

# Concrete Proportioning: the Corrosion Environment for Steel in Concrete

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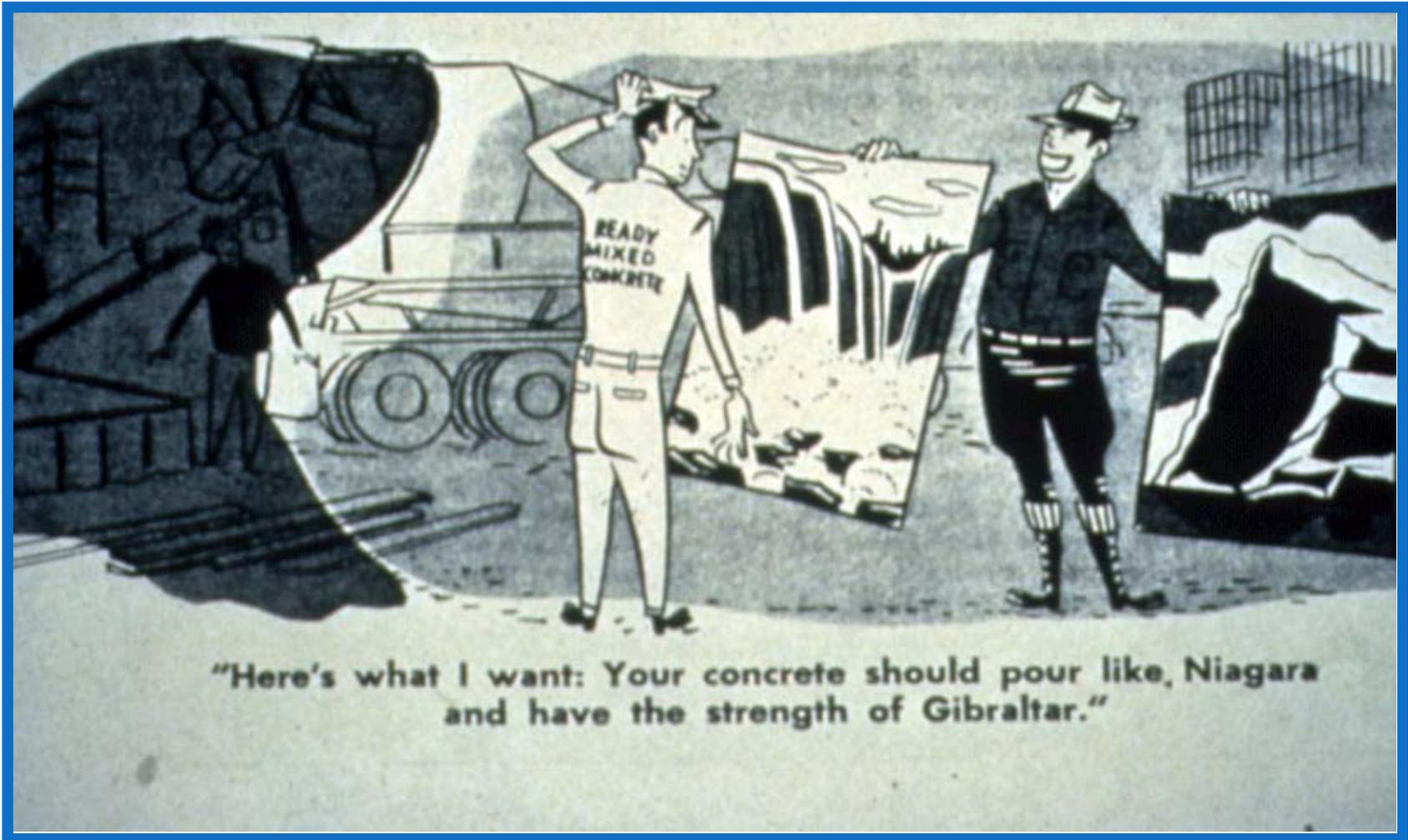
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# Corrosion Prevention is Easy

- a. To prevent corrosion:
  - Change the material
  - Change the environment
  - Isolate the material and the environment
- If these don't work, see a.





**"Here's what I want: Your concrete should pour like Niagara and have the strength of Gibraltar."**



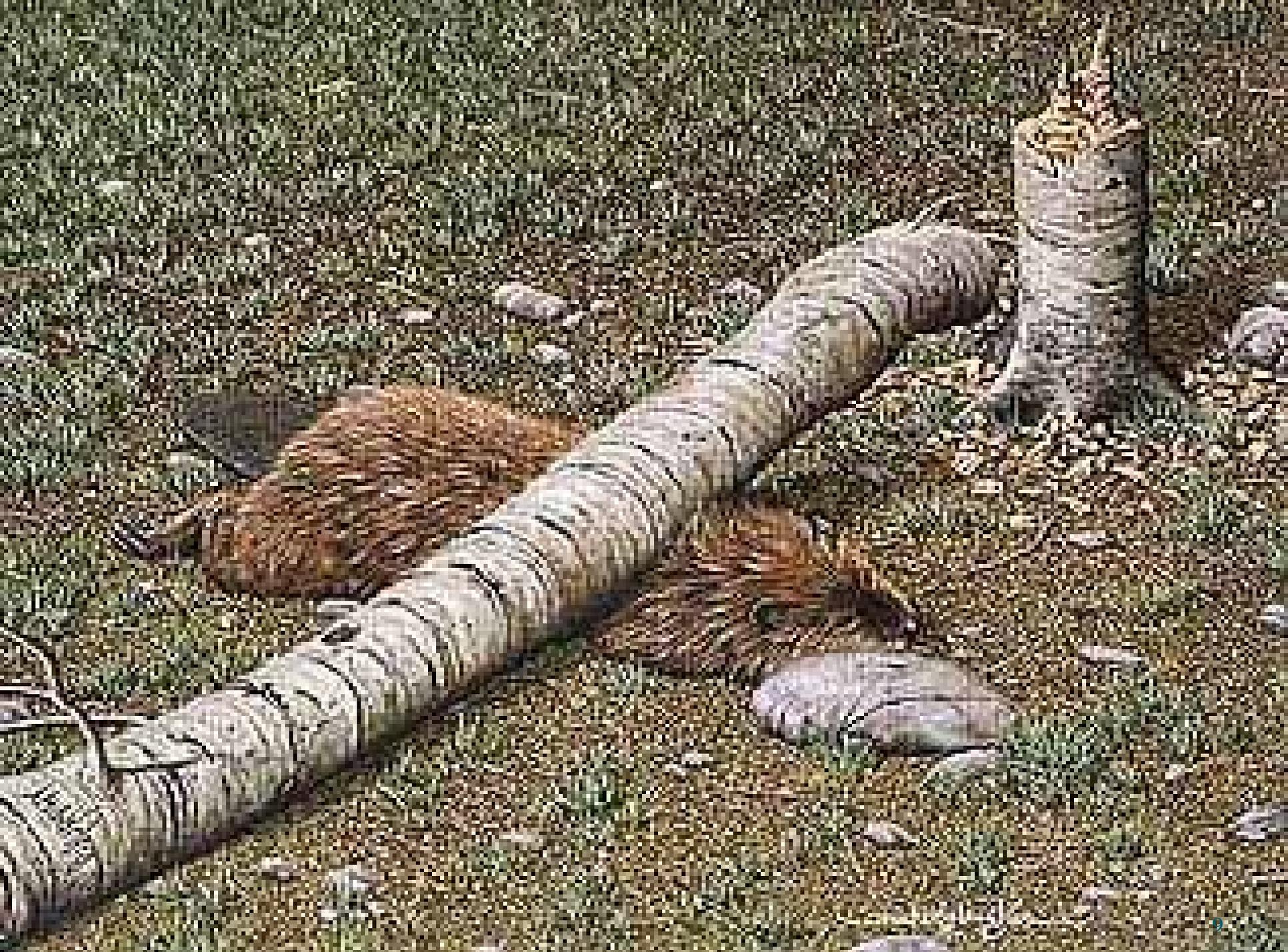
But will it be durable?

Sometimes it is and  
sometimes its not.....

