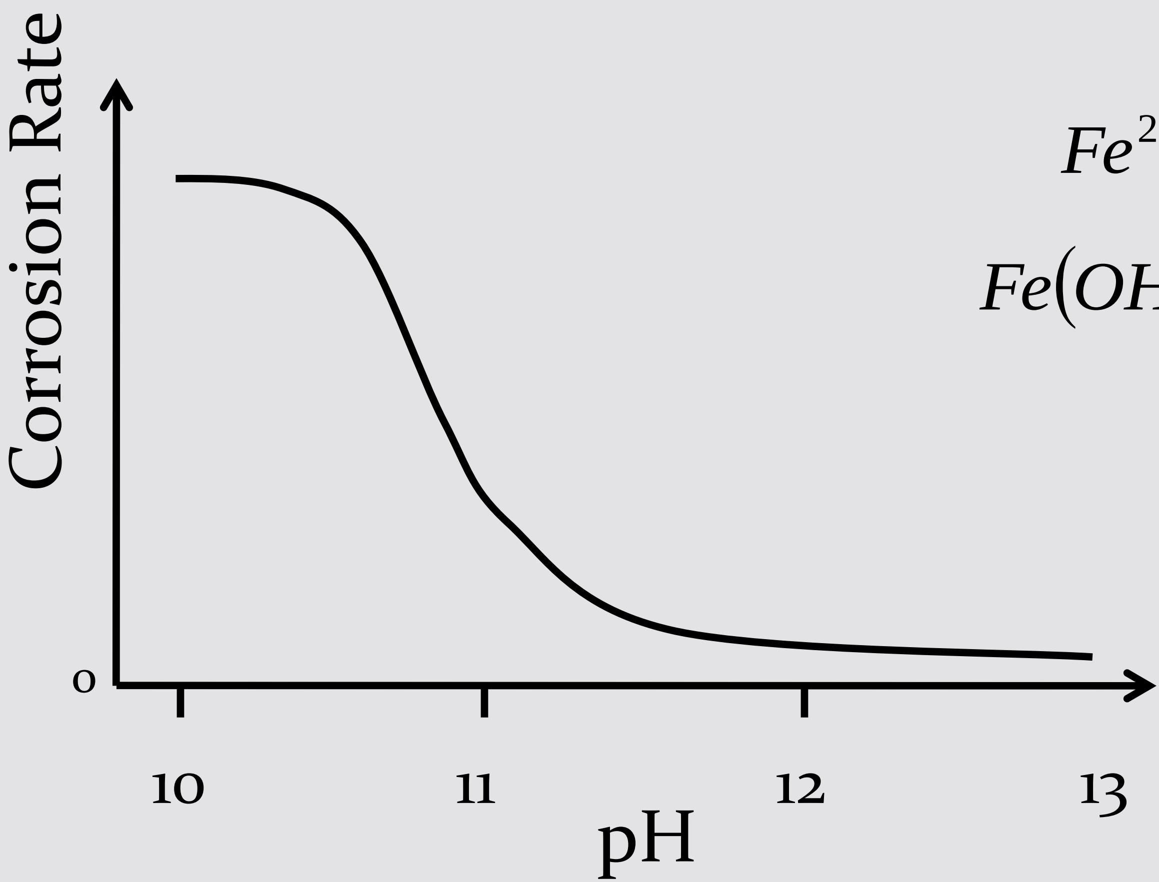


Corrosion of Steel in Electrolyte with Oxygen



Steel Passive Layer – High pH favors formation of Passive layer

Passive layer separates steel from electrolyte & oxygen



$$Fe \rightarrow Fe^{2+} + 2e^-$$

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$$

$$Fe(OH)_2 + O_2 \rightarrow Fe_2O_3 + H_2O$$

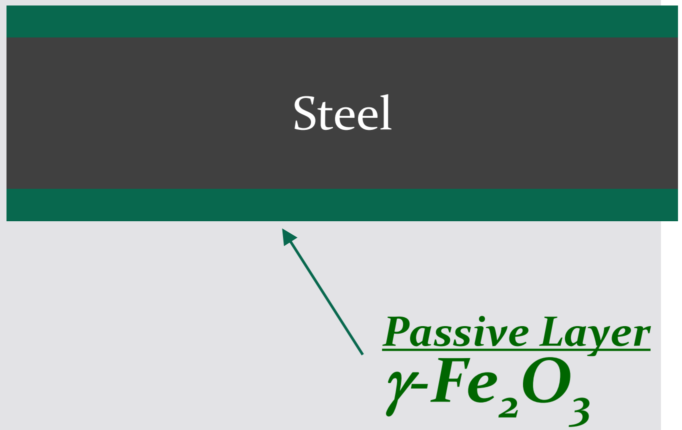


Figure after Bentur Diamond and Berke 1997

Patina – example of a passive layer

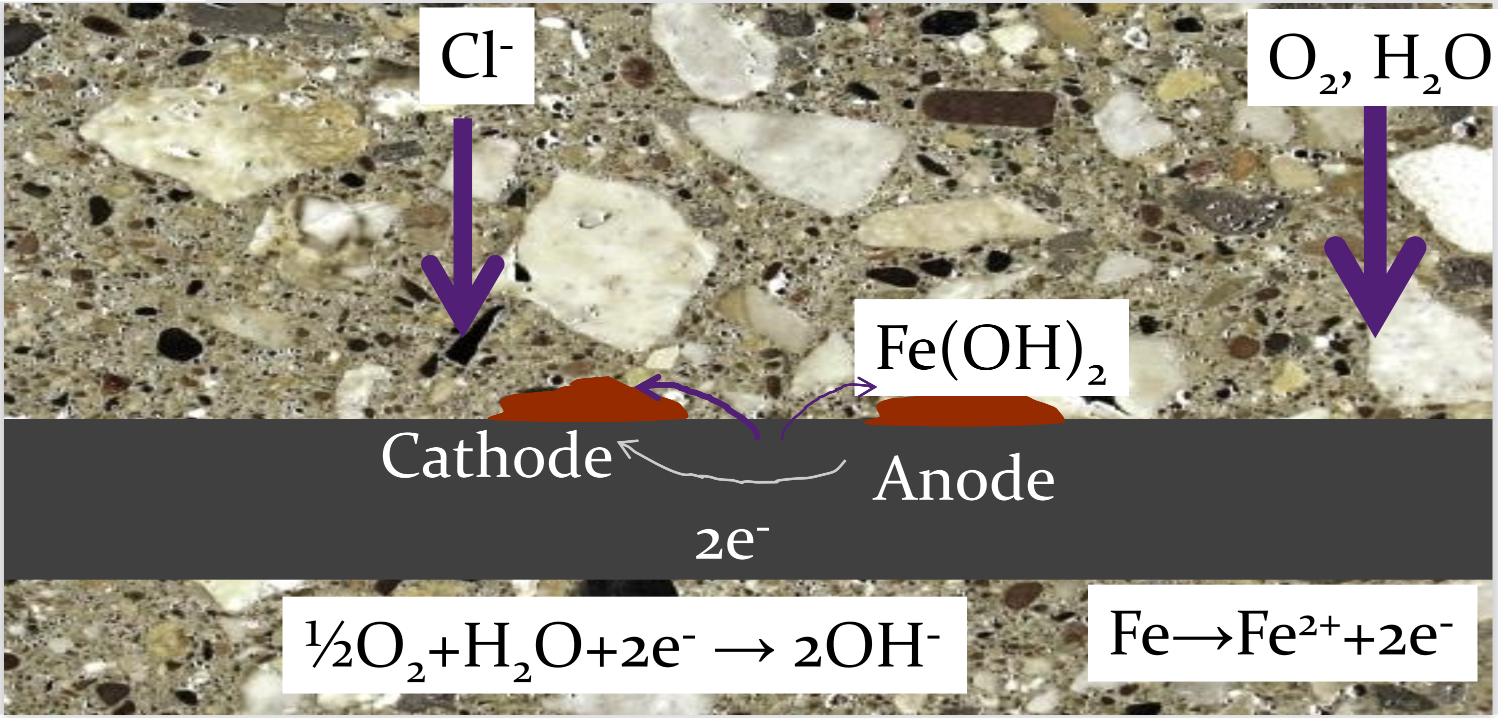
Before removal of patina

After removal of patina

Forms copper carbonate that protects copper

Electrochemical Corrosion Process

Once the chloride concentration at the level reaches a critical amount, called the chloride threshold, corrosion initiates



Corrosion – A Growing Problem

Iron Volume Increase

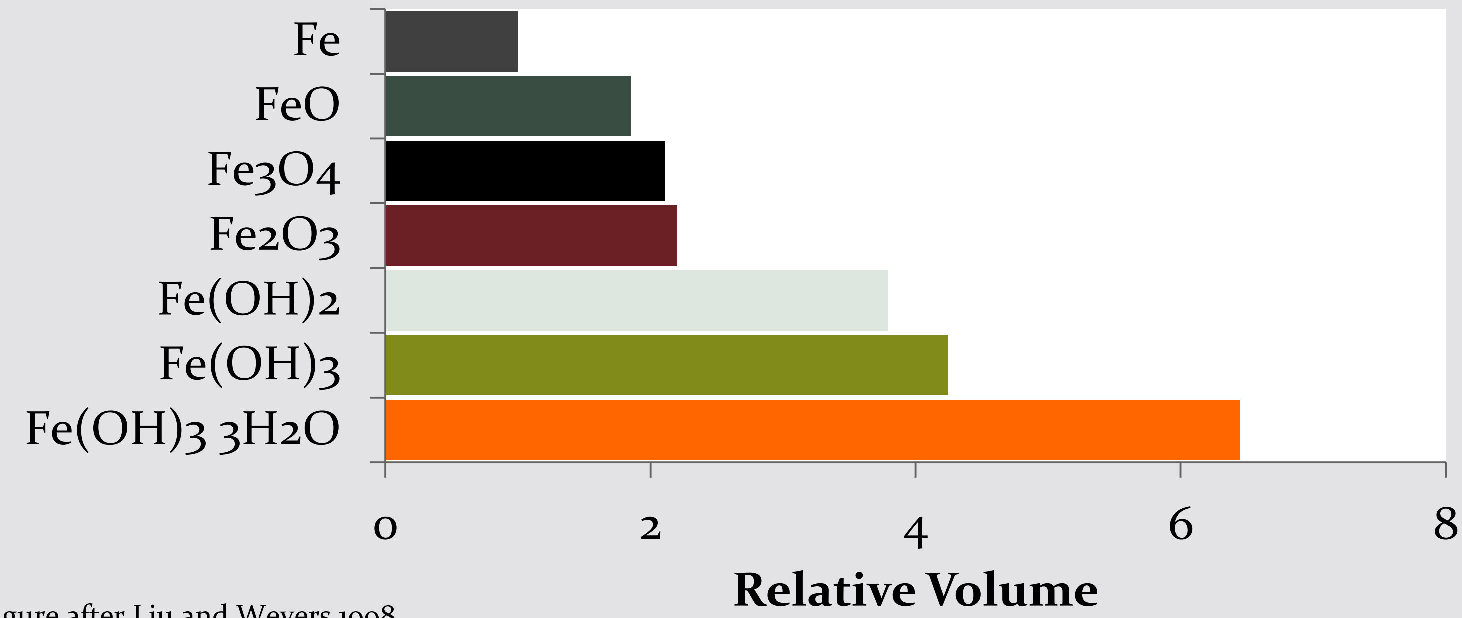


Figure after Liu and Weyers 1998

The graph represents the different colors of oxides that form and their relative volume. Has a volume increase of over 6.

