Concrete Durability Design

Minnesota Concrete Council

21st Annual Seminar

Concrete – A Changing Industry

By

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Acknowledgements

- *Design and Control of Concrete Mixtures*, Portland Cement Association, 14th Edition, 2002
- *Guide to Durable Concrete*, ACI 201 Committee Report, 2008
- *Guide for the Design of Durable Parking Structures*, ACI 362, Committee Report 1997
- Numerous ACI technical articles
- Photos from archives of WJE

Outline

- Durability – Definitions
- What structures require "durability"
- What environmental conditions affect durability
- What concrete mixture and curing conditions affect durability
- How can concrete be designed for durability

Concrete

Objective

- Describe issues that cause concrete durability problems
- Review what approaches can be taken to provide durability to concrete

Definition of Concrete Durability

- Concrete Durability

  Concrete fit for the purpose for which it was intended, under the conditions to which the concrete is expected to be exposed, and for the expected life during which the concrete is to remain in service.

Adam Neville CI July 2000

Definition of Concrete Durability

- ACI 201.2R *Guide to Durable Concrete*

  Durability of hydraulic cement concrete is determined by its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration

ACI 201 Deterioration Modes

- Freezing and thawing
- Alkali-aggregate reaction (AAR)
- Chemical attack
- Corrosion of embedded metals
- Abrasion

Steel Reinforcing

Structure Types

- Structure types needing to be durable
  - Bridge decks
  - Bridge piers, especially when in salt water
  - Parking structures
  - Pavements

Service Life Expectations

- Aspects having direct bearing on durability
  - Nature of the project
    - Type of structure
    - Expected service life
    - Exposure conditions
  - Consider aspects concurrently to assess level of durability

Attack Mechanisms

- Freezing and thawing
- Carbonation
- Chloride penetration
- Cracking
- Leaking
- Aggregates
- Chemical attack
- Abrasion

Making Concrete Durable

- There are two fundamental ways to make concrete durable
  - Address the properties of the concrete
  - Provide protective systems external to the concrete

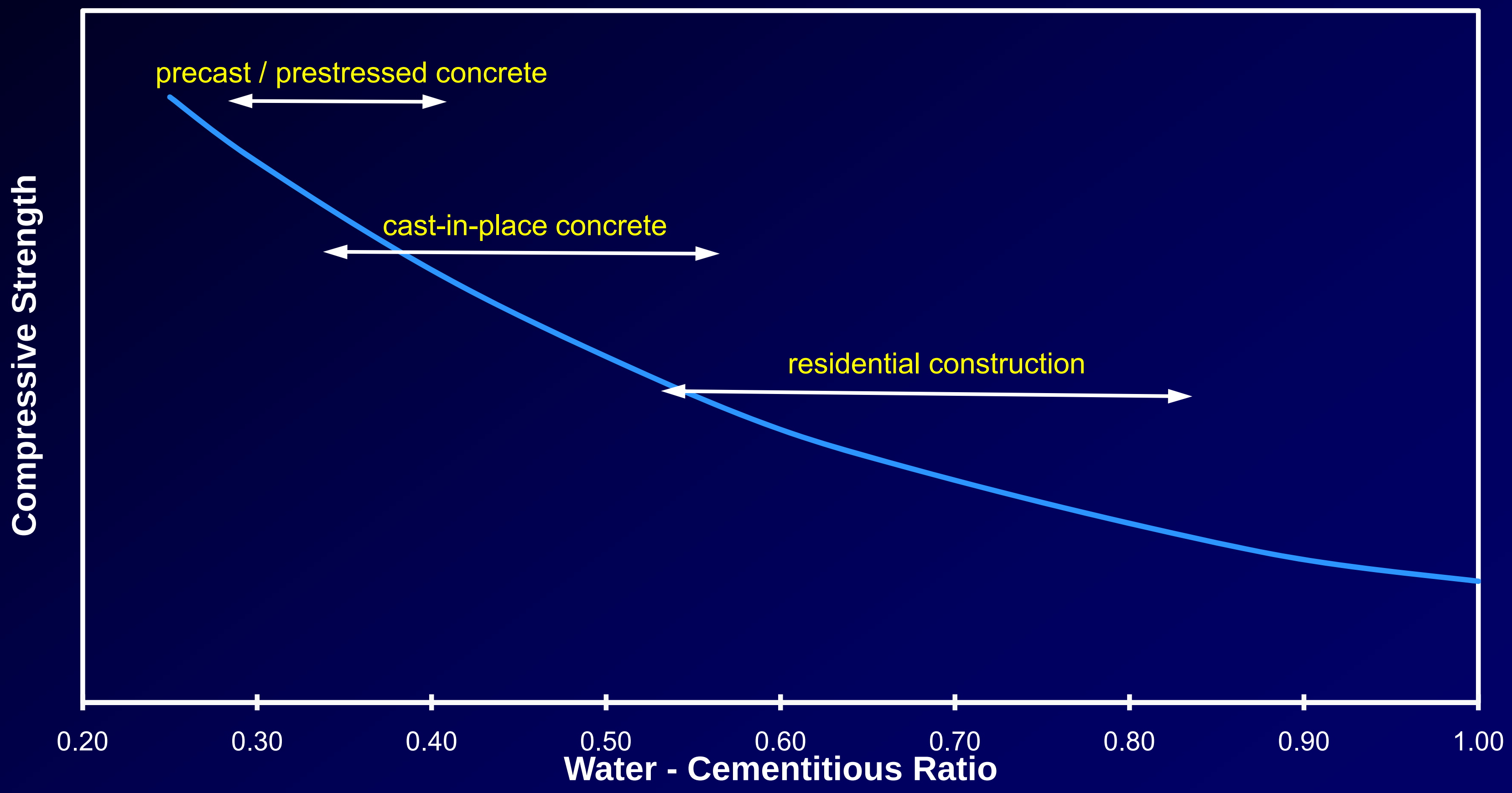
Concrete Mixture Properties

- Basic
  - Cement
  - Coarse aggregate
  - Fine aggregate
  - Water
  - Mixing/Placing
- Admixture and Curing
  - Air entraining
  - Water reducers
  - Other cementitious materials
  - Corrosion inhibitors
  - Curing regimes

Water to Cementitious Ratio

- w/cm plays defining role for concrete durability
- Generally the lower the w/cm ratio the better the performance

Water to Cementitious Ratio



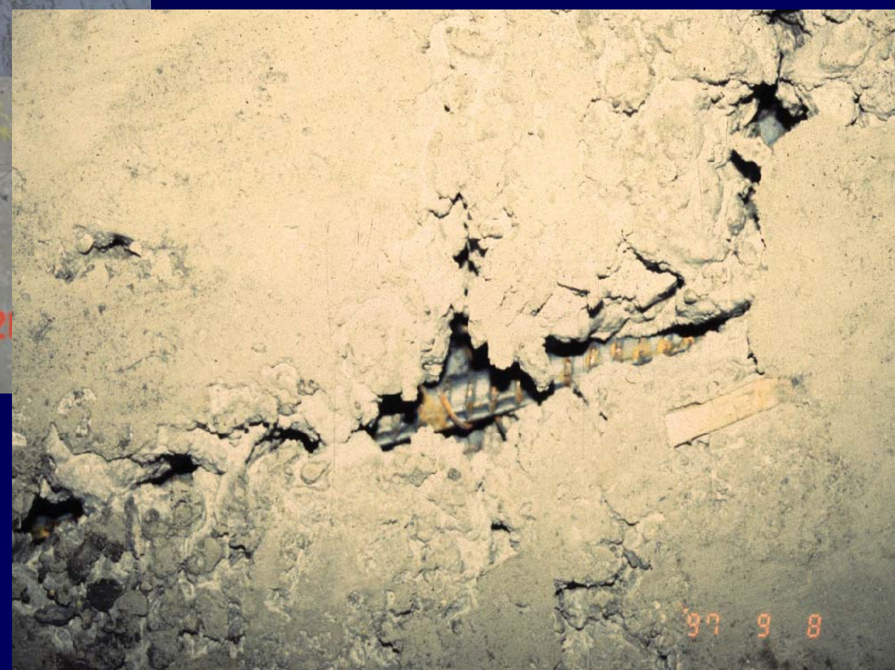
Mixing

- Extended mixing
  - Reduces air entrainment
  - Higher concrete temperatures
  - Slump loss
- Add water to restore slump
  - Increases porosity
  - Impacts air void pore size distribution
  - Increases drying shrinkage
  - Reduces concrete strength

Placing and Consolidation

- Excessive free fall
  - Reduces the entrained air content
- Pumping changes air content
- Vibration duration
  - Increased vibration reduces air content
  - Reduced vibration leaves voids
  - Good vibration reduces permeability

Inadequate Vibration - Honeycombing



Aggregates - Popout

Aggregates

- Alkali-silica reaction (ASR)
  - Involves chemical reaction between alkali source (cement) and reactive silica (siliceous aggregates)
  - Can manifest itself in 5 to 20 years (internal tearing/cracking of the concrete matrix)