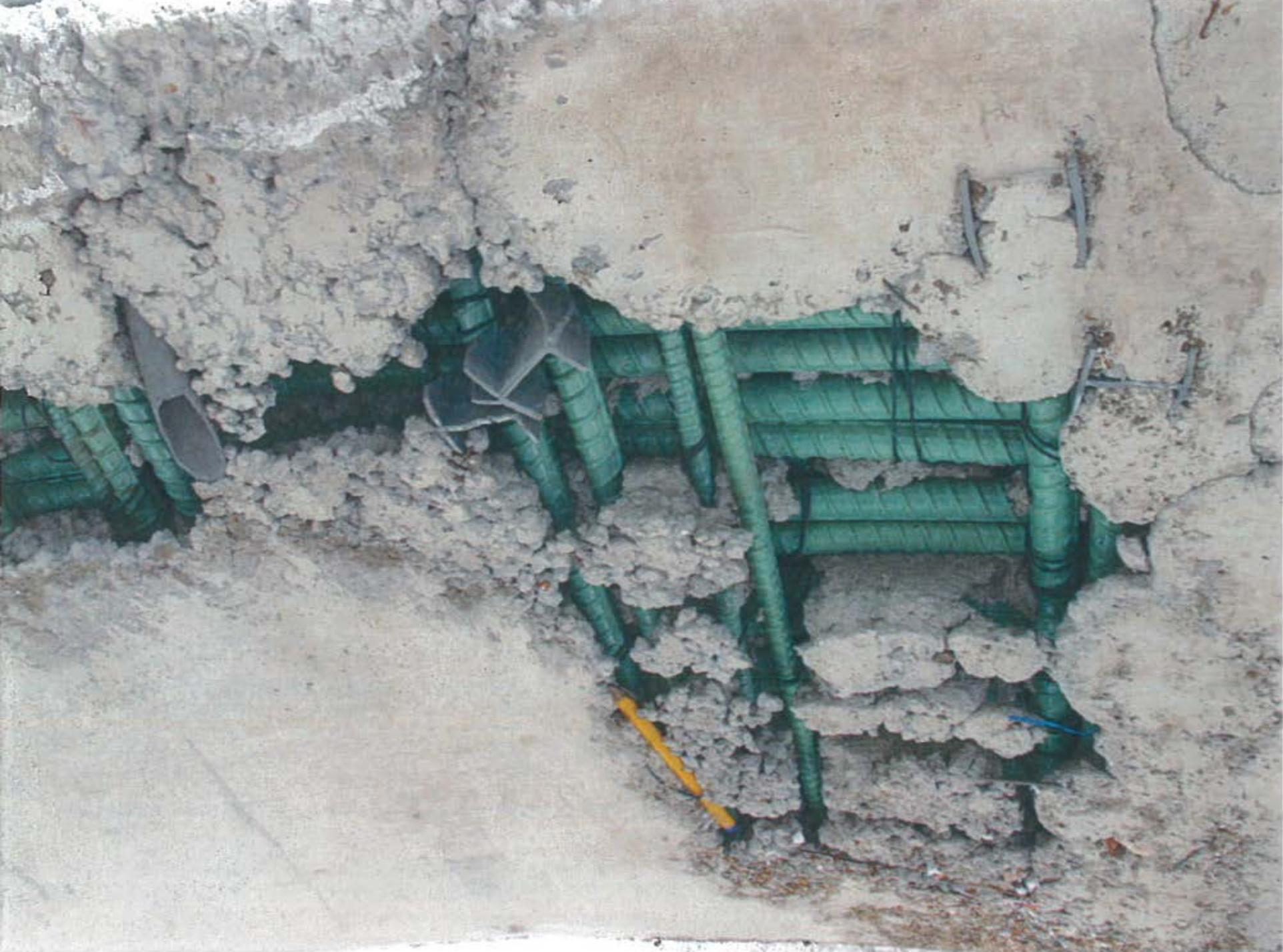


# Pantheon













# Current Approach to Concrete Durability

- Minimum cement content (i.e. 650 lbs, 720 ls)
- Maximum water-cementitious material ratio—0.45
- Slump
- Aggregates are sound, clean, durable, and well graded
- Adequate air void system for freeze-thaw climates
- Proper proportioning, mixing, placing, finishing, and curing