Stages of Damage


Concrete Cracking


Concrete Spalling


Concrete Delamination

Concrete Structural Capacity Impacted

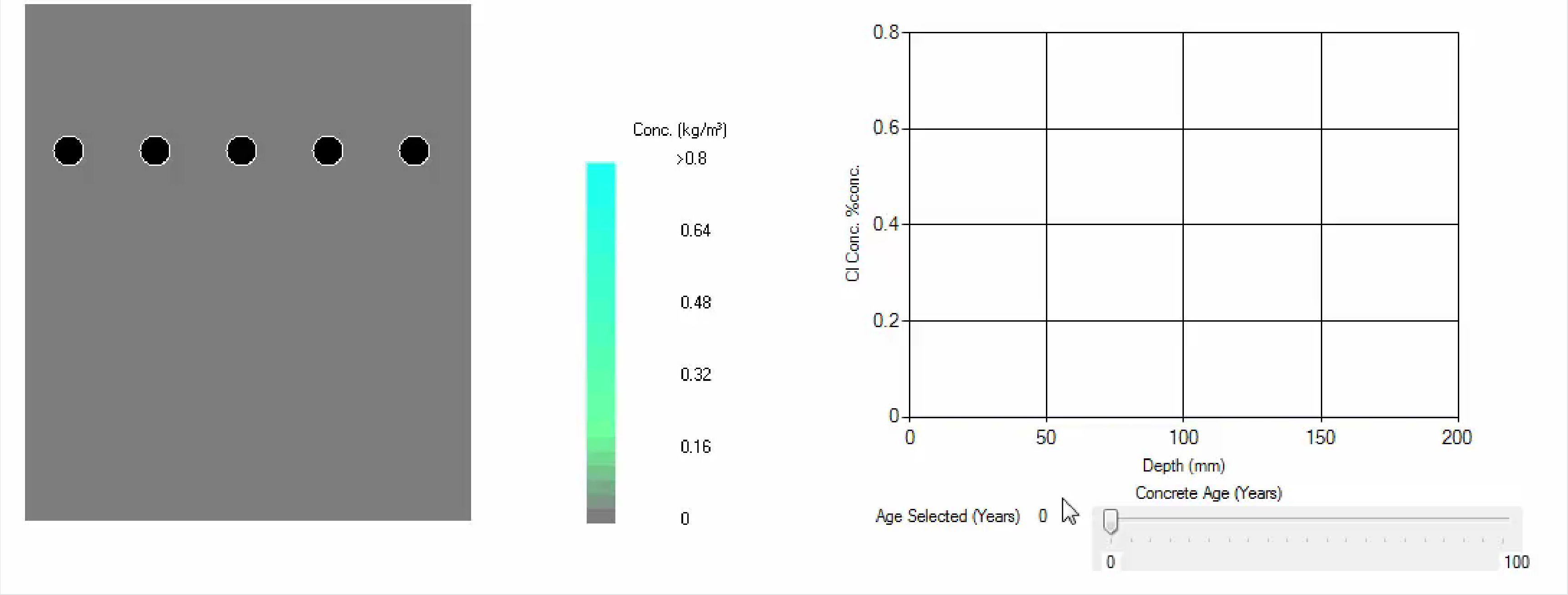
http://www.nace.org/Newsroom/Press-Releases/New-methodology-predicts-onset,-progression-of-corrosion-of-reinforced-concrete

Chloride Ingress In Concrete

- Mechanisms
  - Diffusion
  - Electromigration (electrical current)
  - Thermal migration
  - Absorption – Capillary Suction, Osmosis
  - Pressure

$$\frac{\partial}{\partial x}\left(D_c \frac{\partial C}{\partial x}\right) = \frac{\partial C}{\partial t}$$

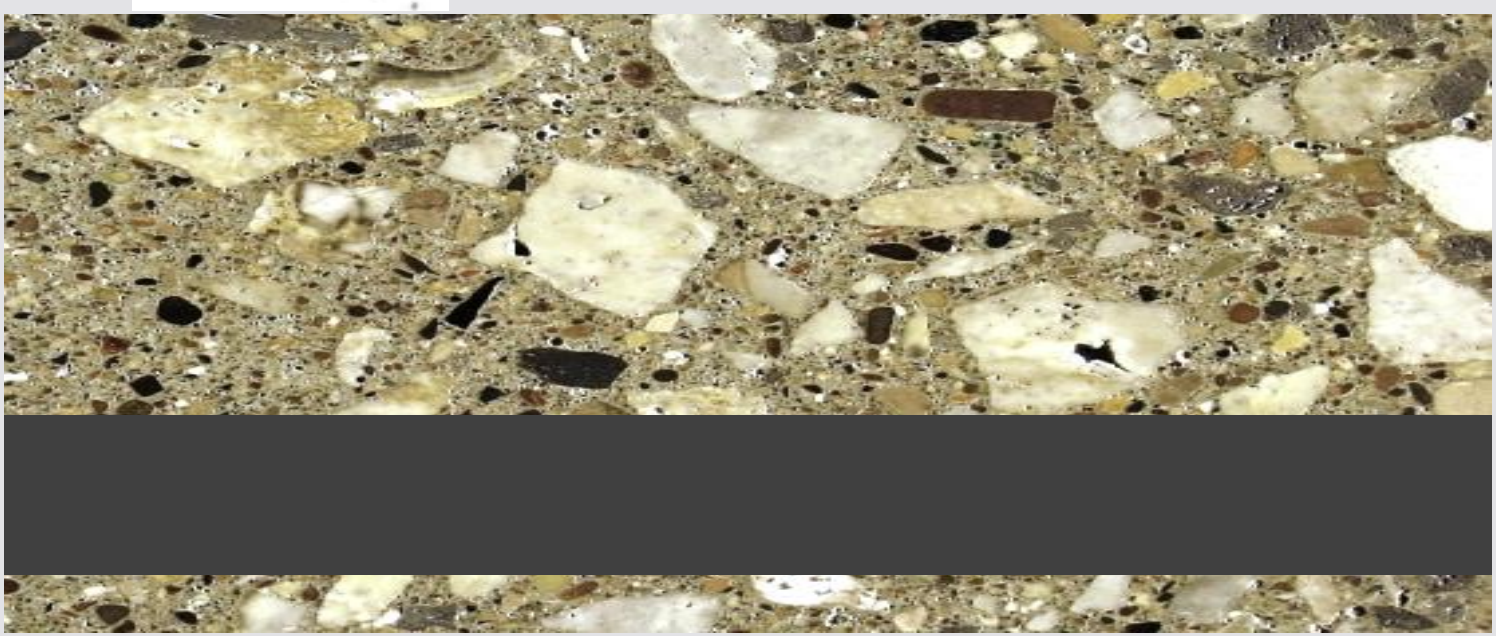
Chloride Ingress in Concrete



Chloride Ingress Prevention

How can we prevent/ reduce rate of chlorides penetrating to steel?