Alkali-silica Reaction (ASR)

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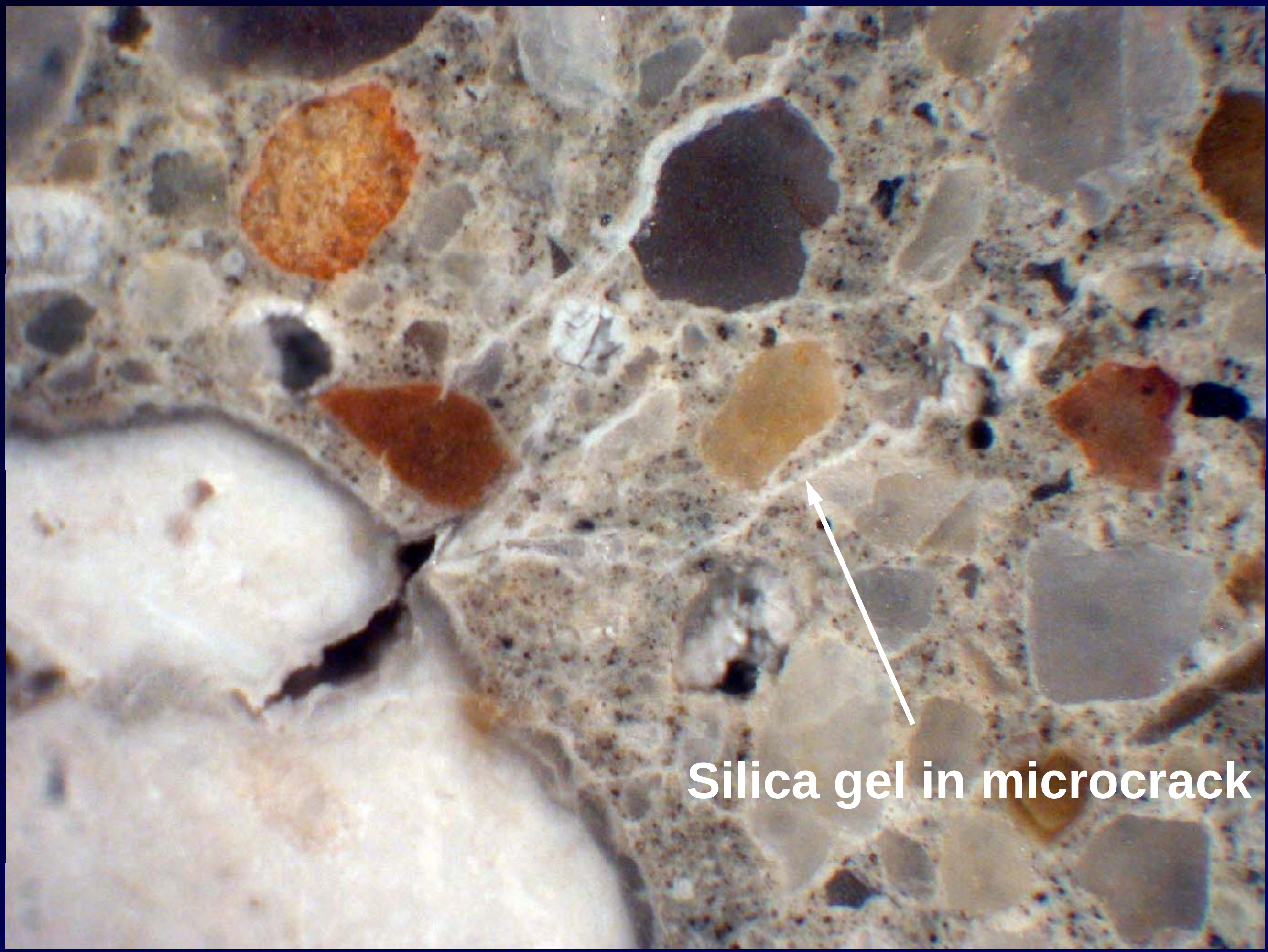
Alkali-silica Reaction (ASR)



Aggregates

- Alkali-carbonate reaction (ACR)
  - Involves certain argillaceous dolomitic limestones
  - Chemical reaction between alkali source (cement) and certain calcium-magnesium carbonate rocks (dolomites)
  - Not a significant issue in U.S. except Virginia

Aggregate Evaluation

- Petrographic examination ASTM C295
- Laboratory testing
  - Mortar Bar Test ASTM C 227
  - Accelerated Mortar Bar Test ASTM C1260
  - Quick Chemical Test ASTM C 289
  - Concrete Prism Tests ASTM C 1293
- Essentially, measure expansion

Prism Tests

Reducing ASR in Concrete

- Use nonreactive aggregates
- Use low alkali cement
- Use fly ash, silica fume, GGBFS
- Use lithium compounds

Concrete Mixture Properties

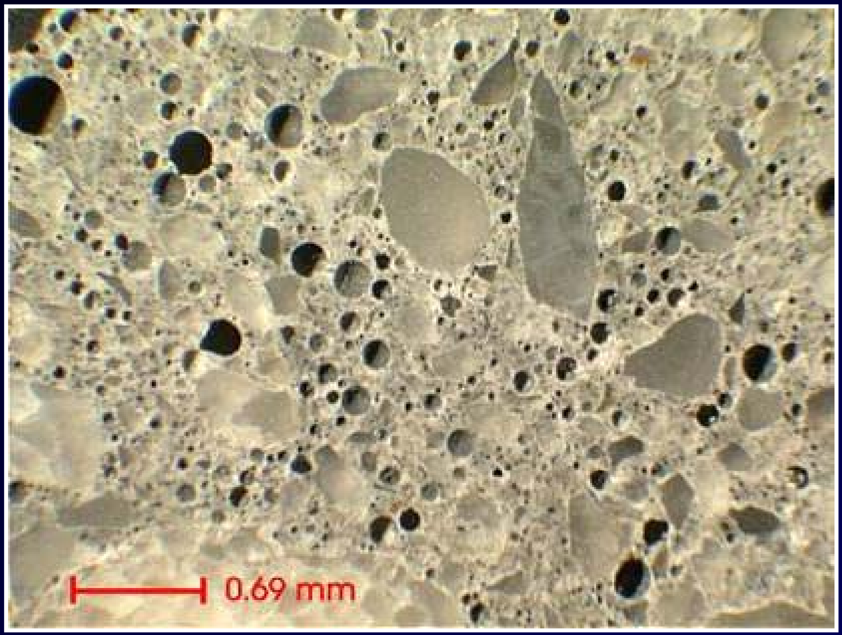
- Basic
  - Cement
  - Coarse aggregate
  - Fine aggregate
  - Water
  - Mixing/Placing
- Admixture and Curing
  - Air entraining
  - Water reducers
  - Other cementitious materials
  - Corrosion inhibitors
  - Curing regimes

Air Entraining

- Air entraining is the most important aspect, next to w/cm, for enhanced durability in concrete
- Air entraining essential in freezing and thawing environments

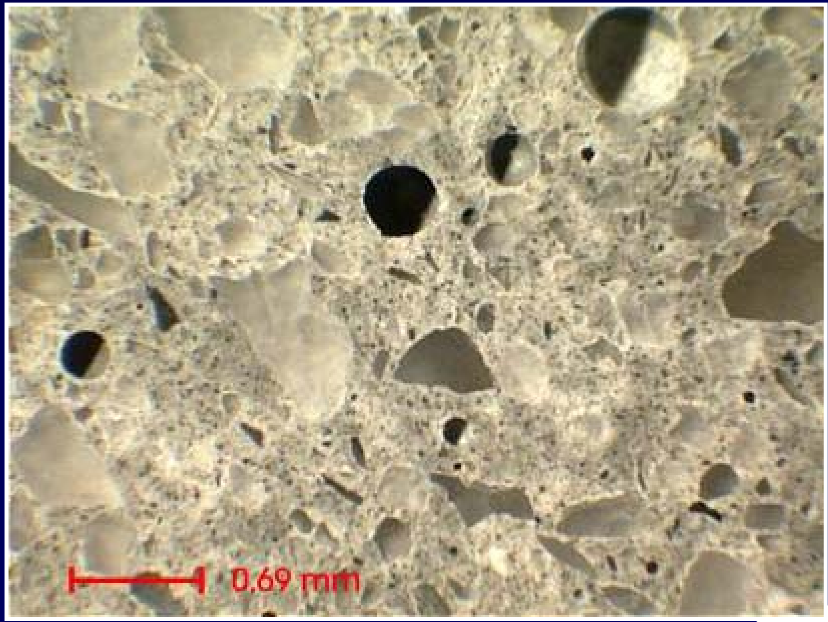
Freezing and Thawing Deterioration

Air Entrainment



Entrained air

No air entrainment



D-Cracking

D-Cracking

Concrete Scaling

Good Deicer

- Rapid ice melting rate
- Minimal scaling
- Minimal freezing and thawing cracking
- Minimal metal corrosion potential