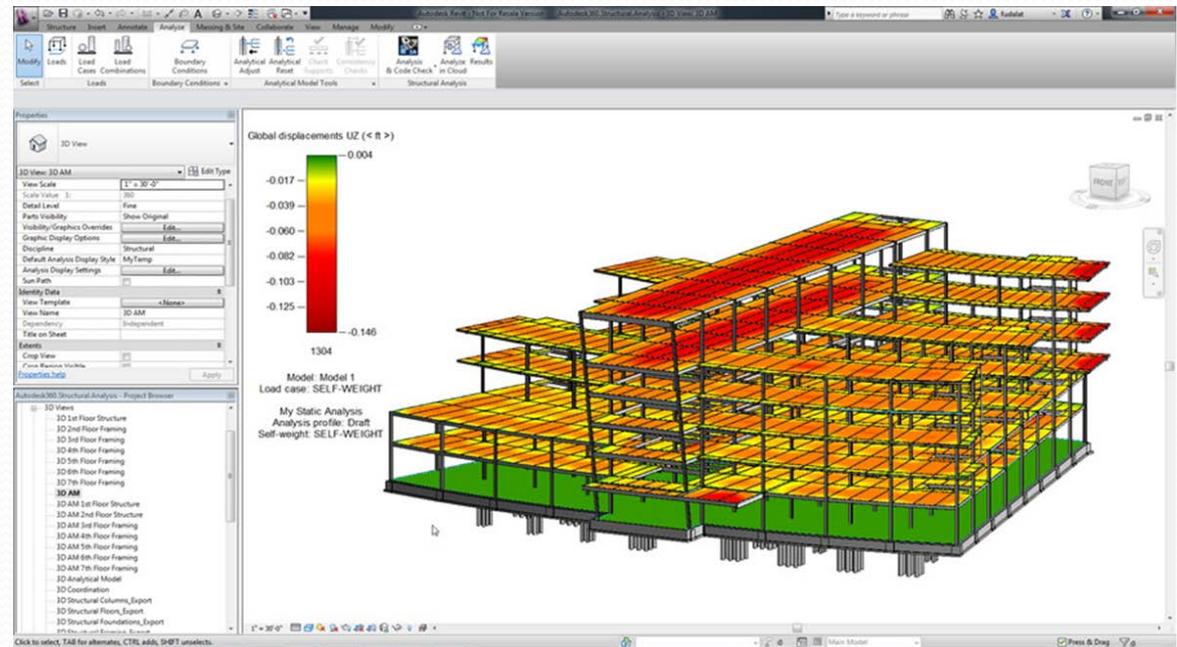


Column on Gardiner  
Expressway 1992  
MacDonald



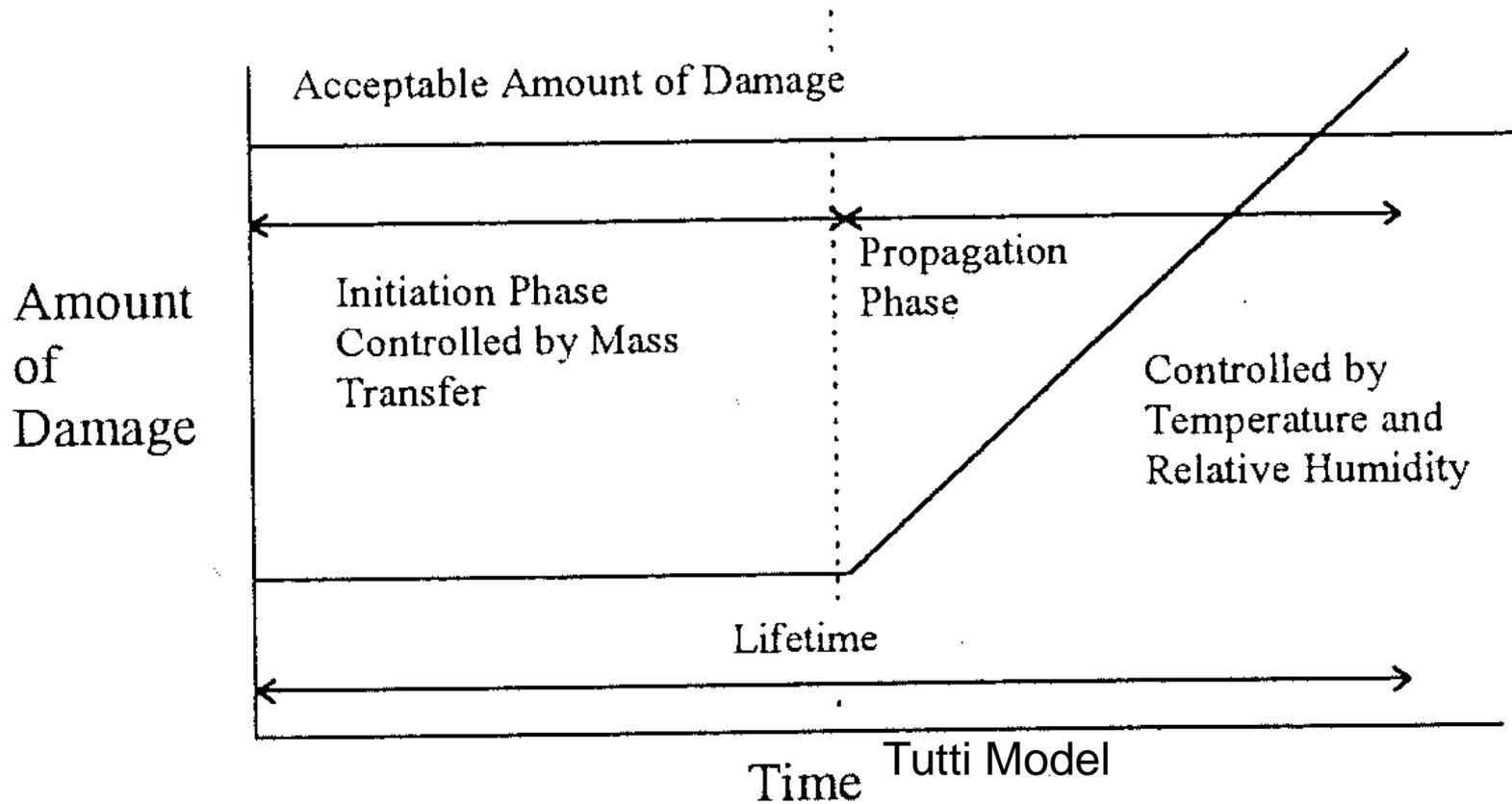
# Evolution of Structural Engineering

- Elasticity
- Plasticity
- Finite Element



# What is lifetime?

- Until the chloride threshold is reached? (0.2% weight of cement a commonly used value)
- Until corrosion potential indicates corrosion
- Until Staining?
- Cracking?
- Spalling?
- Collapse due to loss of section?



# Fick's Law Type Diffusion

$$\frac{\partial C}{\partial t} = -D_{Cl^-} \frac{\partial^2 C}{\partial x^2}$$

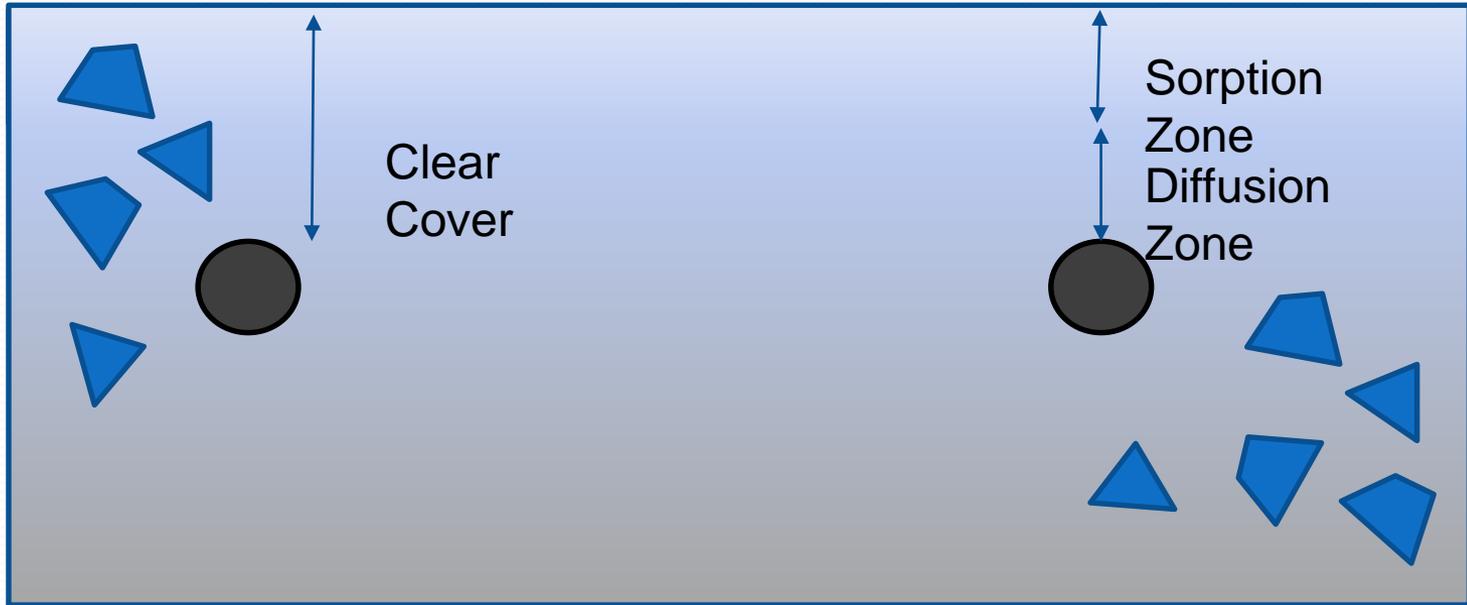
$$C(x,0) = 0$$

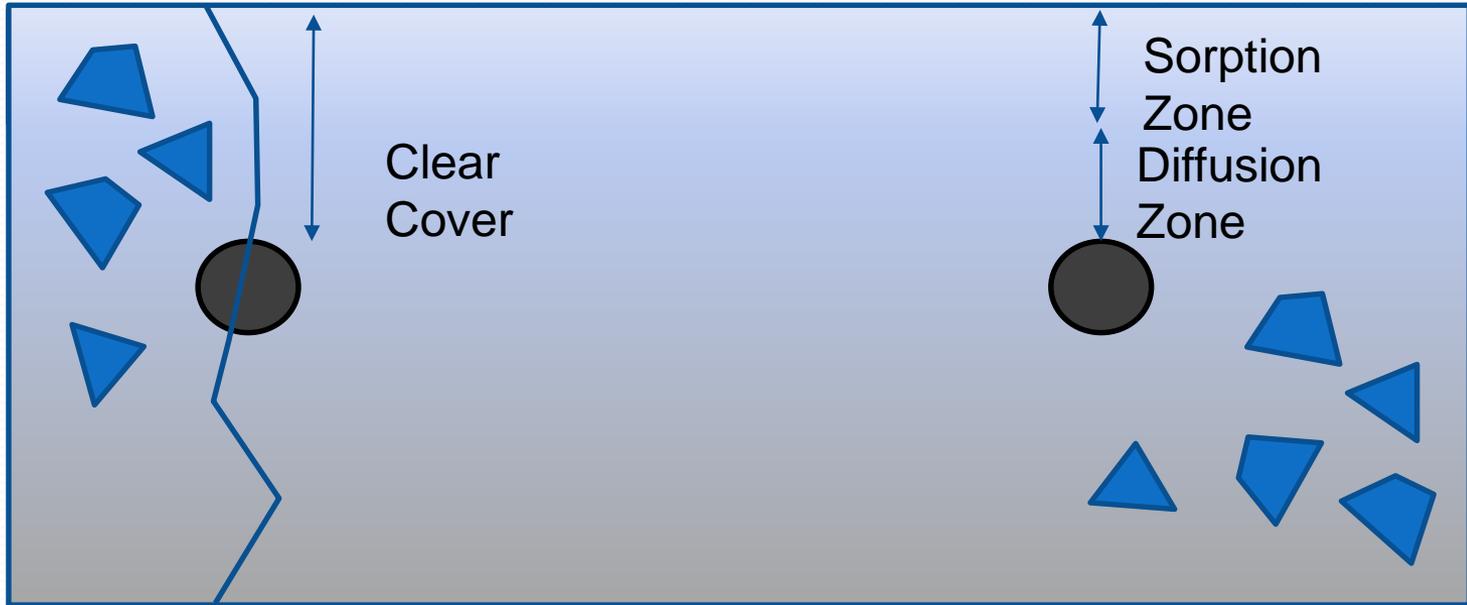
$$C(0,t) = C_o$$

$$C(x,t) = C_o \left( \operatorname{erfc} \left( \frac{x}{2\sqrt{Dt}} \right) \right)$$