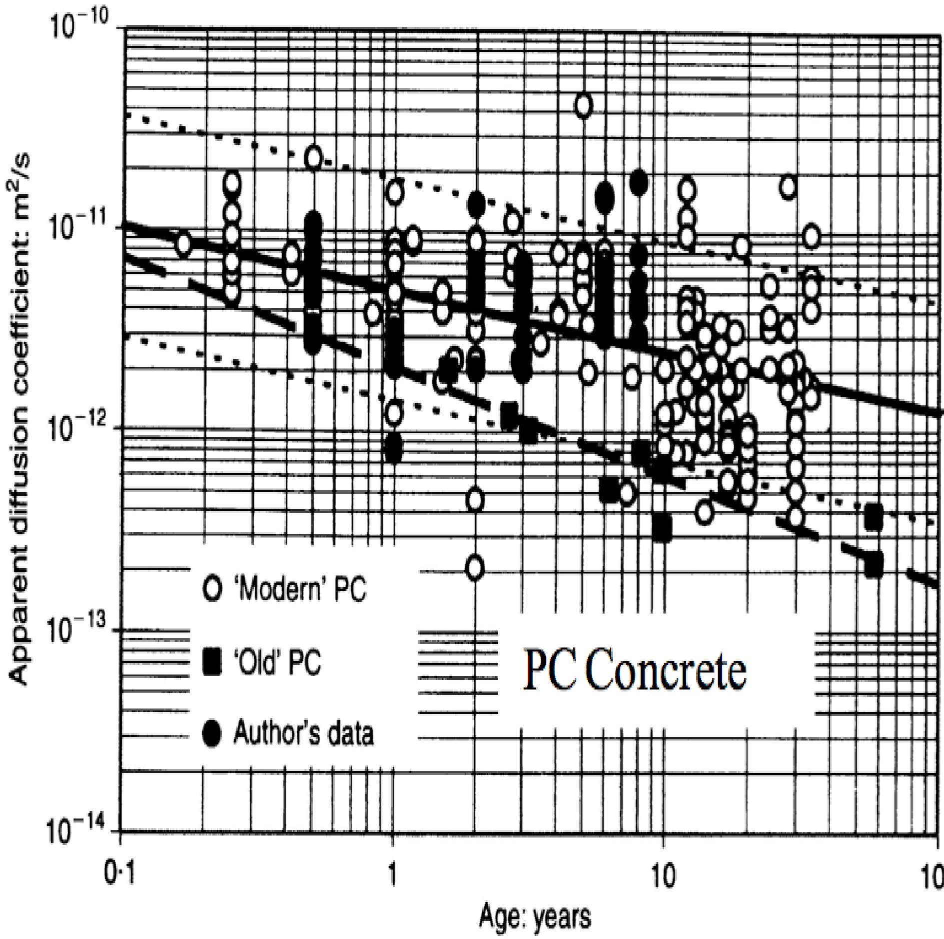
Make concrete less permeable

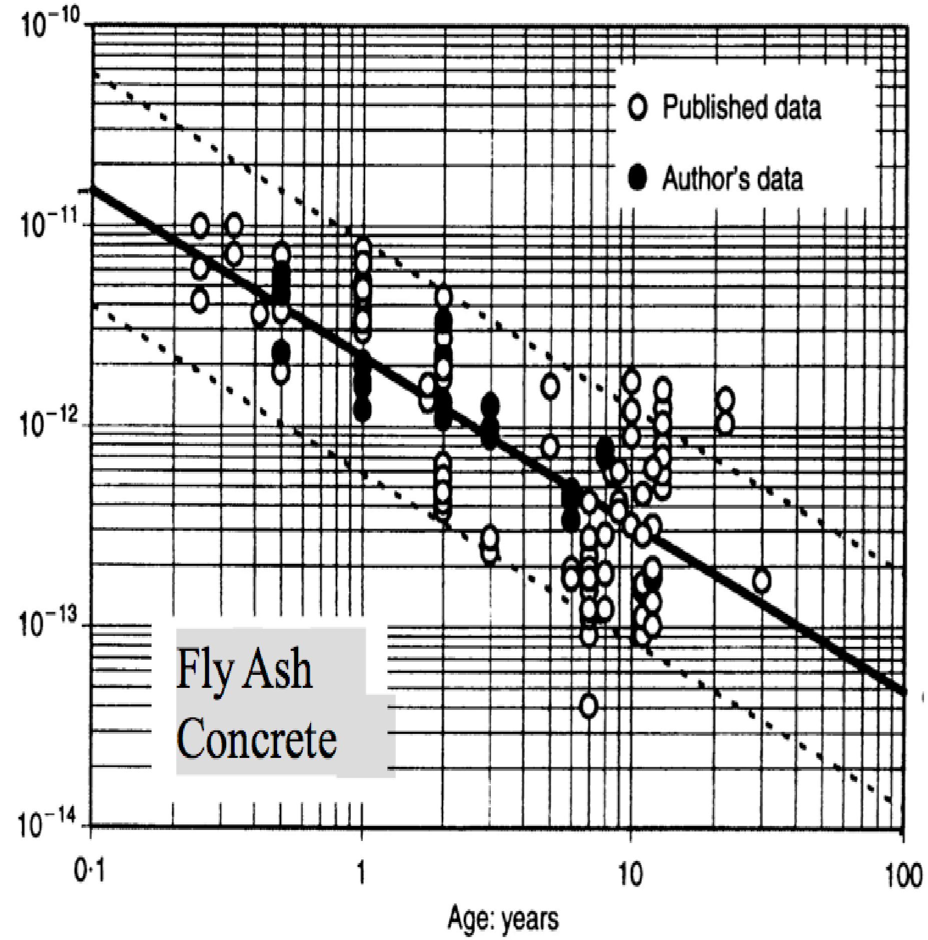


Quantify SCM Effects on Service Life

- Measured diffusion rates of concrete mixtures:
  - Binary & ternary blends
  - Wet curing, curing compound, air curing
- Used measured diffusion parameters to predict service life:
  - Life-365: Free service life software available for download
  - ConcreteWorks: Free service life software for mass concrete temperature calculations and service life

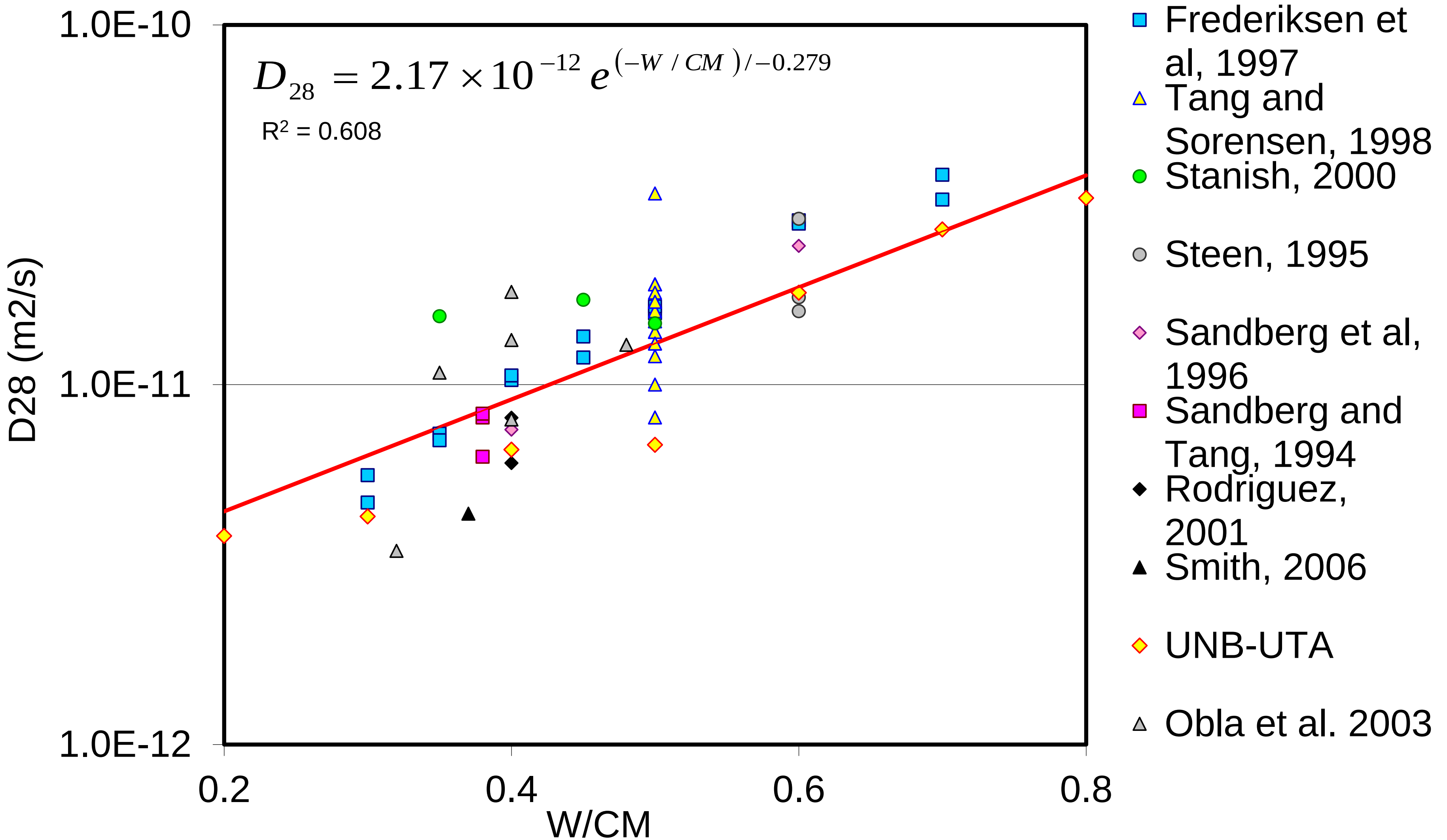
Concrete Apparent Diffusion Coefficient Time-Dependence