Deicing or Anti-icing

- Deicing - an effort to remove ice from surfaces after ice exists
- Anti-icing - a surface treatment applied prior to ice formation; facilitates ice removal by reducing bond between ice and surface

Deicing Chemicals

- Chloride salts
  - Sodium chloride - $NaCl$
  - Calcium chloride - $CaCl_2$
  - Magnesium chloride - $MgCl_2$
  - Potassium chloride - KCl
- Phosphate salts
  - Mono sodium phosphate - NaH_2PO_4
  - Mono calcium phosphate – $Ca(H_2PO_4)H_2O$
  - Mono potassium phosphate - KH_2PO_4

Deicing Chemicals

- Acetates
  - Calcium magnesium acetate - CMA
  - Potassium acetate - $KC_2H_3O_2$
- Benzene
- Alcohol, Glycol
- Synthetic urea

Deicing Chemicals

- Concentrations in concrete of 2 – 4 % cause most damage
  - Lower percentages not as damaging
  - Higher percentages of some deicers - damaging
- Conversion
  - 2 - 4% solutions of NaCl in concrete about equivalent to 0.5 – 1.0 molality

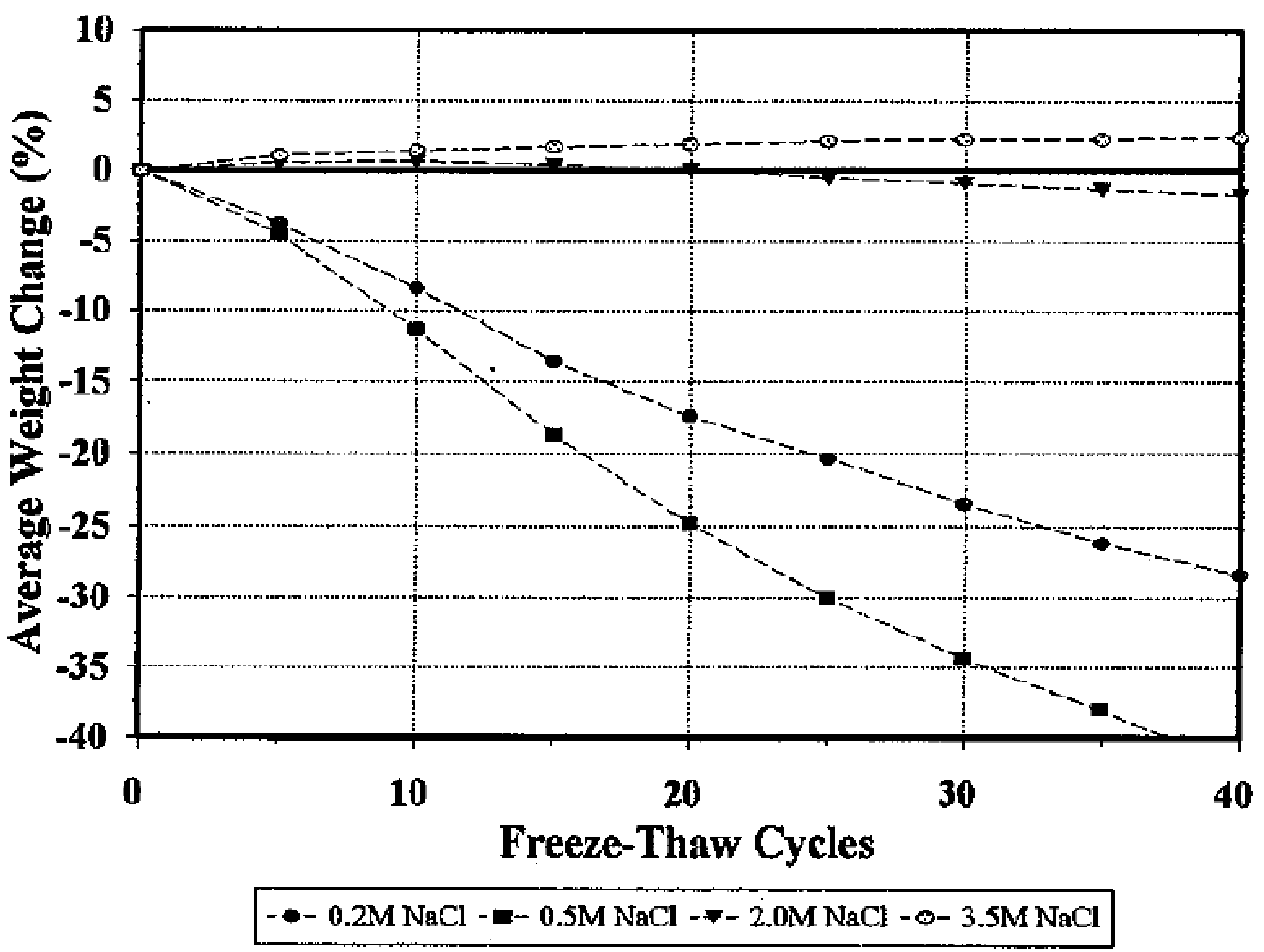
Scaling Mechanism

- Water freezes in capillary pores
  - Ice crystals form
  - Develop hydraulic pressures
- If available pore space is less than required for all the water (critical saturation), excess is driven off by pressure of expansion
- If pressure exceed tensile strength of concrete, local cracking occurs

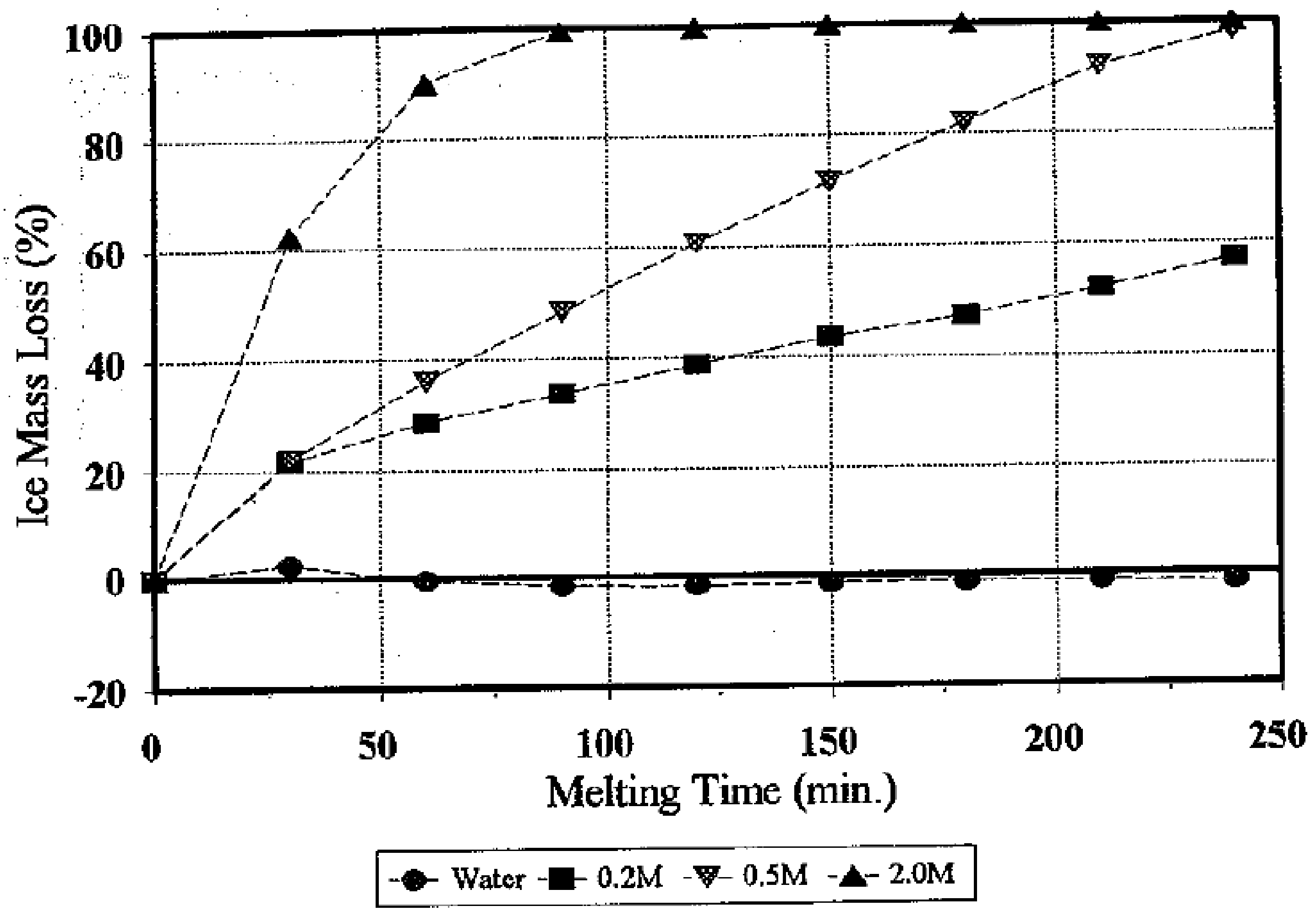
Scaling Mechanism - Deicers

- Concrete is further damaged by deicing agent
  - Increase in the osmotic pressure
- Deicing agent magnifies the pressures in the concrete
  - Increases the potential for surface scaling
- Deicer salt scaling generally thought to be physical rather than chemical

Salt Scaling



Deicing Rate



NaCl Molality

Summary

- Very low concentrations – small effect on durability
- Very high concentrations – cause long-term scaling
- Objective – keep water and salt (chlorides) out
  - Make concrete “tighter”
  - Low w/cm not the answer
  - Add supplementary cementitious materials

Summary

- NaCl - least expensive
  - Most damaging to reinforcing steel
- CMA - more expensive
  - Can chemically damage concrete
  - Does not induce corrosion of reinforcing steel
- Use beet juice?