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt.$$

$$\operatorname{erfc}(x) = 1 - \operatorname{erf}(x)$$





# Cracking

- Restrained shrinkage
- Loading
- Shrinkage is a function of aggregate stiffness and water content (NOT w/cm)
- 0.04 – low shrinkage ASTM C157 – approximately 250 lb / yd<sup>3</sup>
- Model needs to take into account the probability of cracking and related damage

# Correcting for Cracks

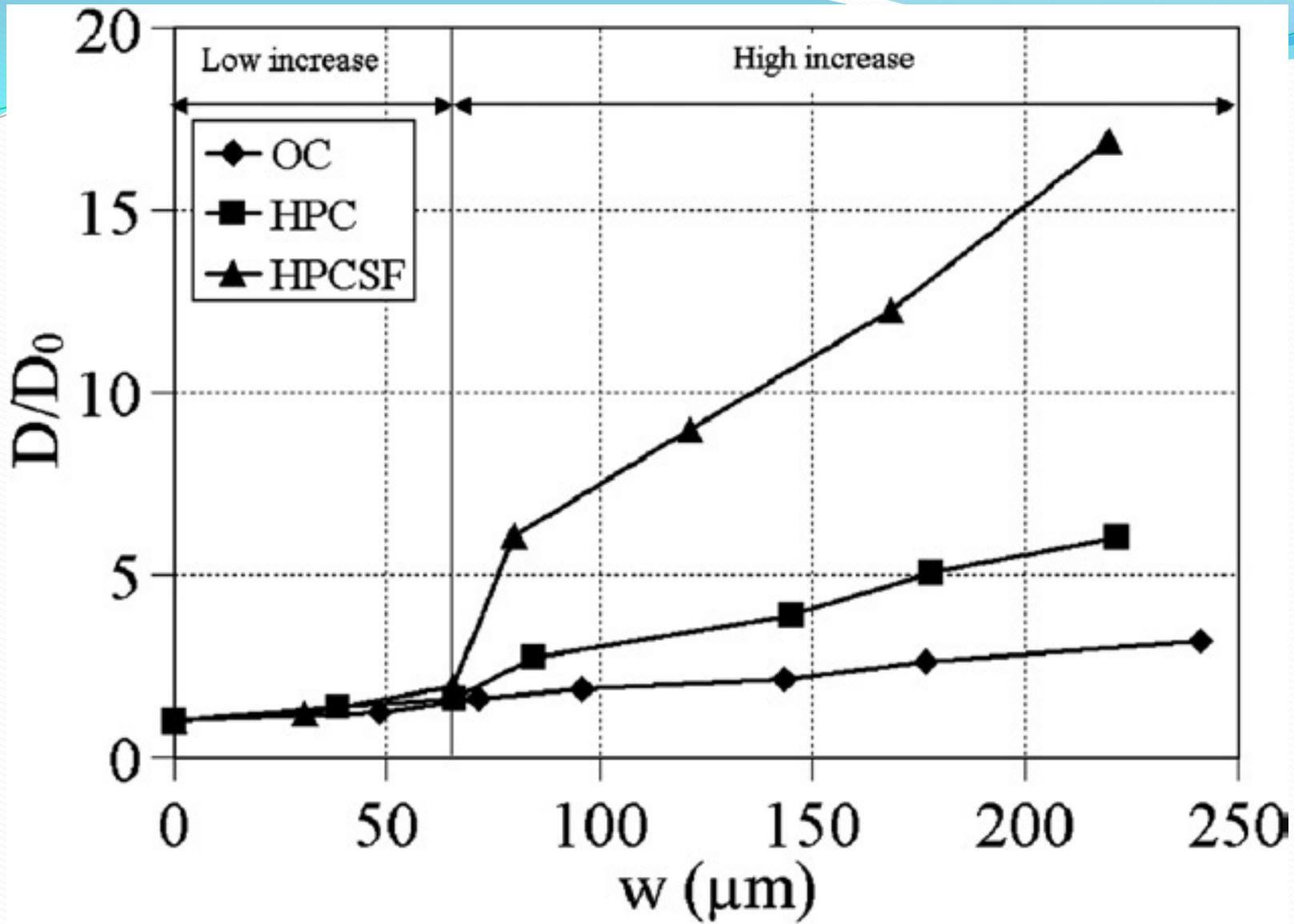
- Pacheco, CTL Group

- $$D_{cr} = \frac{D_0}{1 - \frac{w}{w_{lim}}}$$

- MacDonald, 2003

$$D_{cr} = D_0 + wl10^n D_0$$

Where  $w$  = crack width,  $n$  is a function of binder composition,  $l$  is the specific length of crack in  $m/m^2$



# Reliability

- Strength analogy
- A probability of failure has to be tolerated
- 10 percent is normal in Concrete Design

# Reliability

- $P_r = P_s + \beta\sigma$
- $P_s$  is the specified design value
- $P_r$  is the trial batch mean value required,
- $\beta$  is the reliability factor and
- $\sigma$  the standard deviation.
- The reliability factor is negative where failure is a higher than specified value (such as water:cement ratio) and positive when failure is a lower than specified value (such as strength).

# Modifying the Environment

## Controlling mass transfer

- Sorption
- Diffusion (pore size and number)
- Cracking

This is done with mix design and a focus on tests other than slump, air, and freeze/thaw testing. RCP tests are marginal

- Diffusion Coefficient (ASTM C1556, NTBuild 492)
- Bulk Conductivity (Resistivity (ASTM C1760))