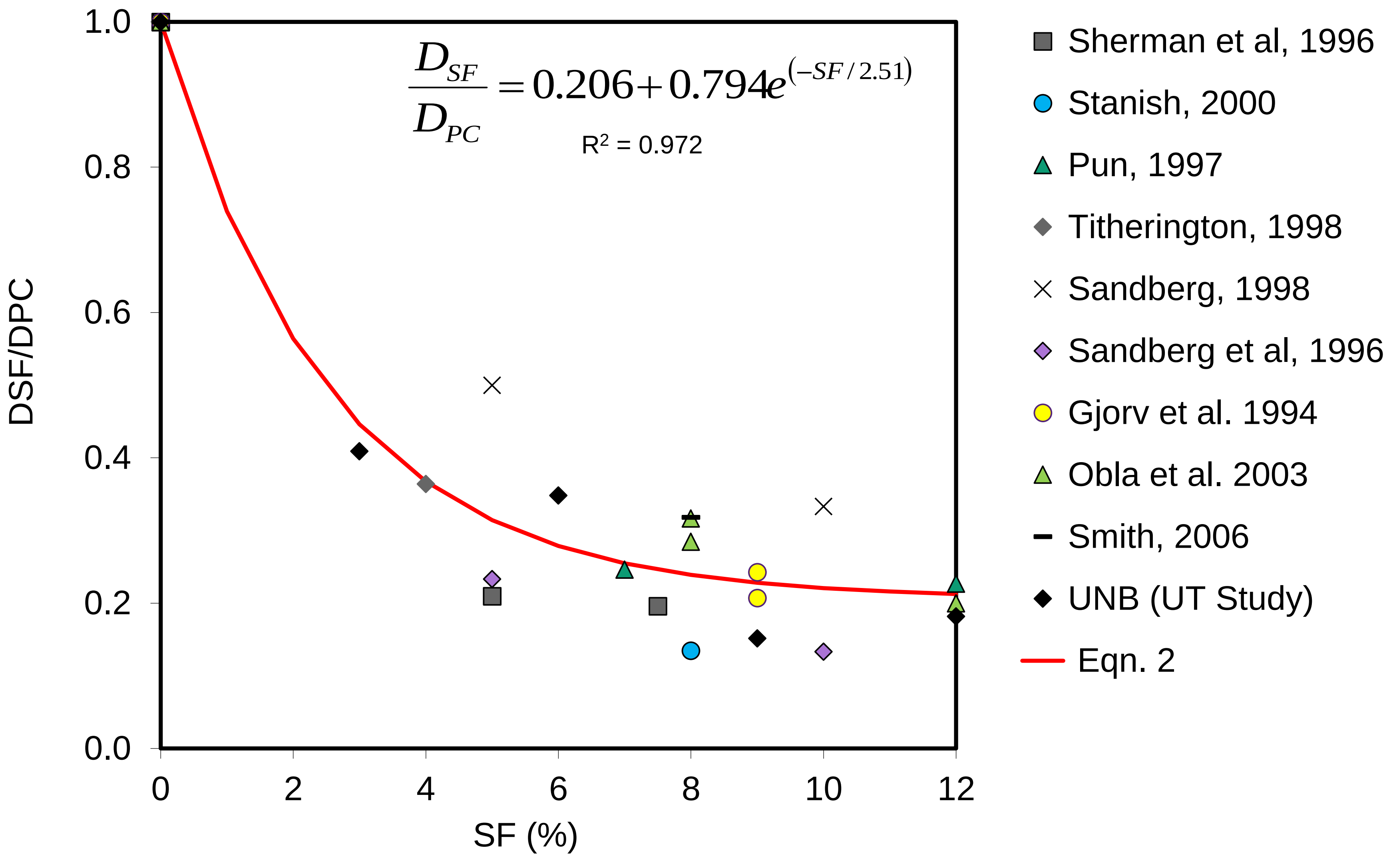


Figures from Life-365V2 User Manual

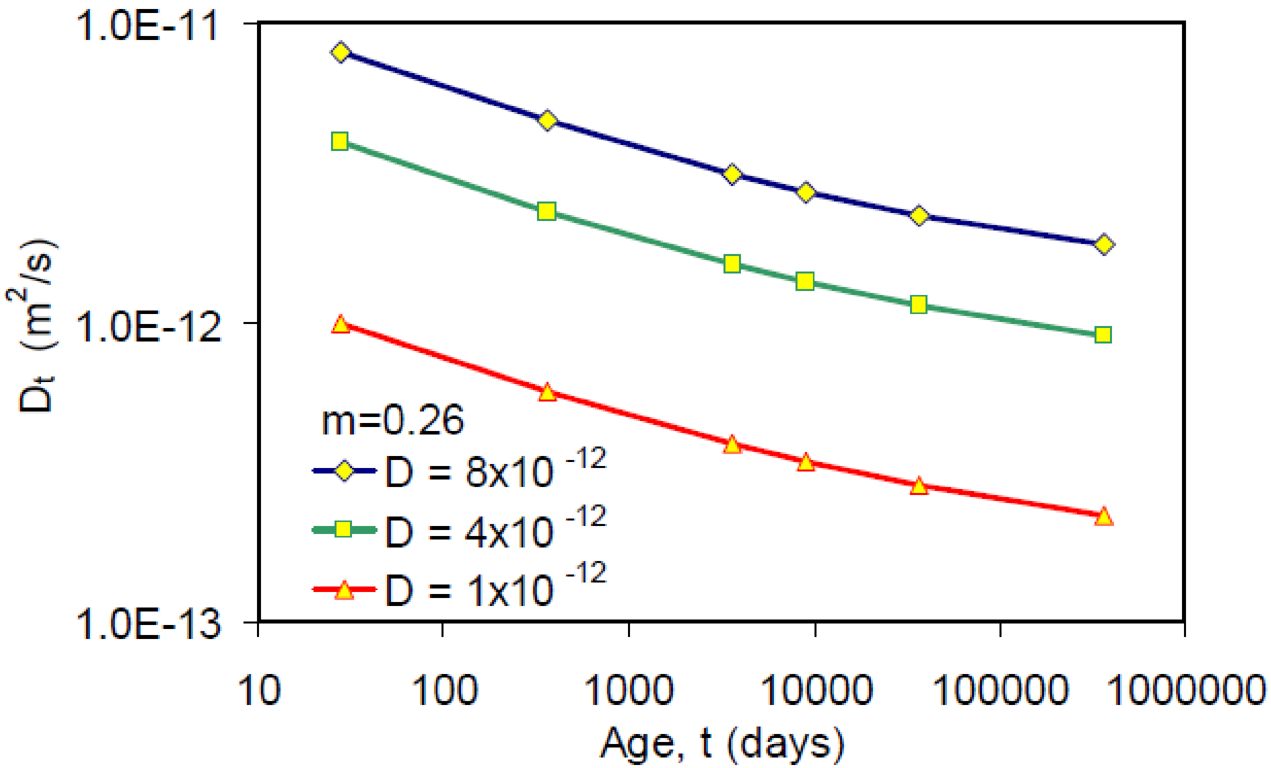
ConcreteWorks



ConcreteWorks



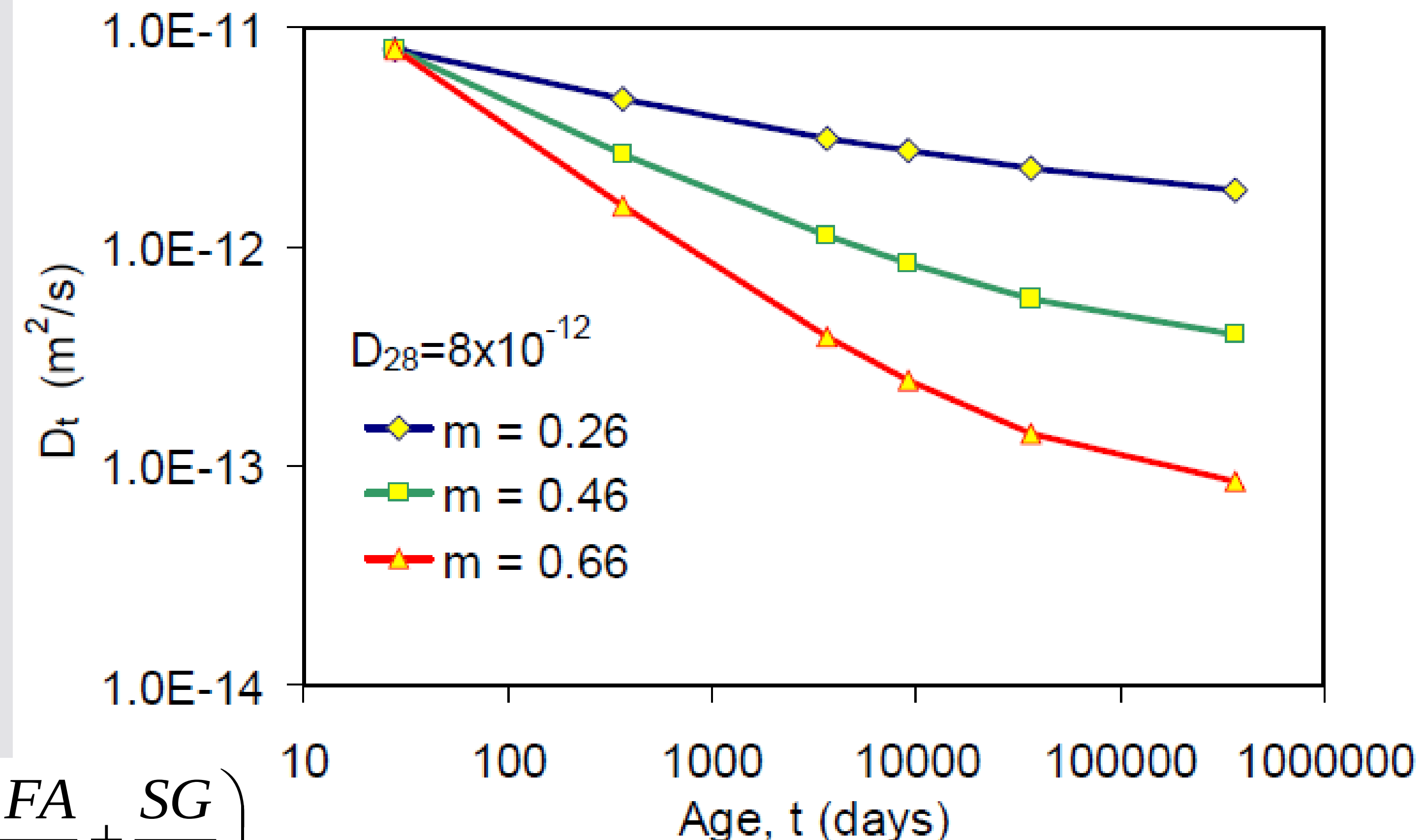
Diffusion Coefficients



$$D_{ult} = D_{28} \cdot \left(\frac{28}{36500} \right)^m \qquad D_t(t) = D_{28} \cdot \left(\frac{28}{t} \right)^m + D_{ult} \cdot \left(1 - \left(\frac{28}{t} \right)^m \right)$$

ConcreteWorks diffusion coefficients

SCMs – Increase Diffusion Coefficient Decrease with Time



$$m = 0.26 + 0.4\left(\frac{FA}{50} + \frac{SG}{70}\right)$$

General assumption is that fly ash and slag only affect decrease with time, not 28 day value