Water Reducers

- Water reducers essential to making low w/cm concrete workable
- Water reducers can effect air content – reduces the effectiveness of air entraining agents (AEA)
- Water reducers can cause slight increase in shrinkage
- Water reducers have no detrimental effects on concrete durability

Supplemental Cementitious Materials

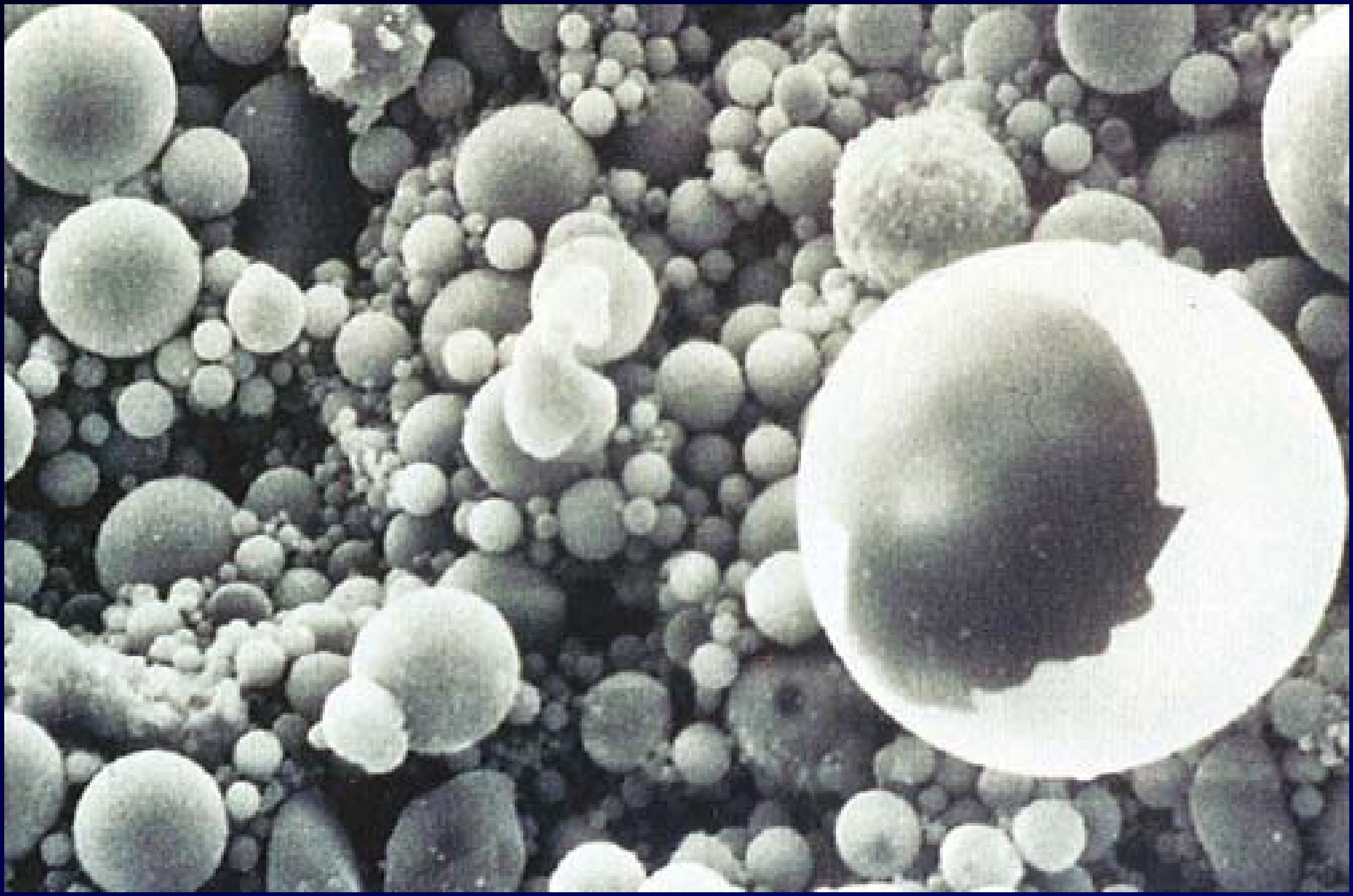
- What are they?
  - Fly ash (Type C)
  - Fly ash (Type F)
  - Silica fume
  - Ground granulated blast furnace slag (GGBFS)
  - Natural pozzolans
    - Metakaolin (Calcined clay)
    - Calcined shale

Supplemental Cementitious Materials

Supplemental Cementitious Materials

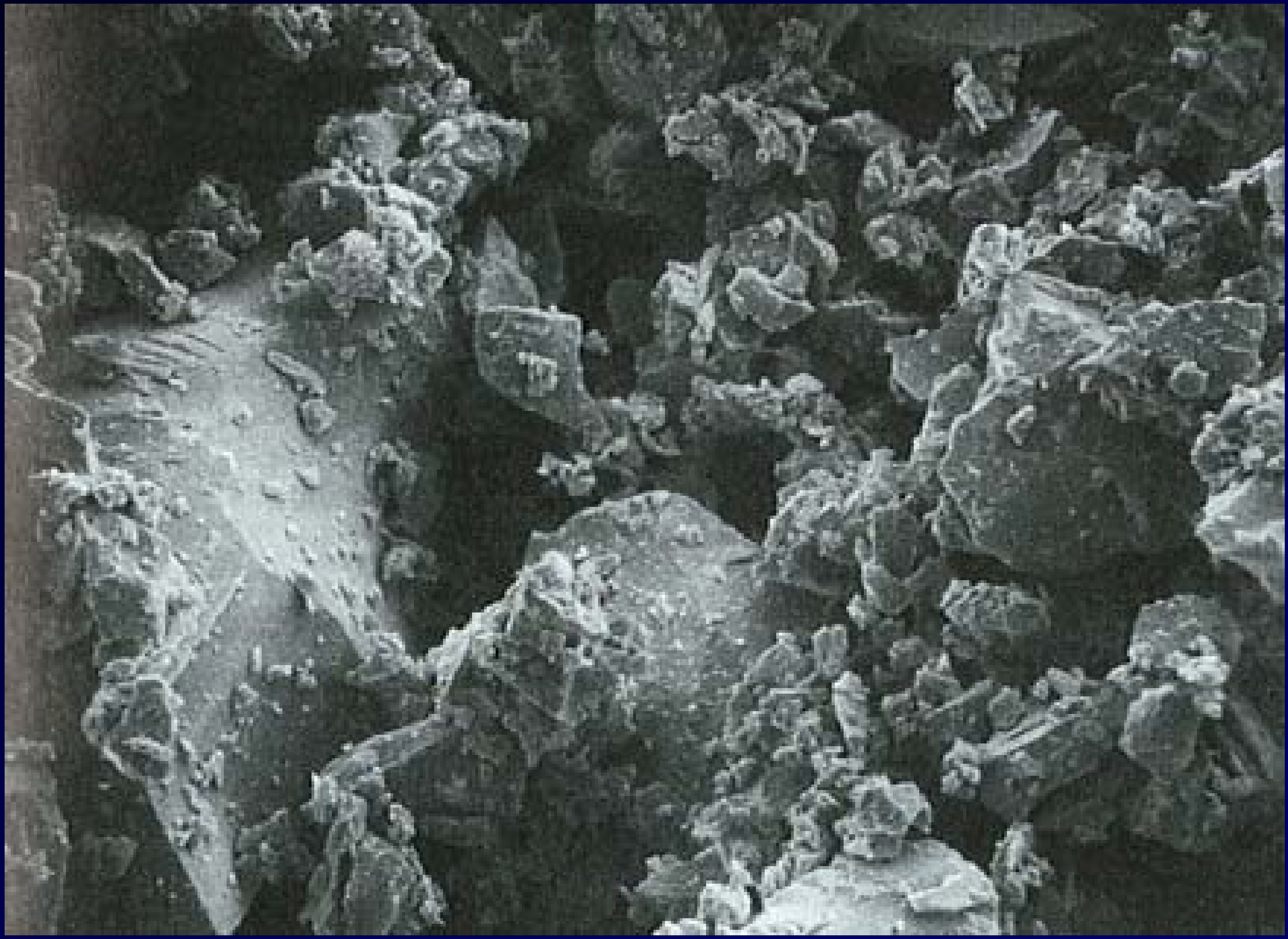
- Gets rid of a waste product (FA, SF, GGBFS)
- Adds a material that has cementing properties
- Reduces permeability
  - Particle size smaller than cement
  - Fills the voids between cement particles