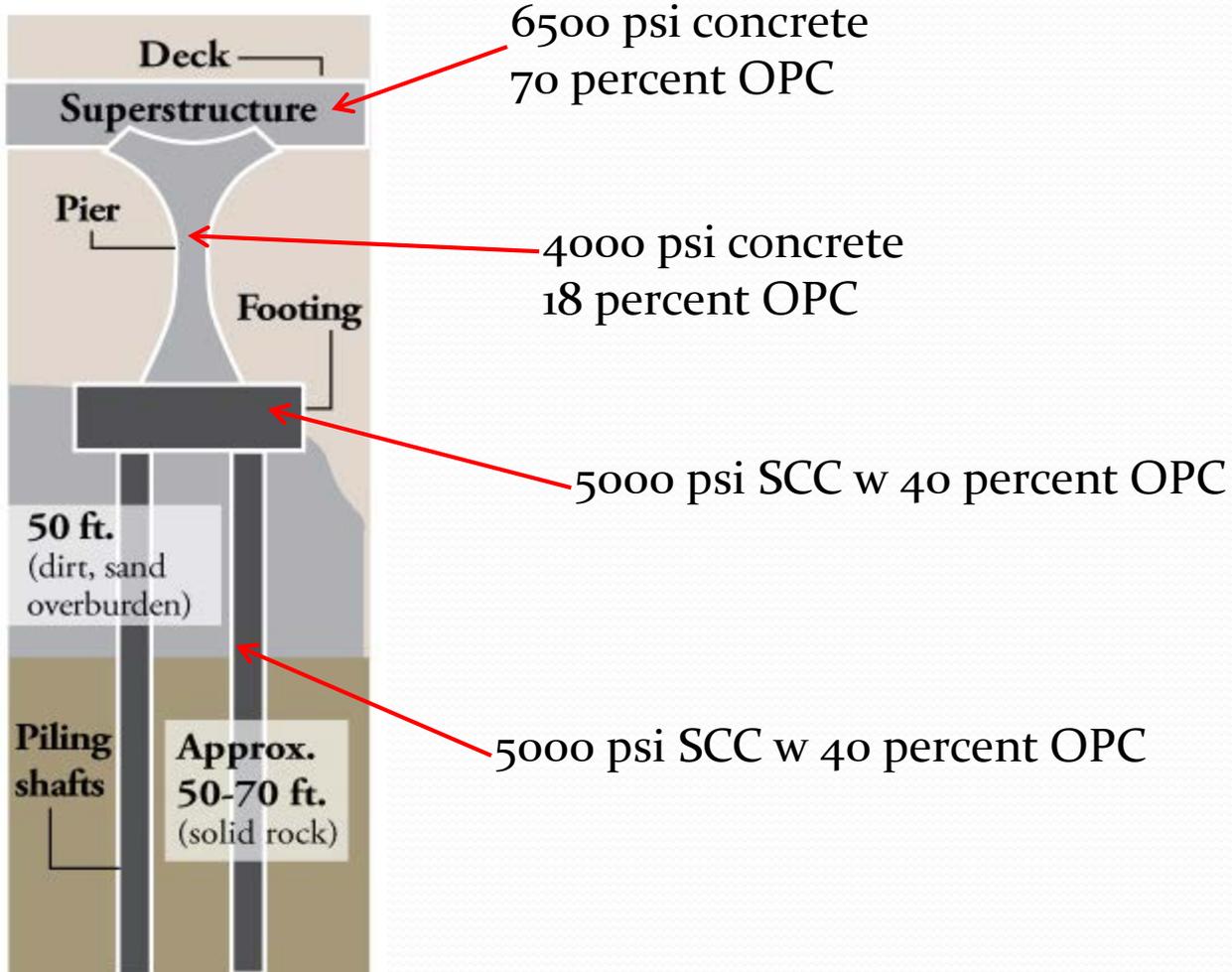
# Concrete Mixture Modification to get Desired Diffusion Properties

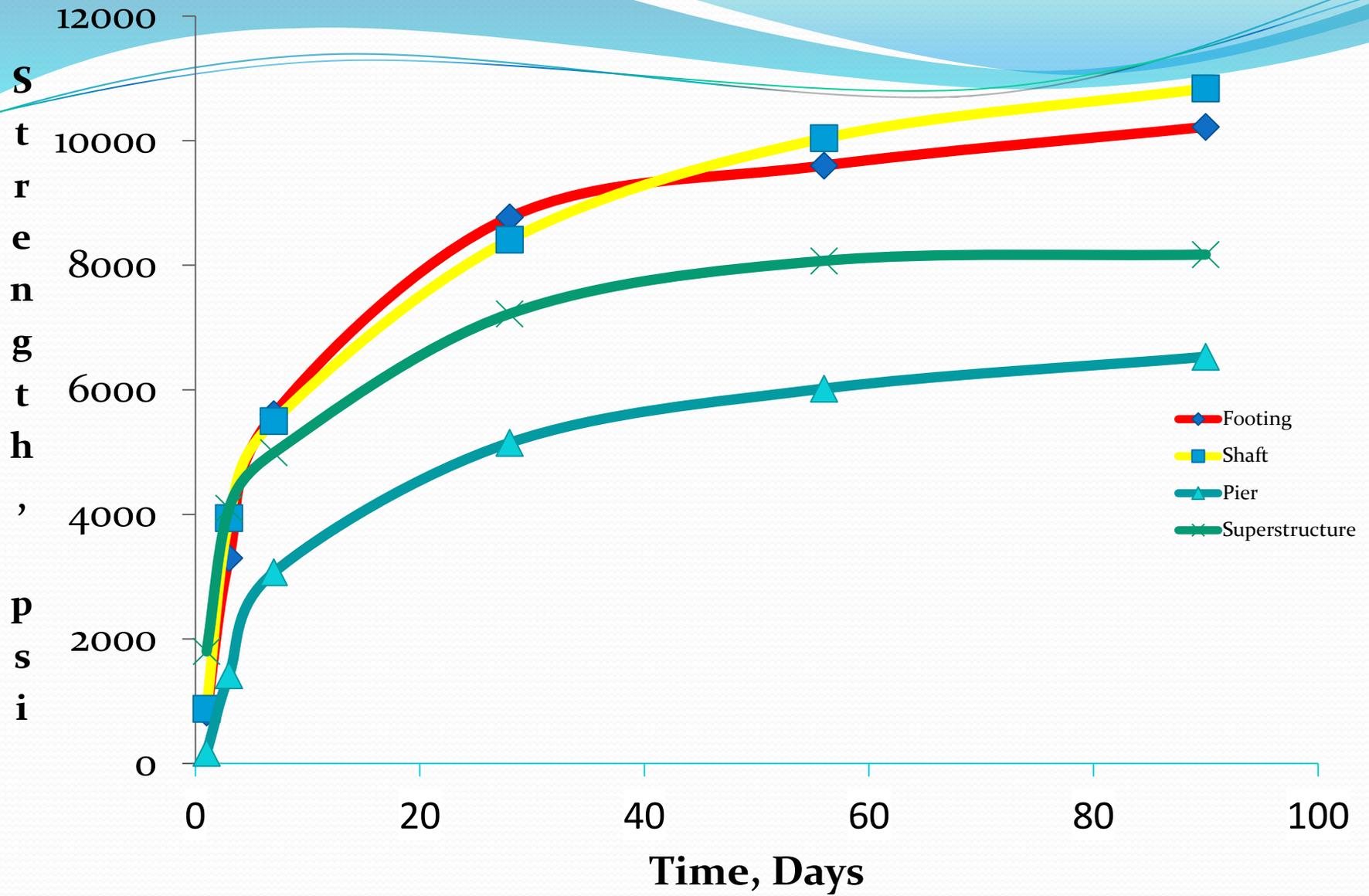
- Ternary Blends can give strength and high resistance to penetration
- Mix 1 100% OPC
- Mix 2 40% Cement, 42% Slag, 18% Ash
- Mix 3 15% Cement, 67% Slag, 18% Ash