Average ~ 100 Freeze/Thaw Cycles per Annum

Highest Tides in the World

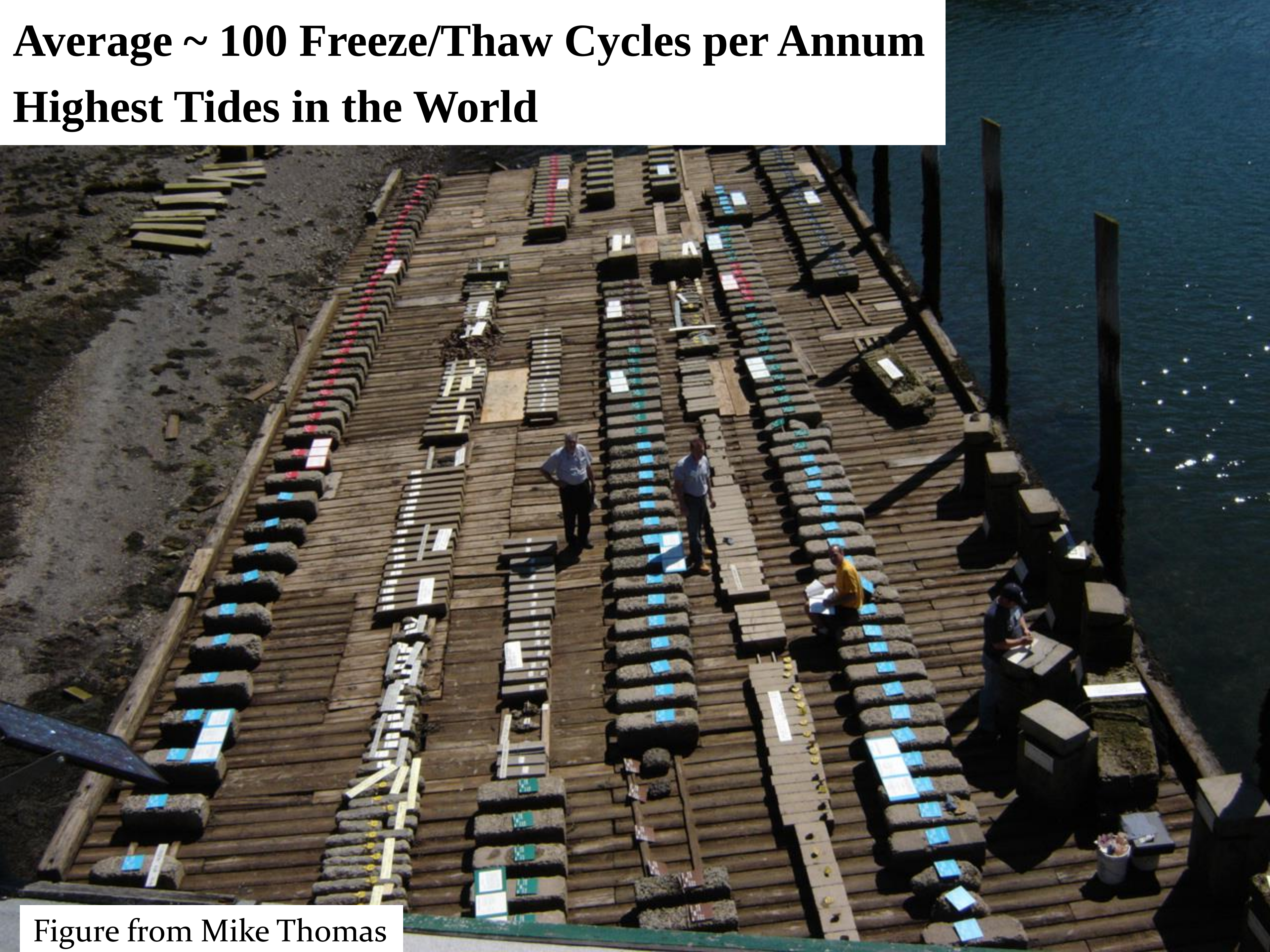
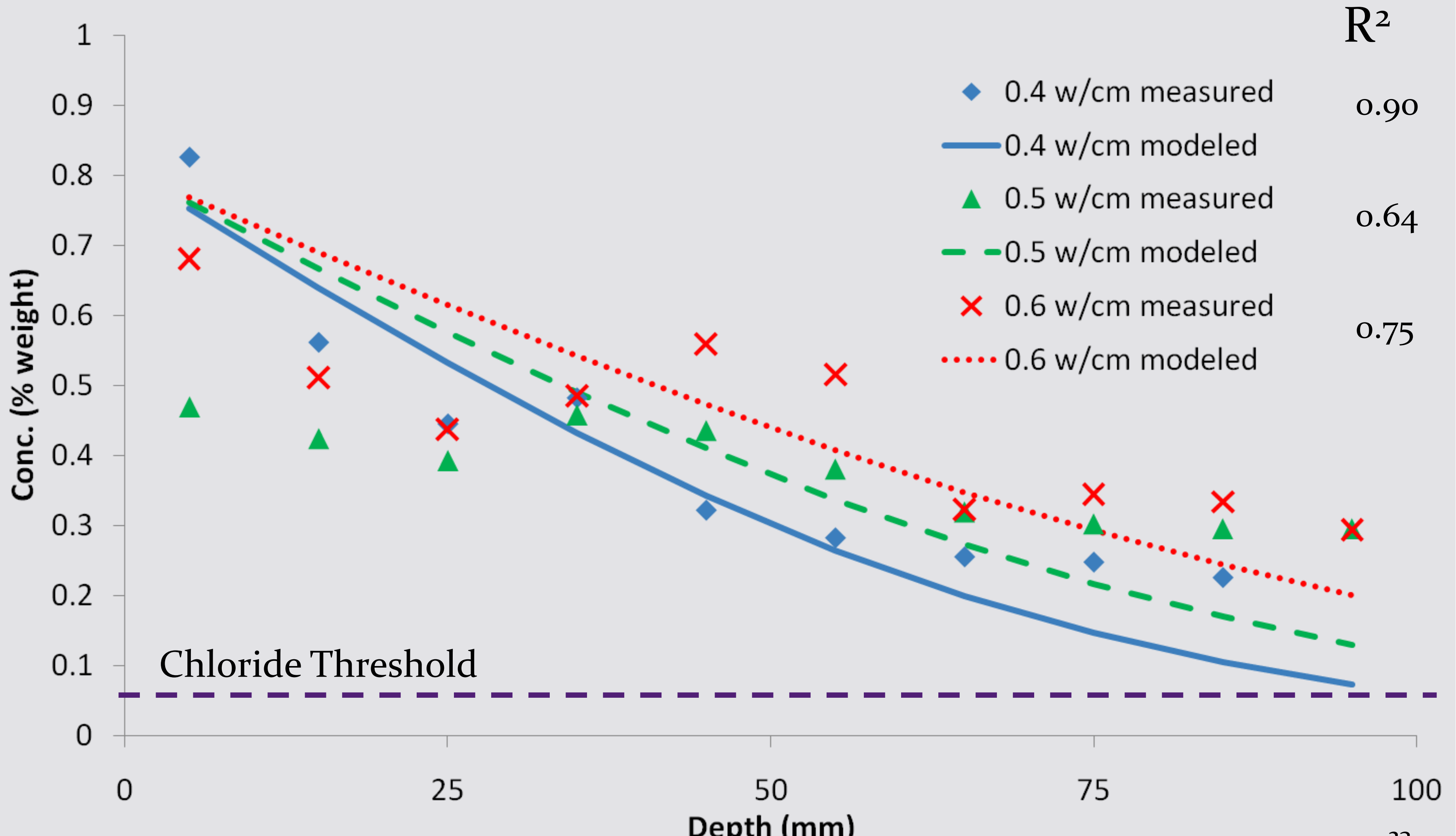