Fly Ash Particles



1,000X

Slag Particles



2,100X

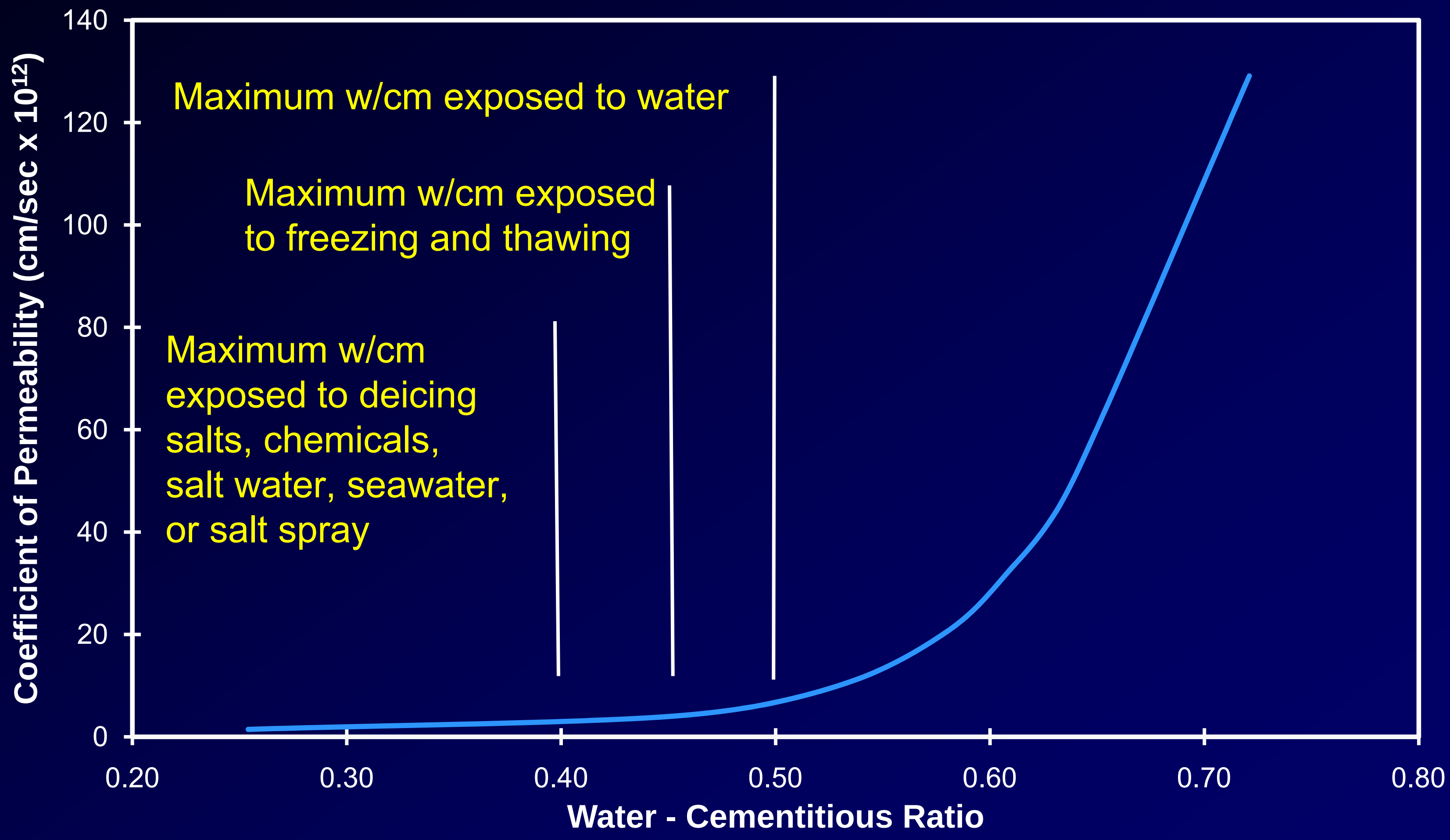
Silica Fume Particles

20,000X

Metakaolin Particles

2,000X

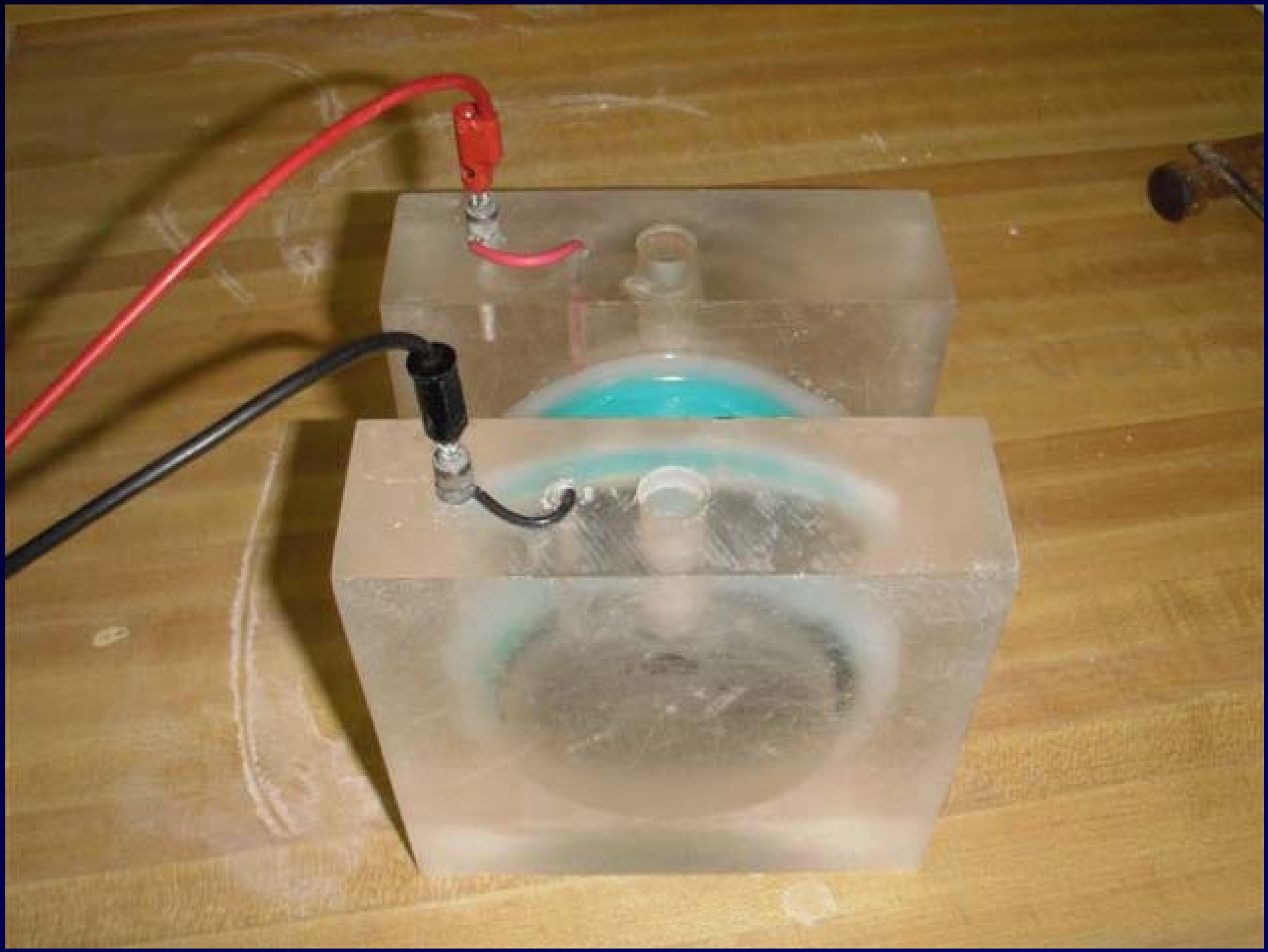
Concrete Permeability



Permeability Measurements

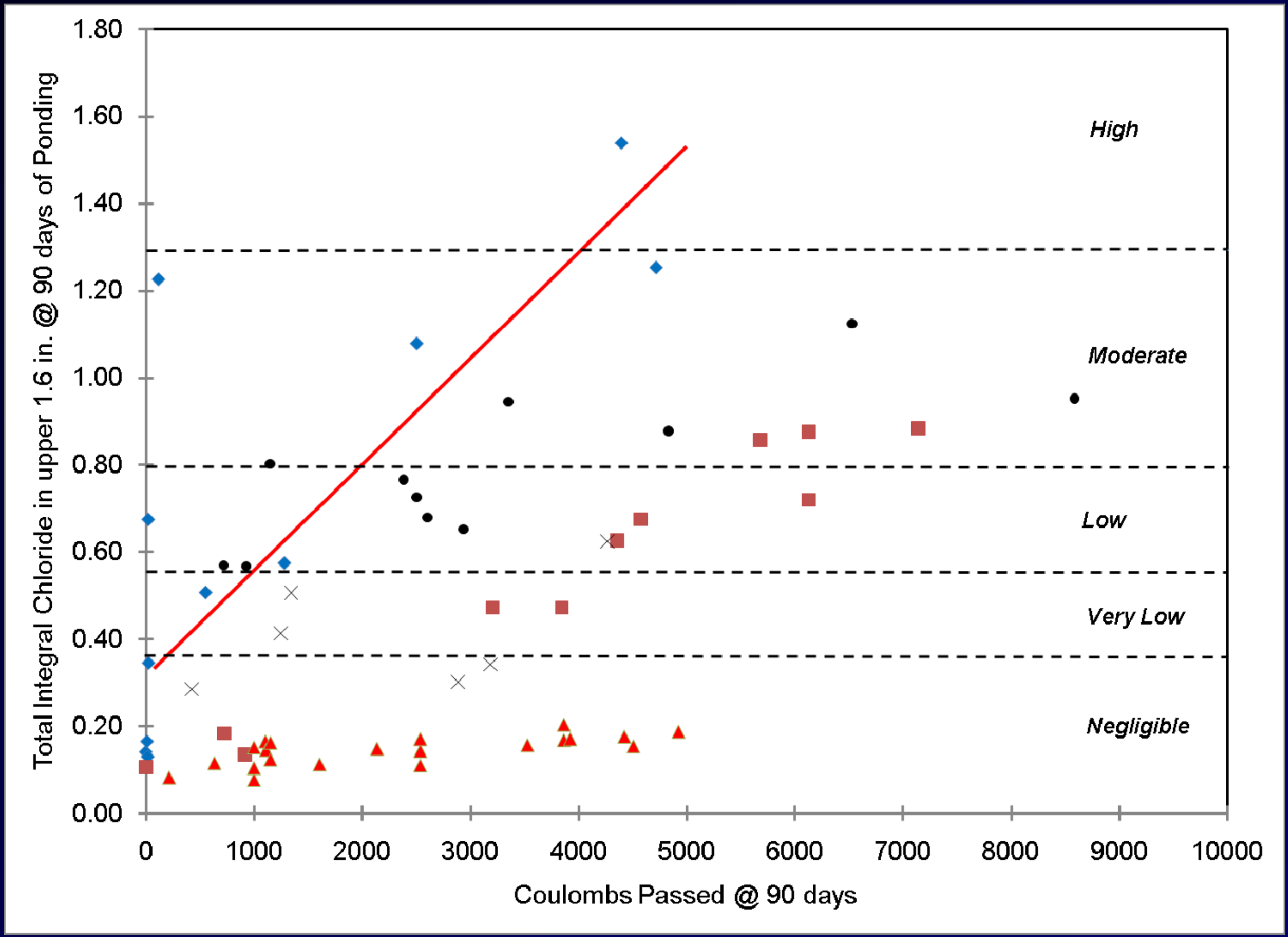
- Two methods exist to assess concrete permeability
  - ASTM C 1202, *Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration* - Rapid Chloride Penetration Test (RCPT)
  - AASHTO T259, *Resistance of Concrete to Chloride Ion Penetration* – 90-day ponding test

Rapid Chloride Permeability Test