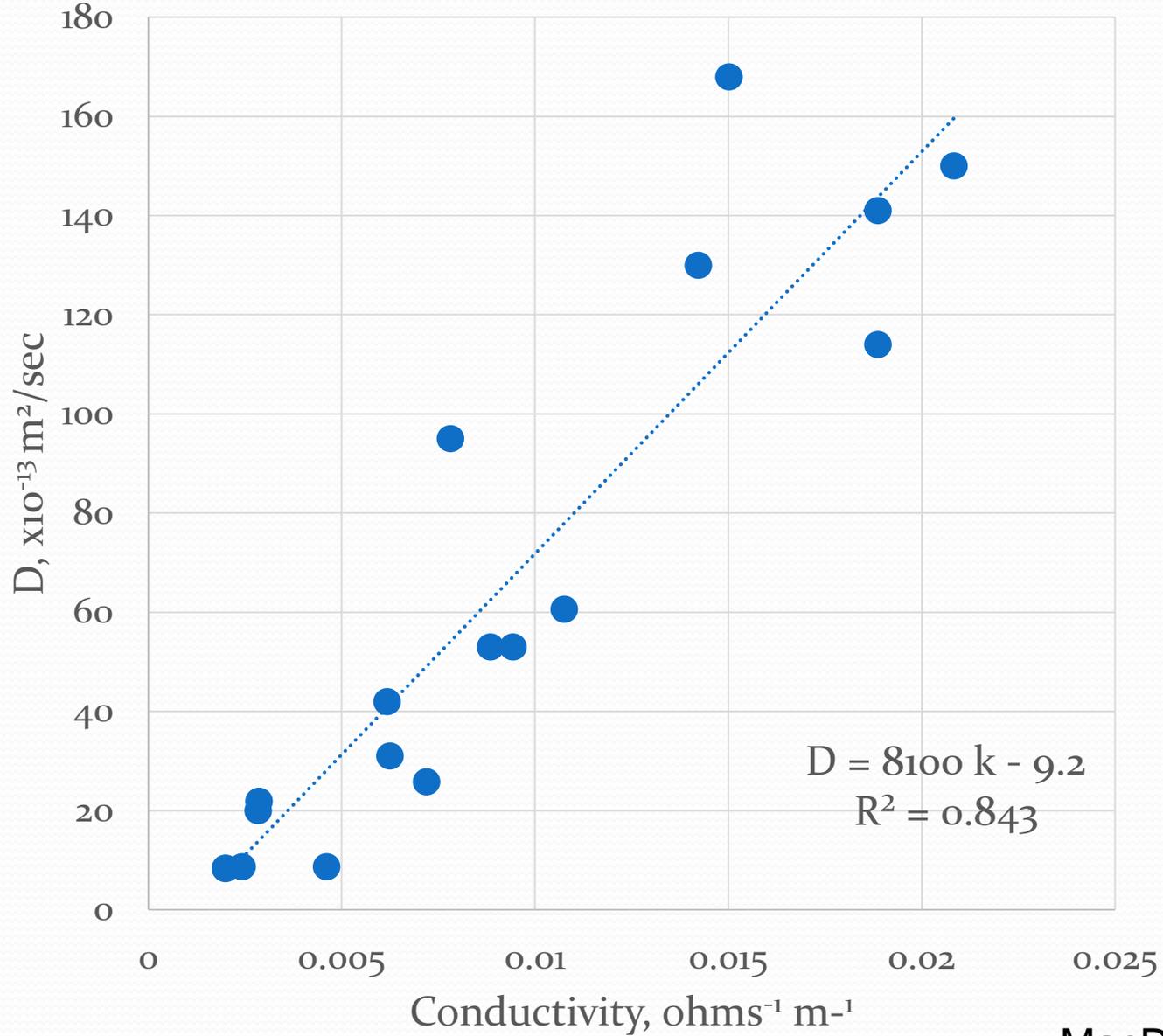
# Mixture Proportioning and Adjustment











# Decay values – measurement

- $f'c(t2) = f'c(t1) \left[ \frac{t1}{t2} \right]^m$
- $D(t2) = D(t1) \left[ \frac{t1}{t2} \right]^m$
- $k(t2) = k(t1) \left[ \frac{t1}{t2} \right]^m$
- It's the same m value, as it is a result of the reduction in porosity with hydration.

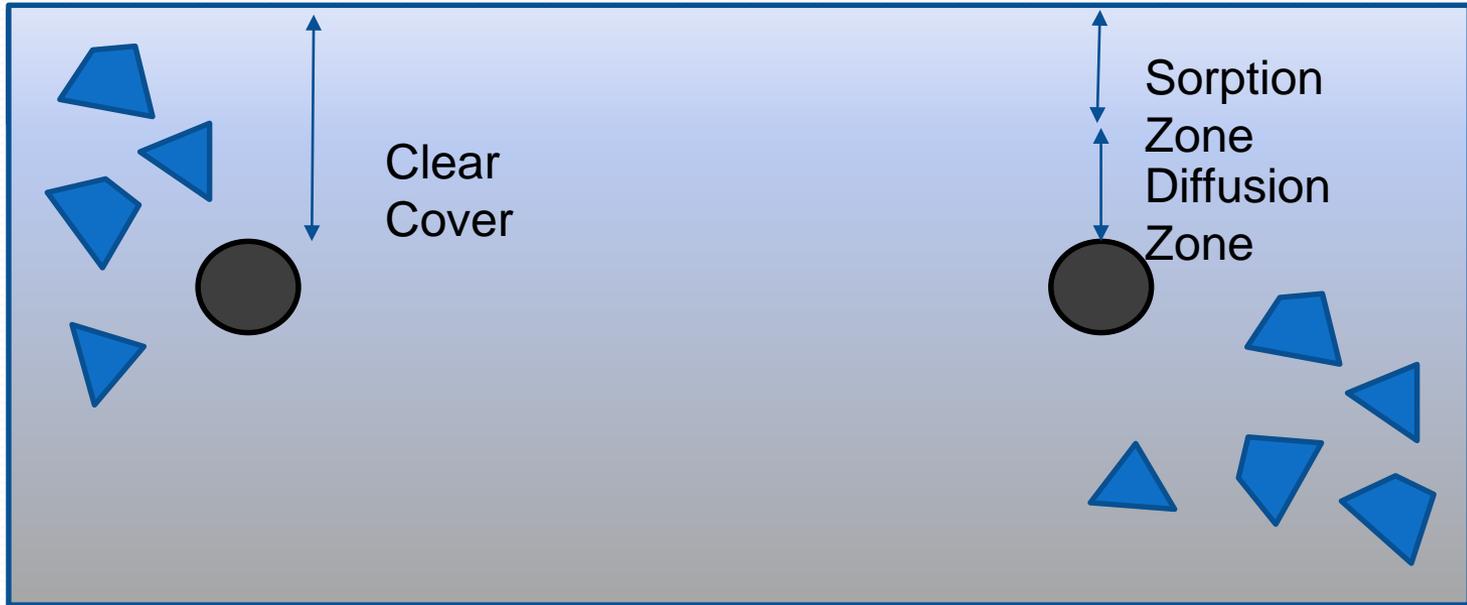
# Prescription vs. Performance

- US lagging behind Europe / Canada in code development
- I.e. CSA A23.1 class C1 exposure
- Economic advantage of “how” is removed
- Innovation is stifled
- Often meeting the prescription can result in undesirable, unintended consequences

**Table 20.6.1.3.1—Specified concrete cover for cast-in-place nonprestressed concrete members**

Concrete exposure	Member	Reinforcement	Specified cover, in.
Cast against and permanently in contact with ground	All	All	3
Exposed to weather or in contact with ground	All	No. 6 through No. 18 bars	2
		No. 5 bar, W31 or D31 wire, and smaller	1-1/2
Not exposed to weather or in contact with ground	Slabs, joists, and walls	No. 14 and No. 18 bars	1-1/2
		No. 11 bar and smaller	3/4
	Beams, columns, pedestals, and tension ties	Primary reinforcement, stirrups, ties, spirals, and hoops	1-1/2

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**Table 4.1—Effect of cover and diffusion coefficient on time to initiation of corrosion of reinforced concrete**

Cover, mm	Chloride ion diffusion coefficient $D$ , $m^2/s^*$		
	$5 \times 10^{-11}$	$5 \times 10^{-12}$	$5 \times 10^{-13}$
	Time, yr		
25	0.56	5.6	56
50	2.3	23.0	230
75	5.0	50.0	500
100	9.0	90.0	900

\* Based on setting  $C_t / C_0 = 0.55$ , with  $C_t = 0.4\%$  (by mass cement), and  $L = 300$  mm.