Figure from Mike Thomas

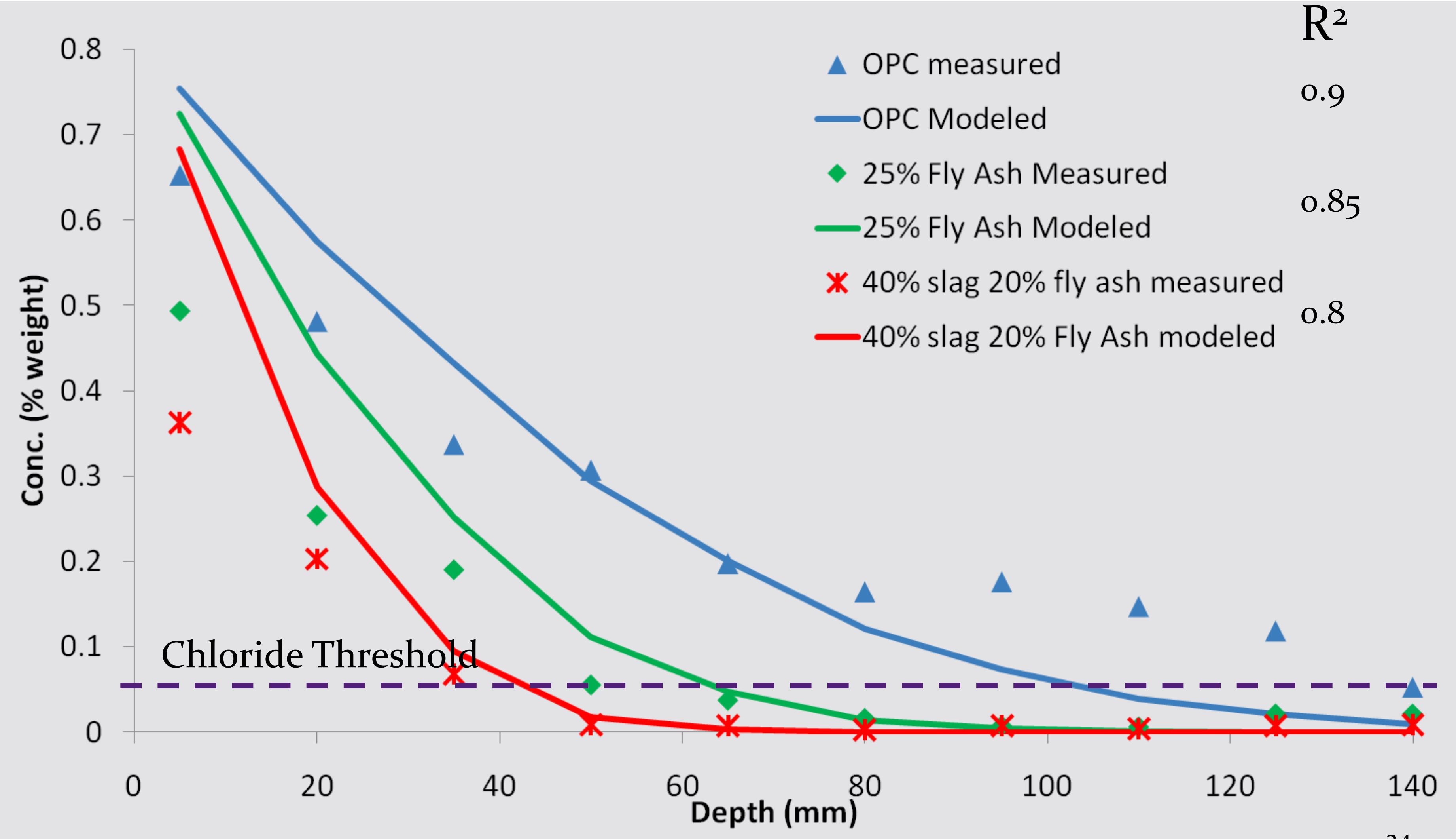
Figure from Mike Thomas

Specimens retrieved after 25 years exposure

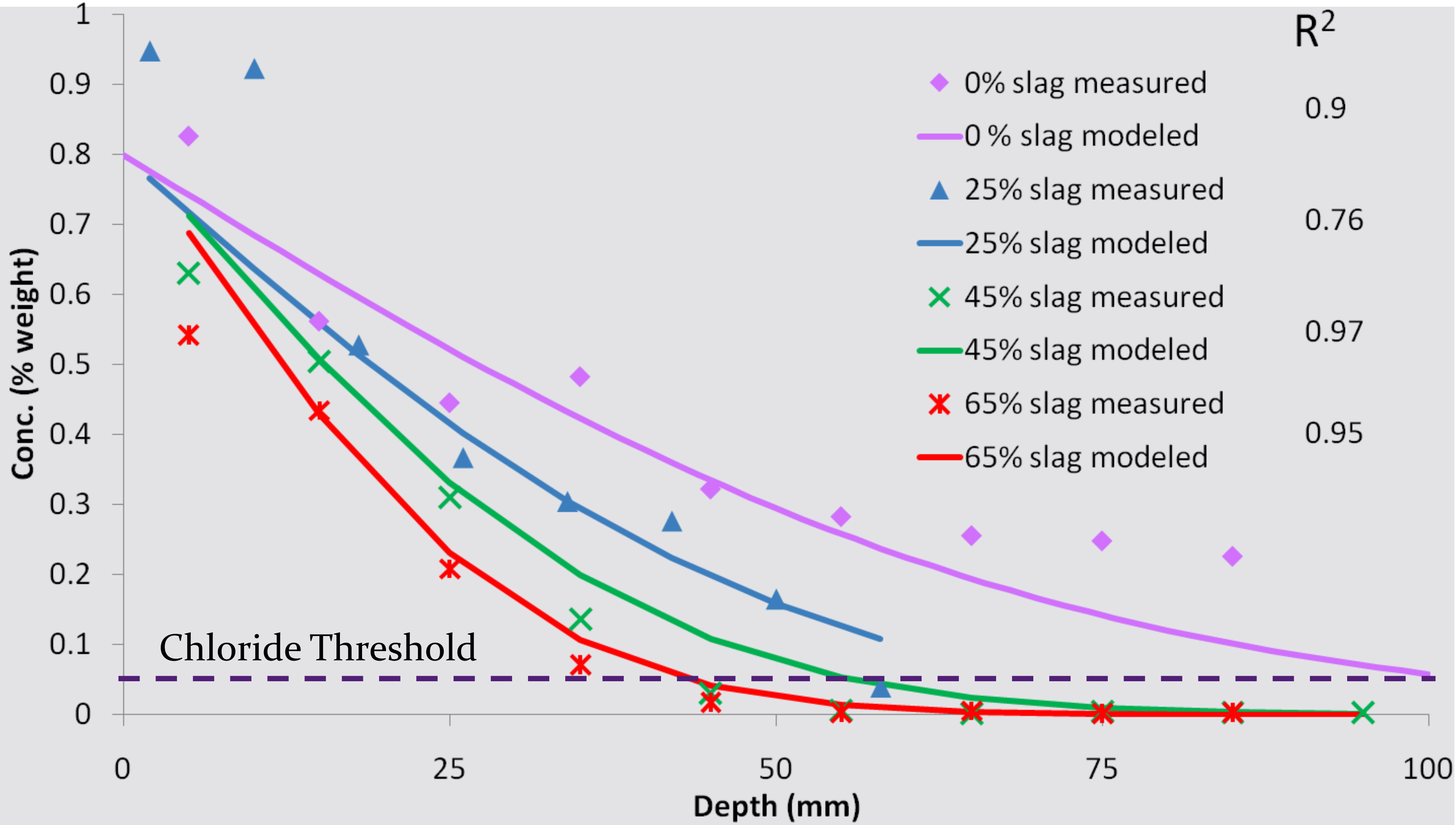
OPC – Effect of w/cm



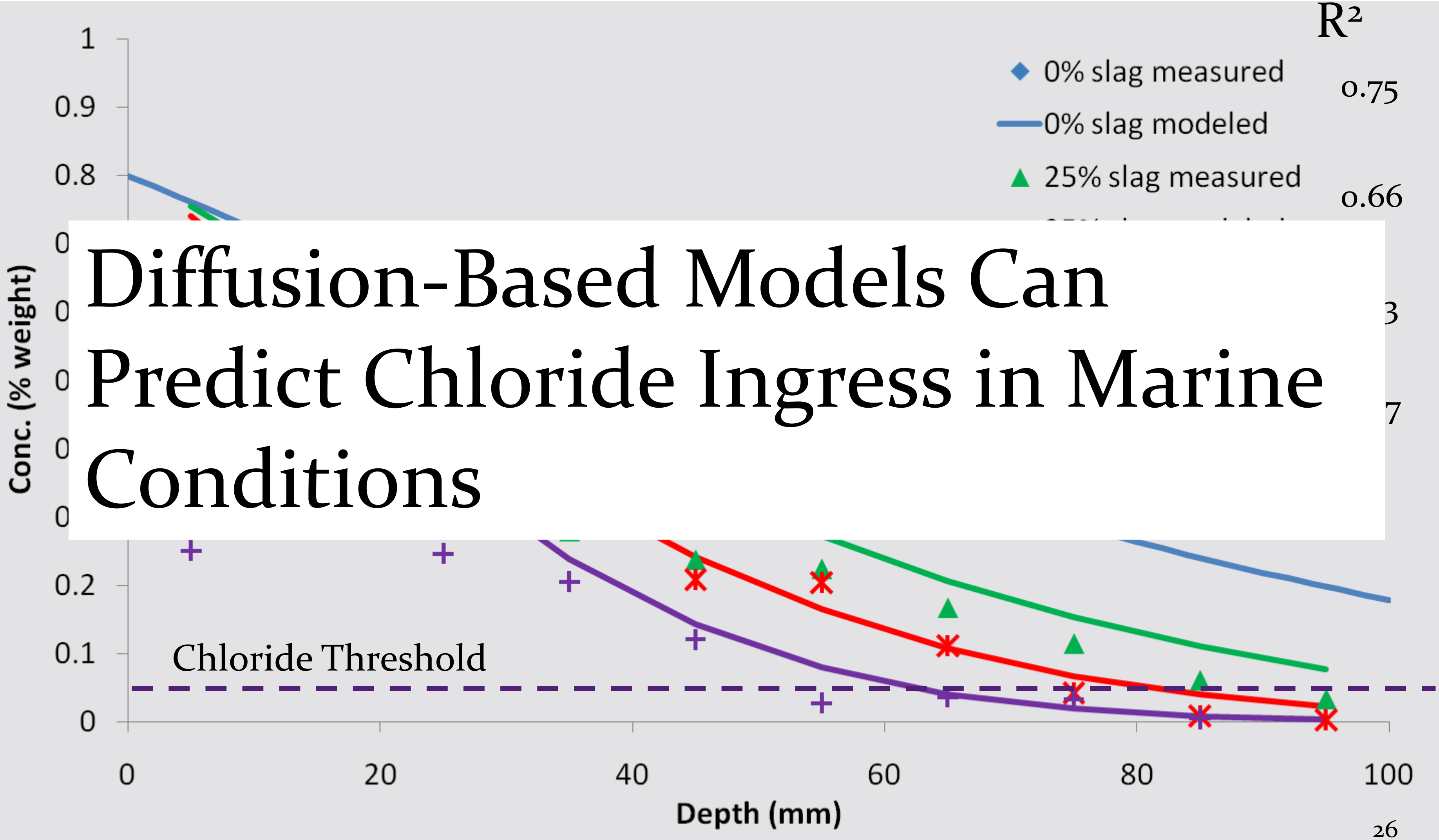
0.4 w/cm - Fly Ash



Effect of Slag – 0.4 w/cm



Effect of slag cement – 0.6 w/cm



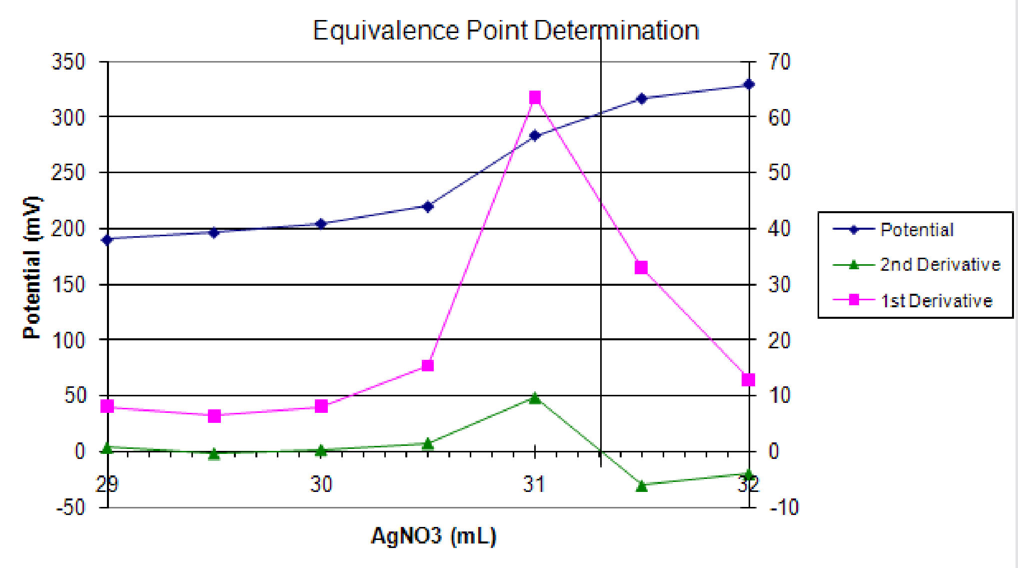
Diffusion-Based Models Can Predict Chloride Ingress in Marine Conditions

Bulk Diffusion (ASTM C1556) of Ternary SCM Blends

- 0.34 w/cm
- Demolded after 24 hours
- Cured:
  - Wet cured 28 days, 35 day in NaCl solution
  - Wet cured 91 days, 35 days in NaCl solution
  - Wet cured 91 days, 127 days in NaCl solution
  - Curing compound & cured outside for 6 months, 35 days in NaCl solution
  - Air cured outside for 6 months, 35 days in NaCl solution

Bulk Diffusion (ASTM C1556) of Ternary SCM Blends

- After ponding, sample chlorides were analyzed by:
  - Profile grinding
  - Acid dissolution of powders
  - Titration to measure %Cl vs. depth