90 Day Ponding Test

Permeability Measurement



Chemical Attack

- Carbonation
- Sulfate attack
- Acid attack
- Corrosion of embedded steel

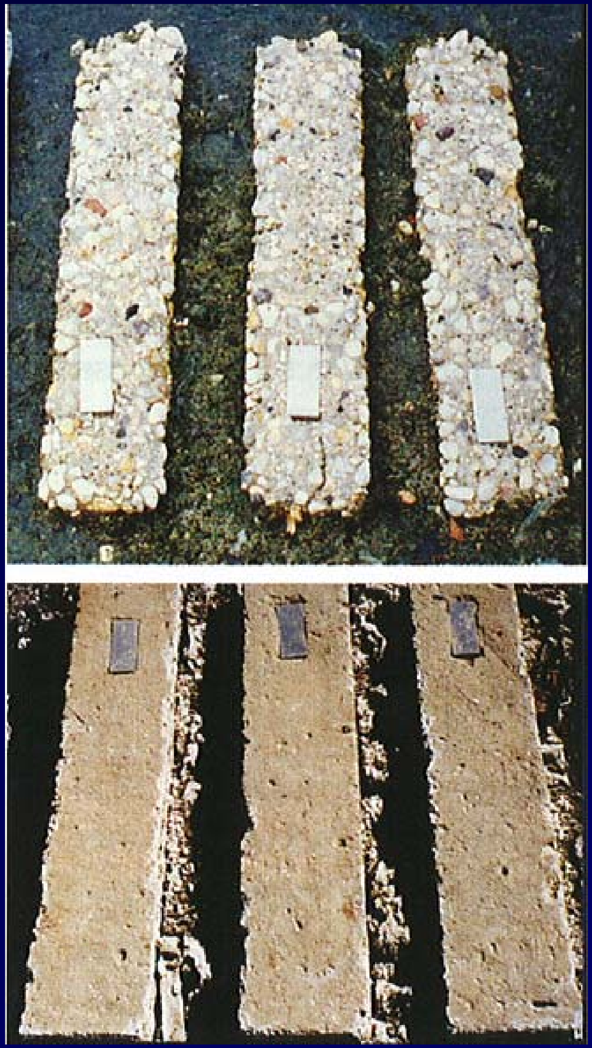
Carbonation

- Hardened concrete exposed to CO_2
- CO_2 penetrates concrete and reacts with hydroxides

Sulfate Attack

- Sulfates in soil, usually, react with hydrated compounds in hardened concrete
- Chemical reactions cause internal pressure
  - Disrupts the cement paste
- Internal compounds formed
  - Ettringite
  - Gypsum
  - Brucite (magnesium hydroxide)
  - Thaumasite (forms in moist conditions)