**Table 26.4.2.2(b)—Limits on cementitious materials for concrete assigned to Exposure Class F3**

<b>Cementitious materials</b>	<b>Maximum percent of total cementitious materials by mass</b>
Fly ash or other pozzolans conforming to ASTM C618	25
Slag cement conforming to ASTM C989	50
Silica fume conforming to ASTM C1240	10
Total of fly ash or other pozzolans and silica fume	35
Total of fly ash or other pozzolans, slag cement, and silica fume	50

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Mix Number	Exposure Class	Cement	Slag	Flyash	Silica Fume	w/c ratio	Total Pozzolan	Flyash	Total Pozzolan
1	C2,F3	40%	42%	18%	0%	0.45	60%	Meet	Fail
2	C2,F3	40%	42%	18%	0%	0.45	60%	Meet	Fail
3	C2,F3	15%	67%	18%	0%	0.45	85%	Meet	Fail
4	C2,F3	15%	67%	18%	0%	0.45	85%	Meet	Fail
5	C2,F3	60%	0%	30%	4%	0.35	34%	Fail	Meet
6	C2,F3	60%	0%	30%	4%	0.35	34%	Fail	Meet
7	C2,F3	29%	43%	29%	0%	0.36	71%	Fail	Fail
8	C2,F3	33%	50%	17%	0%	0.35	67%	Meet	Fail

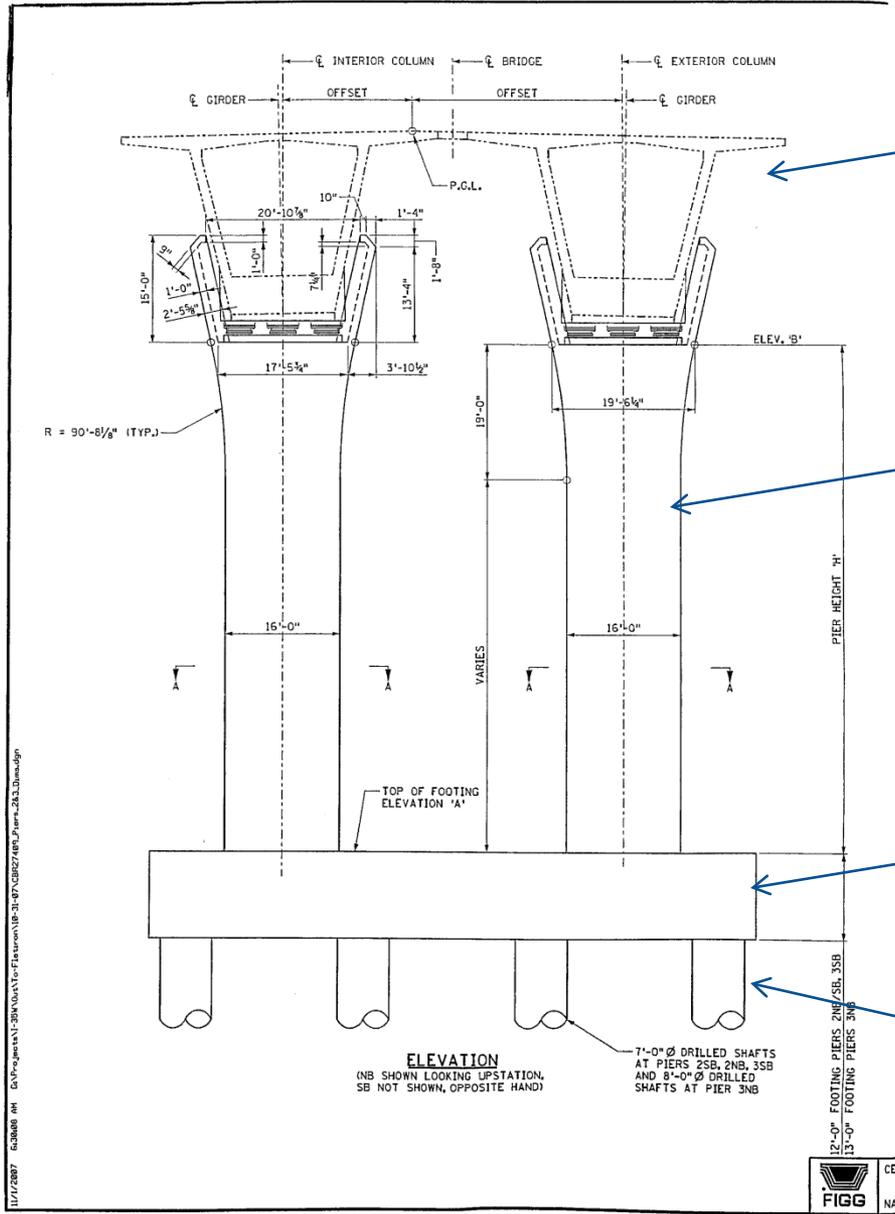
Mix Number	Exposure Class	C157 Drying Shrinkage, percent	RCP, C passed - 28 days	RCP, C passed - 56 days	ASTM C666 Retained Durability	ASTM C1556, m <sup>2</sup> /sec x10 <sup>-12</sup>
1	C2,F3	-0.028	1097	380	94	0.17
2	C2,F3	-0.029	918	523	76	0.9
3	C2,F3	-0.024	291	177	90	0.15
4	C2,F3	-0.025	386	232	85	0.60
5	C2,F3	-0.026	548	366	98	1.2
6	C2,F3	-0.028	750	530	85	2.4
7	C2,F3	-0.025	442	300	100	0.5
8	C2,F3	-0.026	340	225	100	0.08

# Conclusions

- Concrete is rapidly changing – codes are not (cannot)
- The code already restricts durability -
- A model code as a companion to ACI 318 and the Bridge design code is required now

# Questions

- Thank you for your time and attention!