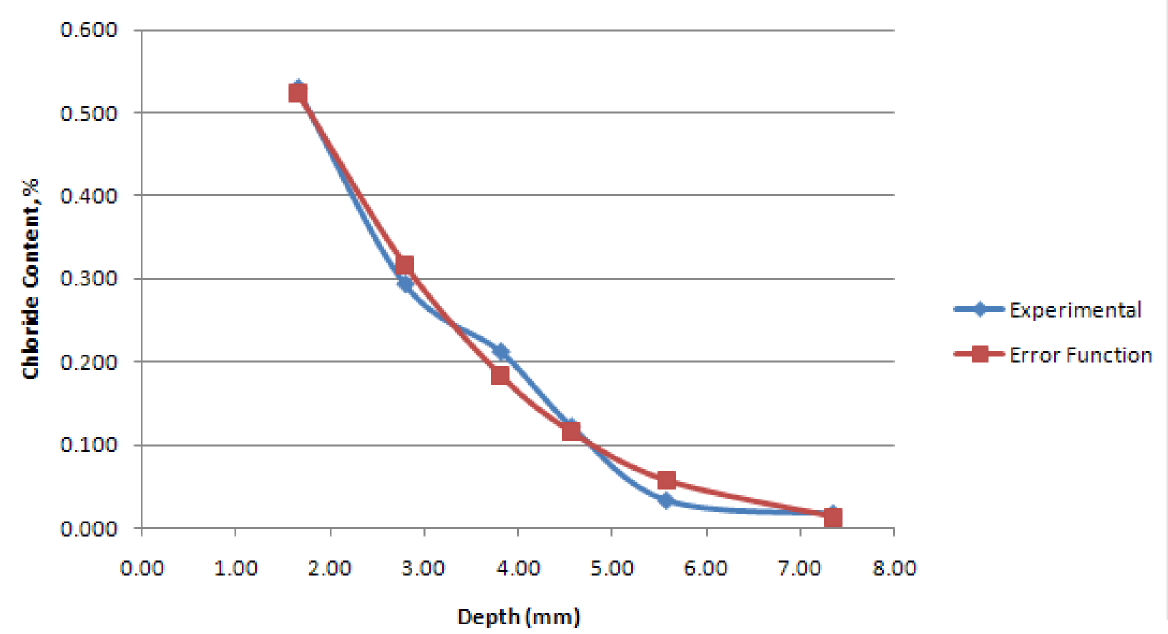


Bulk Diffusion (ASTM C1556) of Ternary SCM Blends

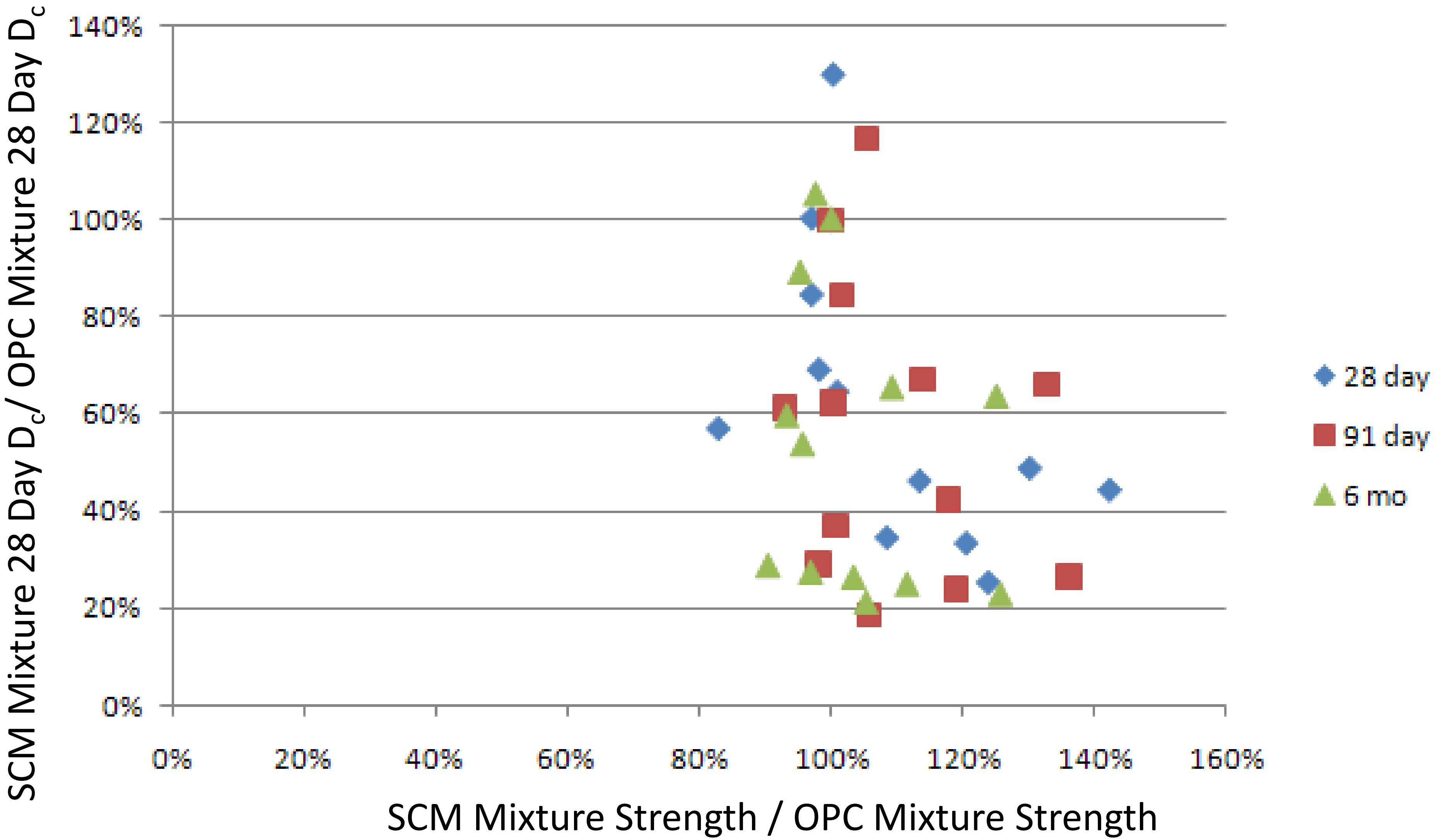
- Fit D_c using:
  - Error function (assumes constant D_c with time)

$$C(x,t) = C_s - (C_s - C_i) \cdot erf\left(\frac{x}{\sqrt{4 \cdot D_c \cdot t}}\right)$$

  - Finite difference method – decreasing D_c with time

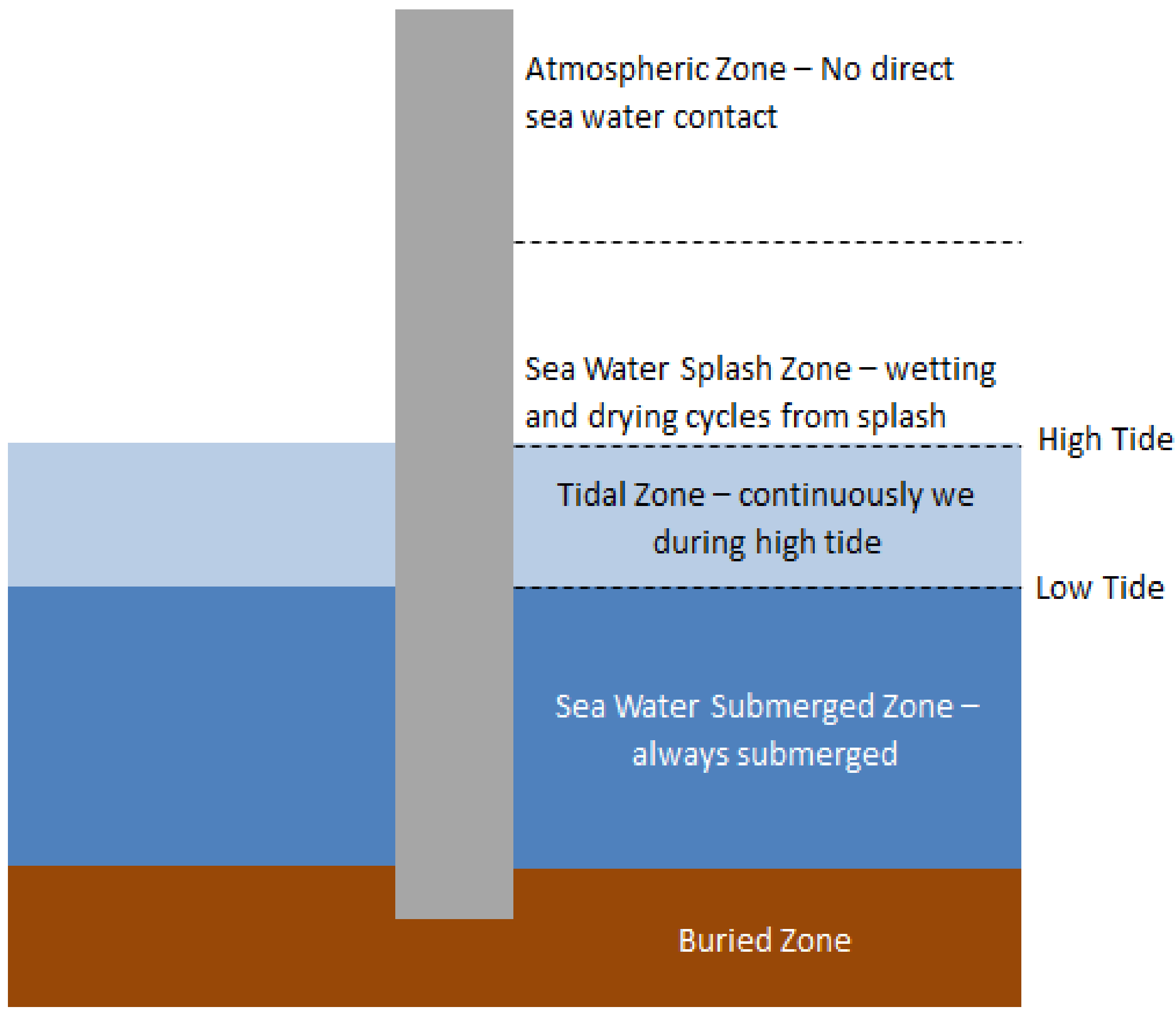


No Relationship seen between compressive strength and diffusion coefficient!