Sulfate Attack

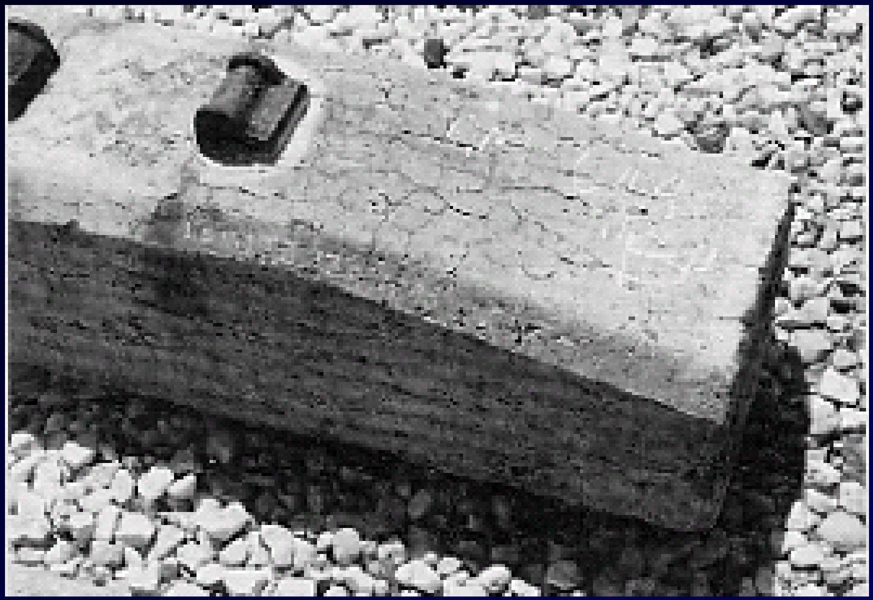


Sulfate Attack

Delayed Ettringite Formation

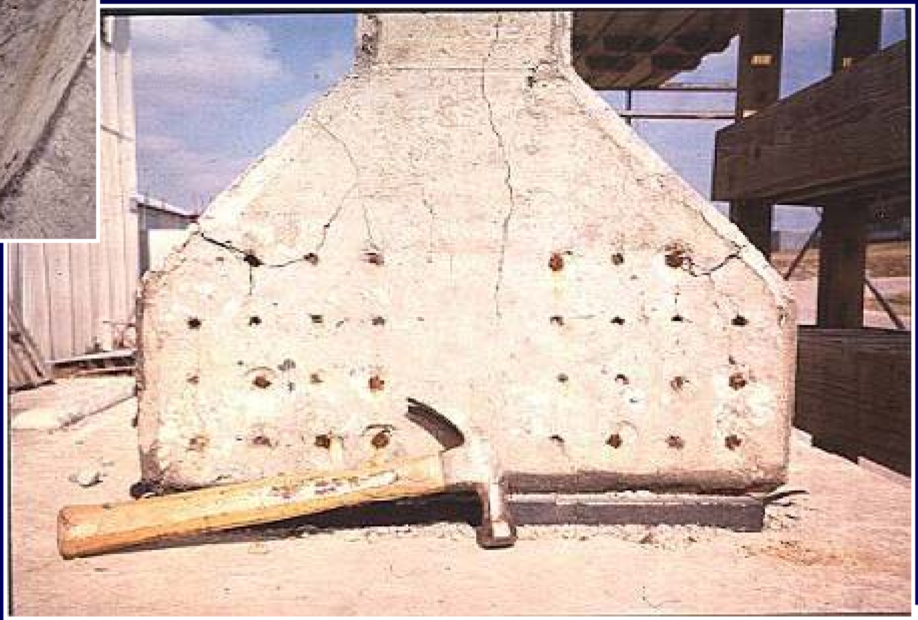
- DEF - Deleterious formation of ettringite
  - Form of sulfate attack
- Ettringite is normal component of cement hydration
- Late formation causes expansion distress
- Expansion causes cracking – premature deterioration
  - Found in many precast products

Delayed Ettringite Formation

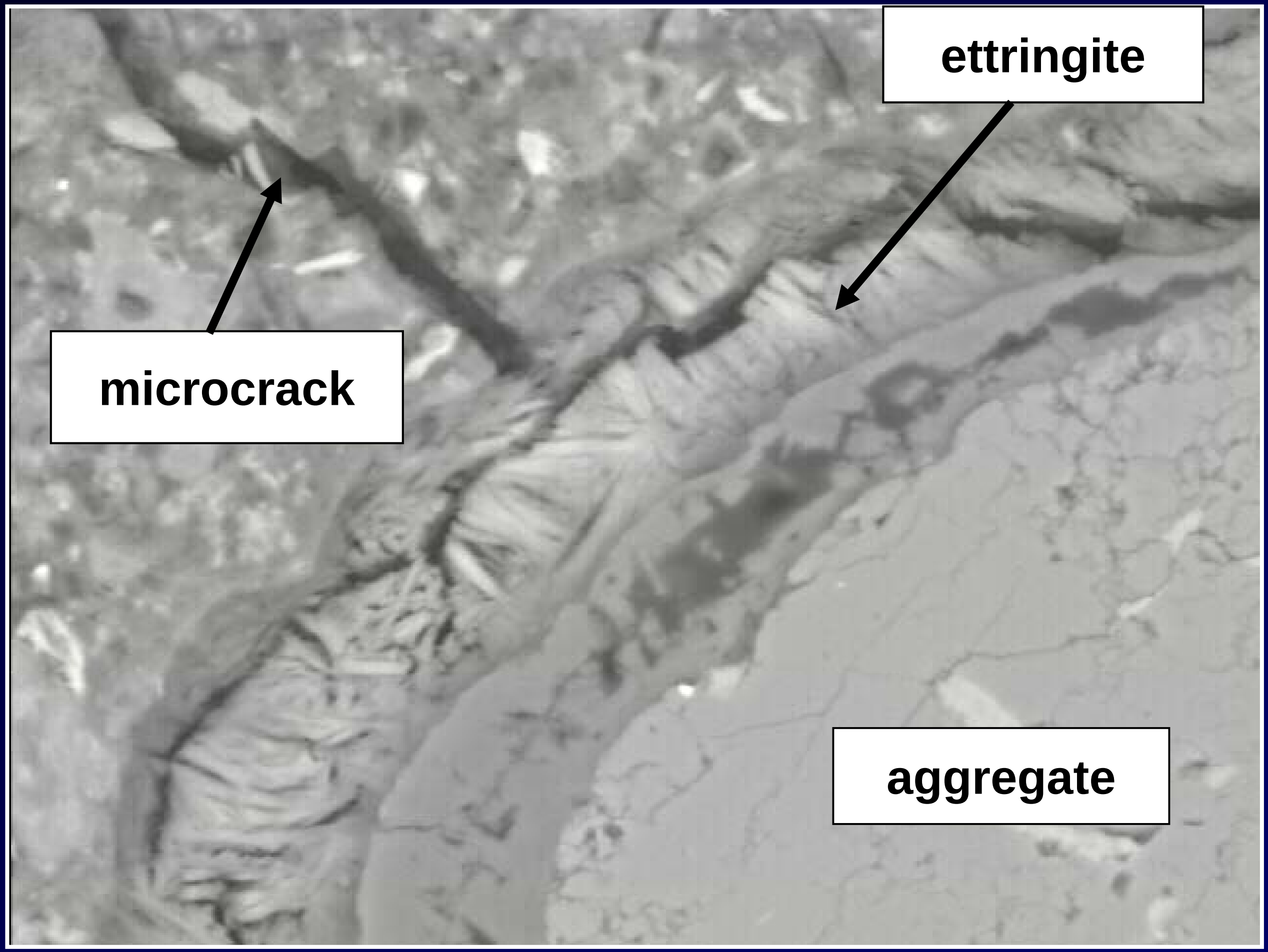


- Ettringite is compound that naturally forms when portland cement sets up
- Formation delayed by high initial temperatures (T ≥ 160 °F)
- Requires moisture