Superstructure

Chloride  
 Freeze Thaw  
 Scaling  
 Creep and Shrinkage

Piers

Mass Concrete  
 Freeze-Thaw Exposure  
 Chlorides

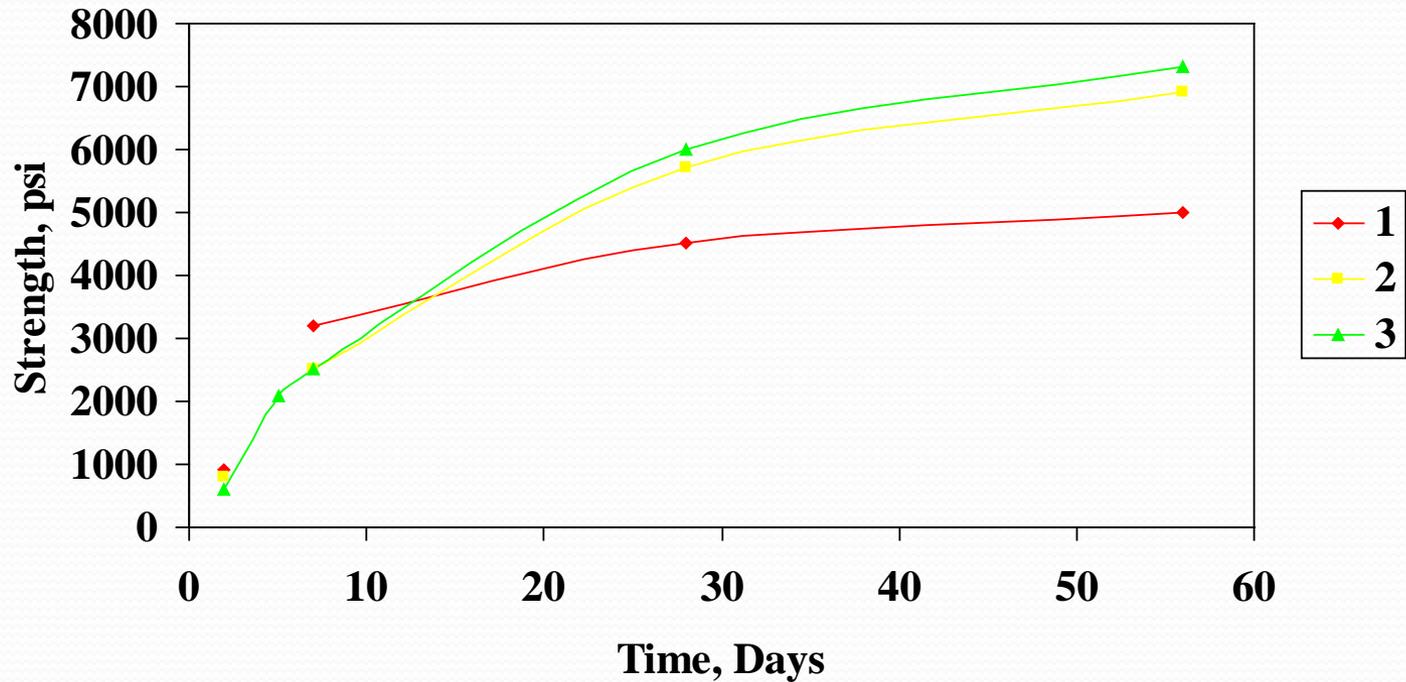
Footing

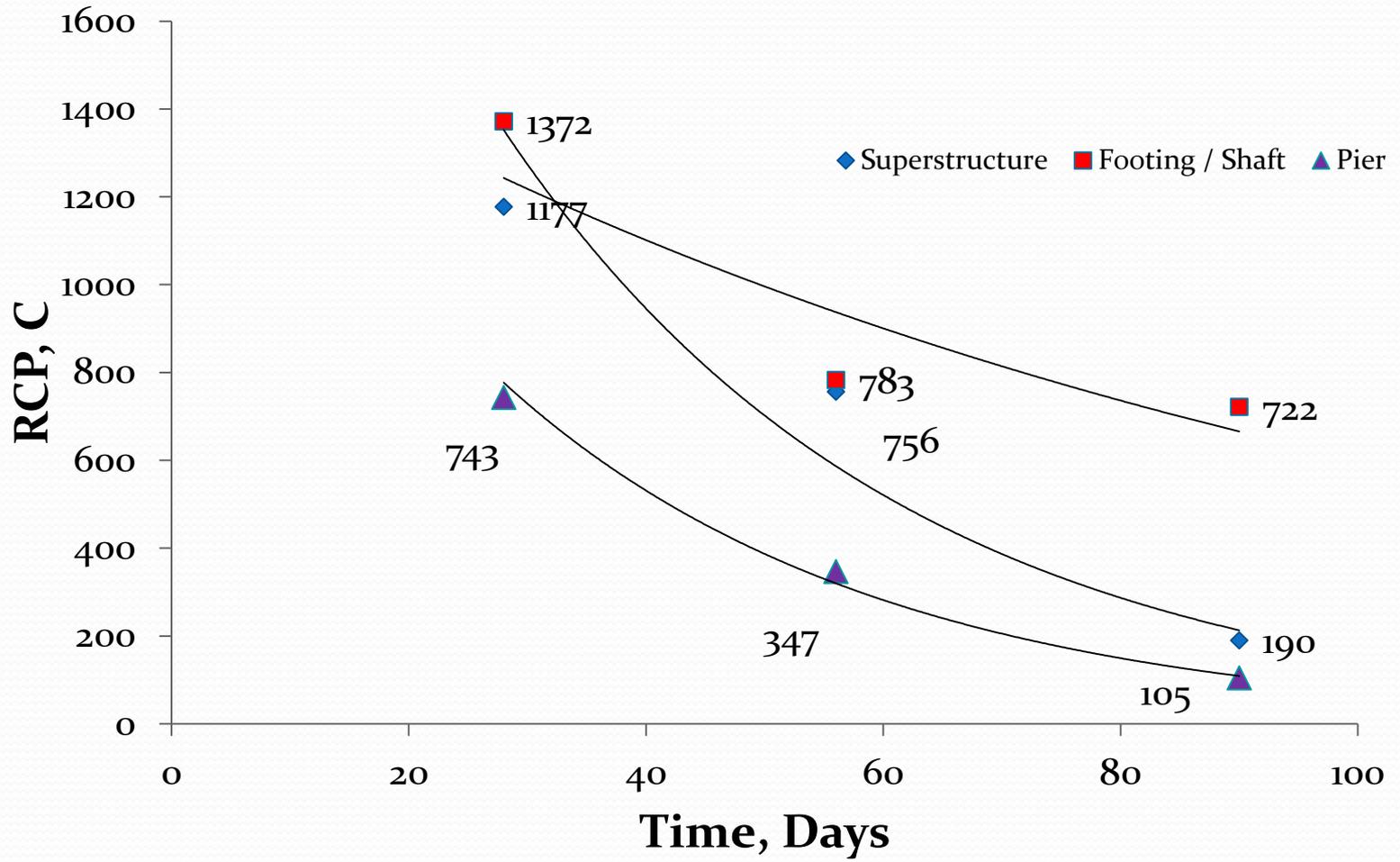
Mass Concrete  
 Freeze-Thaw Exposure  
 Chlorides

Shafts

Consolidation  
 Freeze Thaw  
 Chlorides /  
 Permeability

# Strength Gain





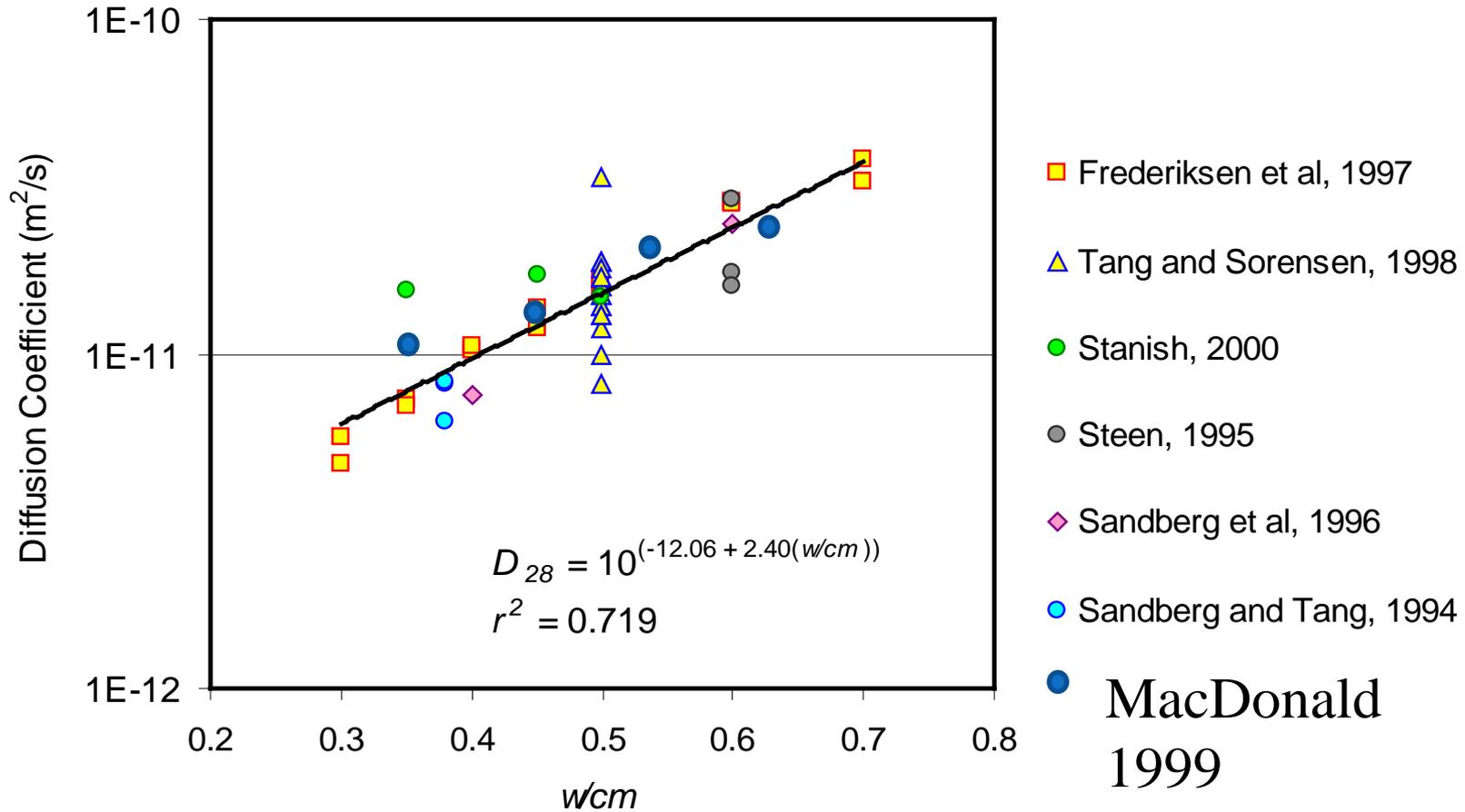


Figure 4.3 Relationship between  $D_{28}$  and  $w/cm$  for concrete at  $20^{\circ}C$