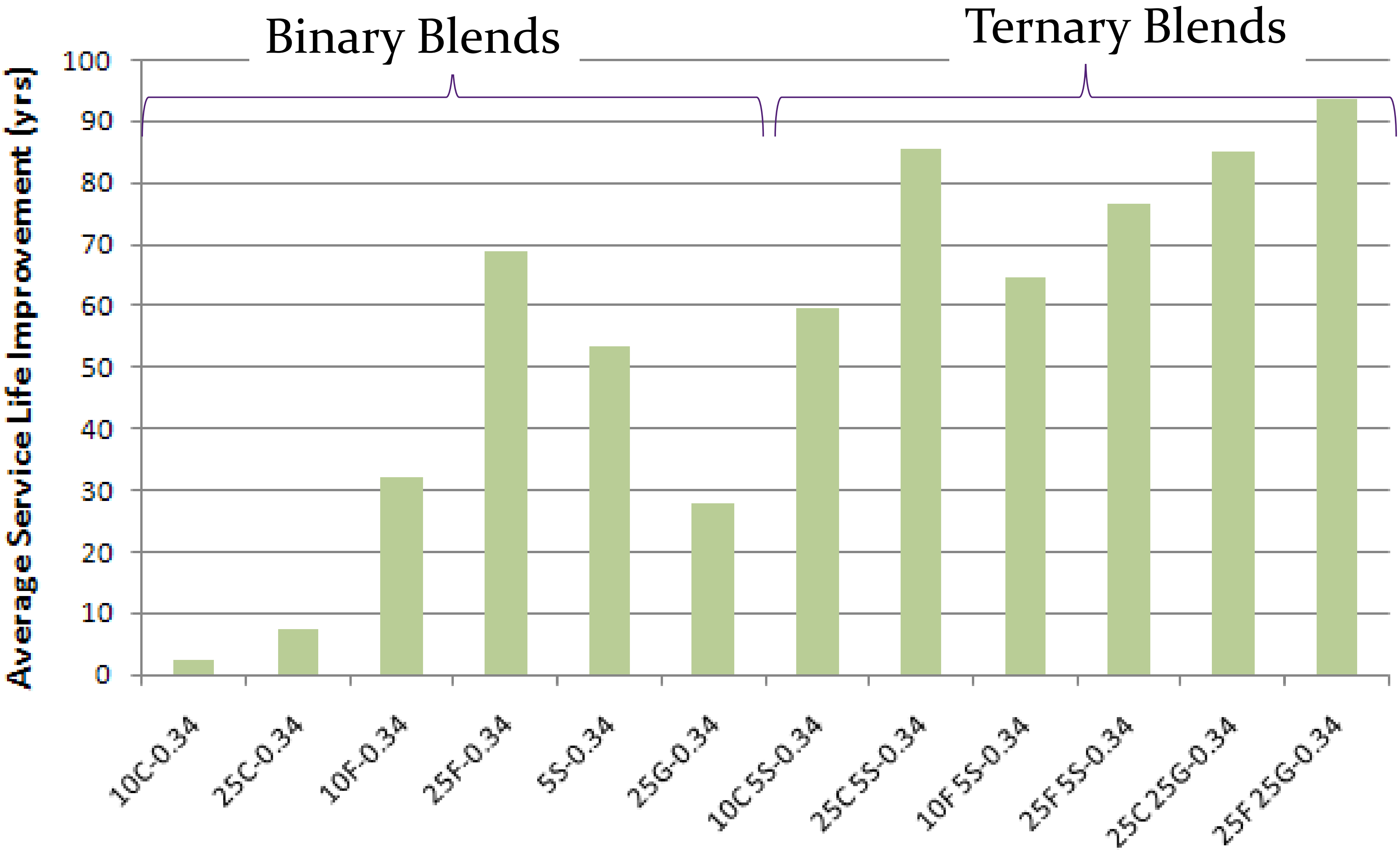


Service Life Modeling Comparison

- Key West, Florida splash zone
- 51 mm concrete cover

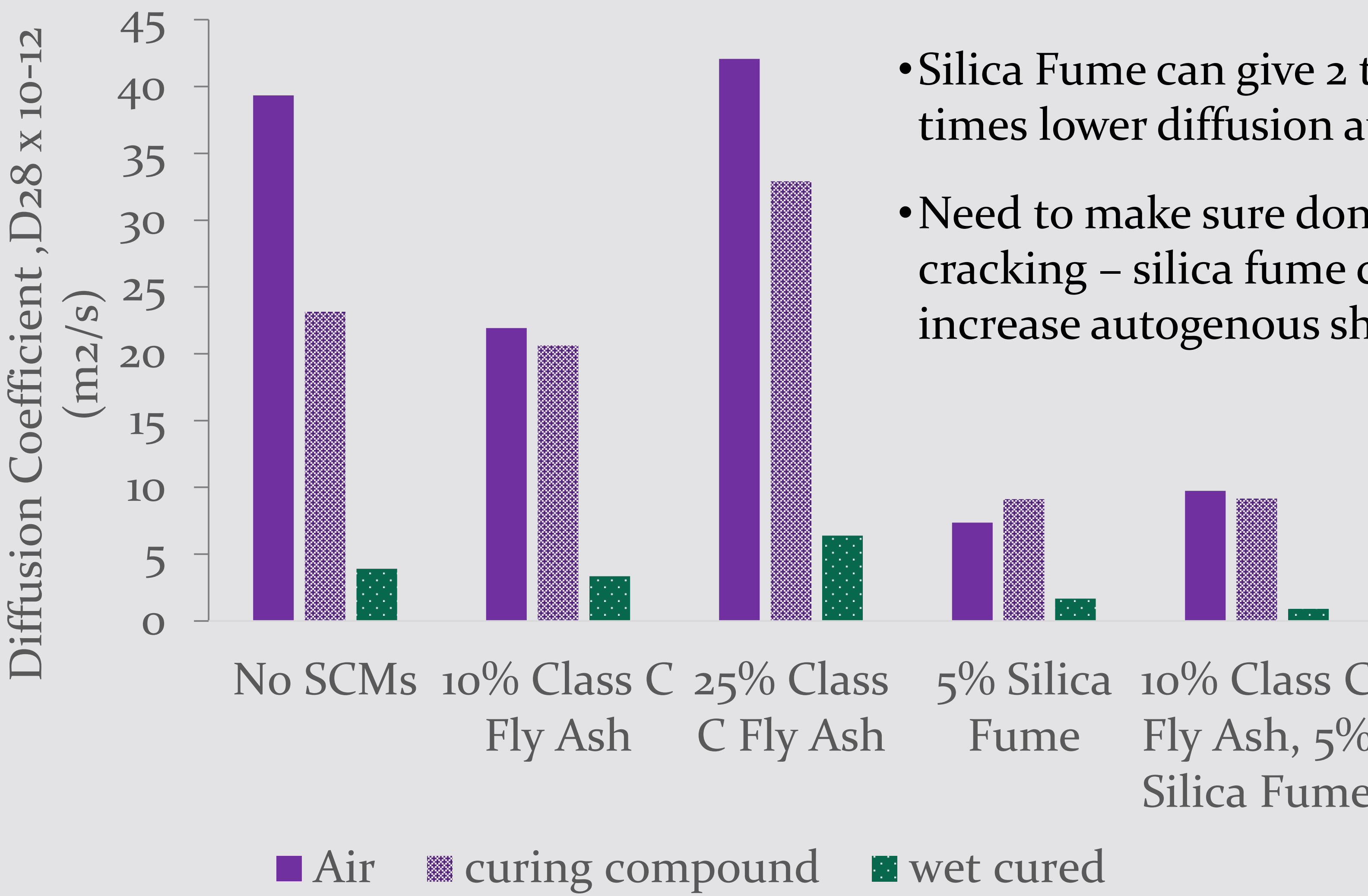


Service Life Increase Compared to Control Mixture



C= Class C fly ash; F=Class F fly ash; G=slag cement; S= silica fume

SCMs - Curing



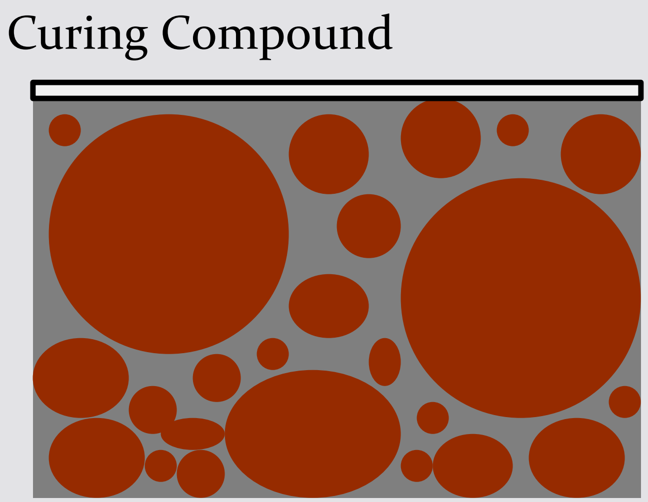
- Silica Fume can give 2 to 5 times lower diffusion at 28 days
- Need to make sure don't get cracking – silica fume can increase autogenous shrinkage

Curing

- Should be applied immediately after finishing

In hot weather, black plastic is not advisable

Curing Compound



Curing Compound

Place curing compound in 2 passes, perpendicular to each other to ensure best coverage

Summary

- Service-life models can help you design your concrete mixture and improve service life
- SCMs can greatly improve the service life of reinforced concrete
  - Use of SCMs is even more effective than reducing w/cm
  - Ternary blends can be especially effective in increasing service life
- Curing is essential to achieving long-service life
  - Wet curing is especially good
  - Curing compound can improve diffusion coefficient by 6 to 41%

References

- Riding, K.A., Thomas, M.D.A., Folliard, K.J., “Apparent Diffusivity Model for Concrete Containing Supplementary Cementitious Materials,” ACI Materials Journal, Vol. 110, No. 6, pp. 705-714, 2013.
- Burris, L.E., Riding, K.A., “Diffusivity of Binary and Ternary Concrete Mixture Blends,” ACI Materials Journal, Vol. 111, No. 4, pp. 373-382, 2014.