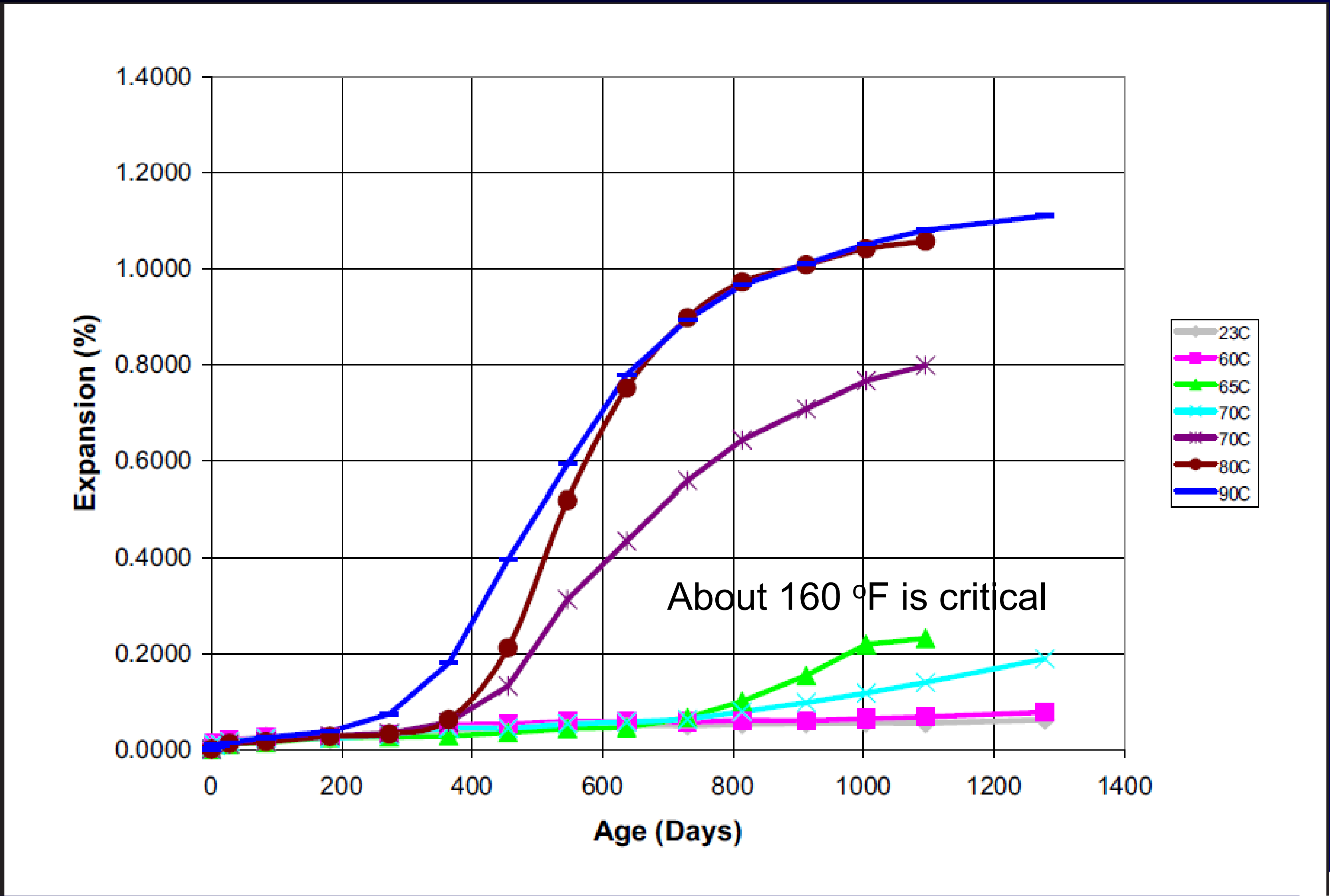
Delayed Ettringite Formation Examples



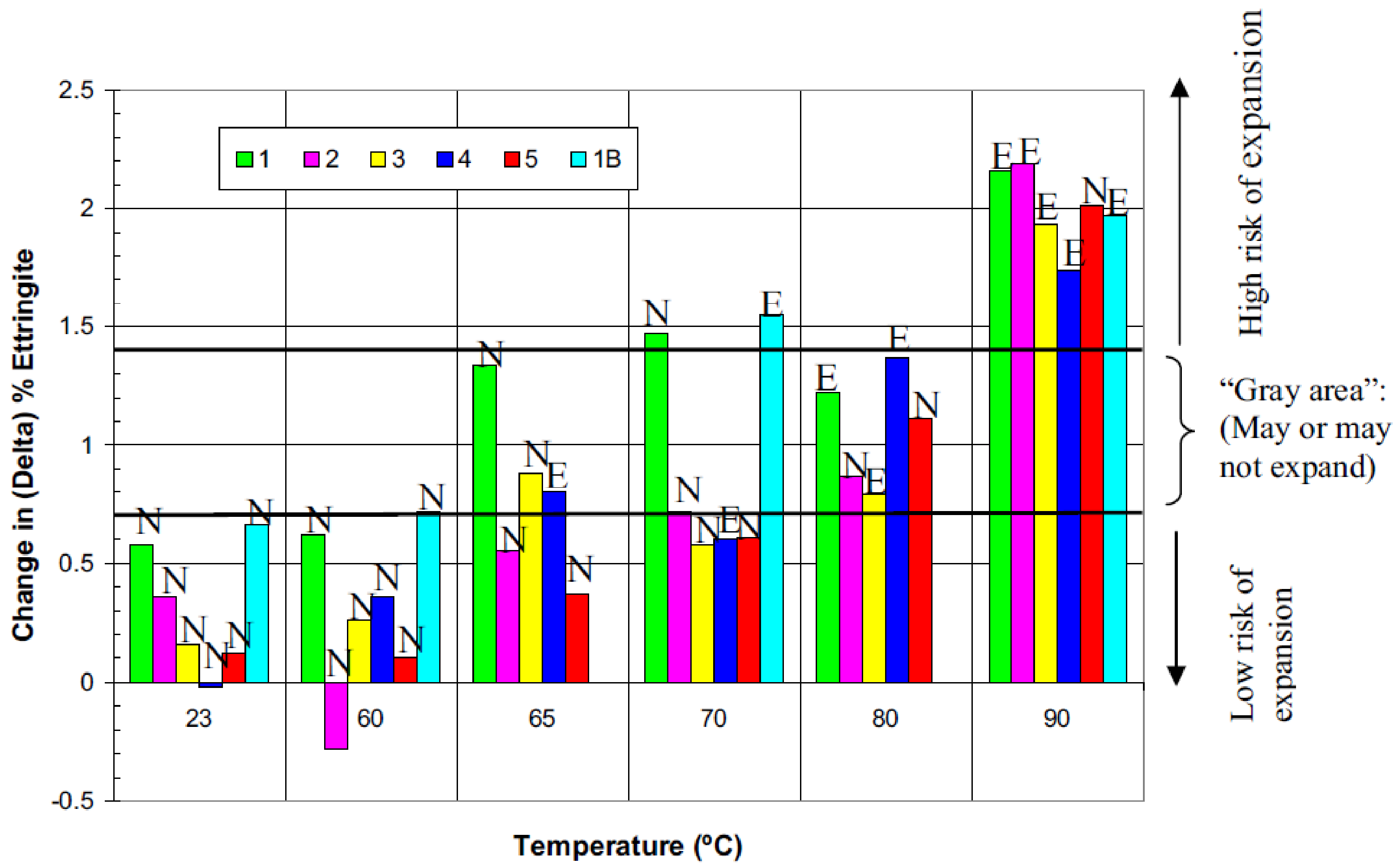
Delayed Ettringite Formation Microstructure



Delayed Ettringite Formation



Delayed Ettringite Formation



Acid Attack

- Some acids dissolve cement paste and calcareous (limestones) aggregates
- Protection for portland cement concrete is not feasible with “admixtures”
- Need a protection system (coating/surface treatment)
- ACI code does not cover external protection systems

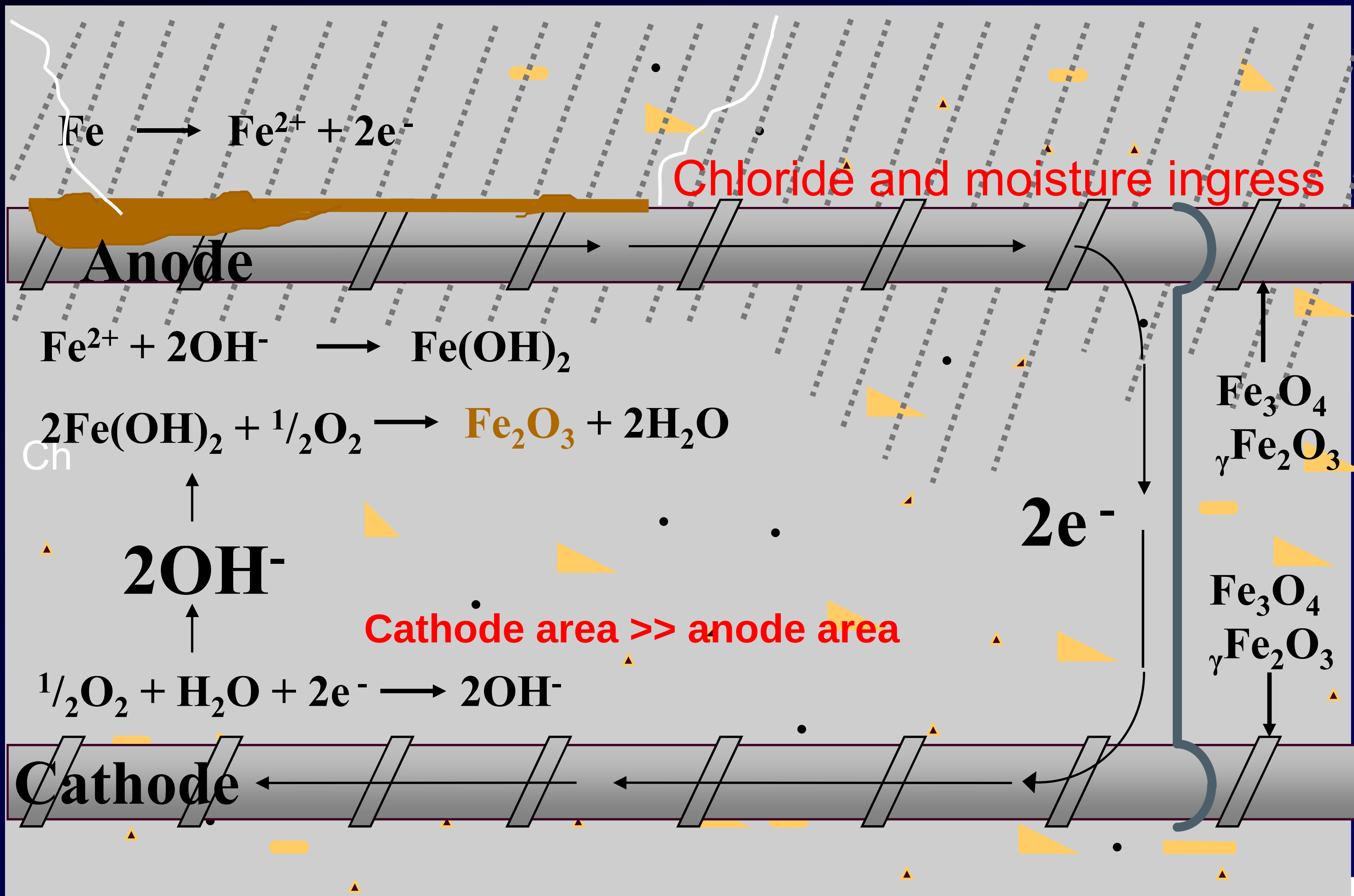
Paste erosion by acid attack

Level of paste erosion

Corrosion of Embedded Steel

- Objective - limit the ingress of chemicals that corrode reinforcing steel (chloride ions)
- Methodologies to limit corrosion by modifying the concrete
  - Decrease diffusion rate into concrete
  - Use chloride inhibitor admixtures
  - Cathodic protection
  - Eliminate cracking
  - Increase cover
  - Reduce the w/cm ratio

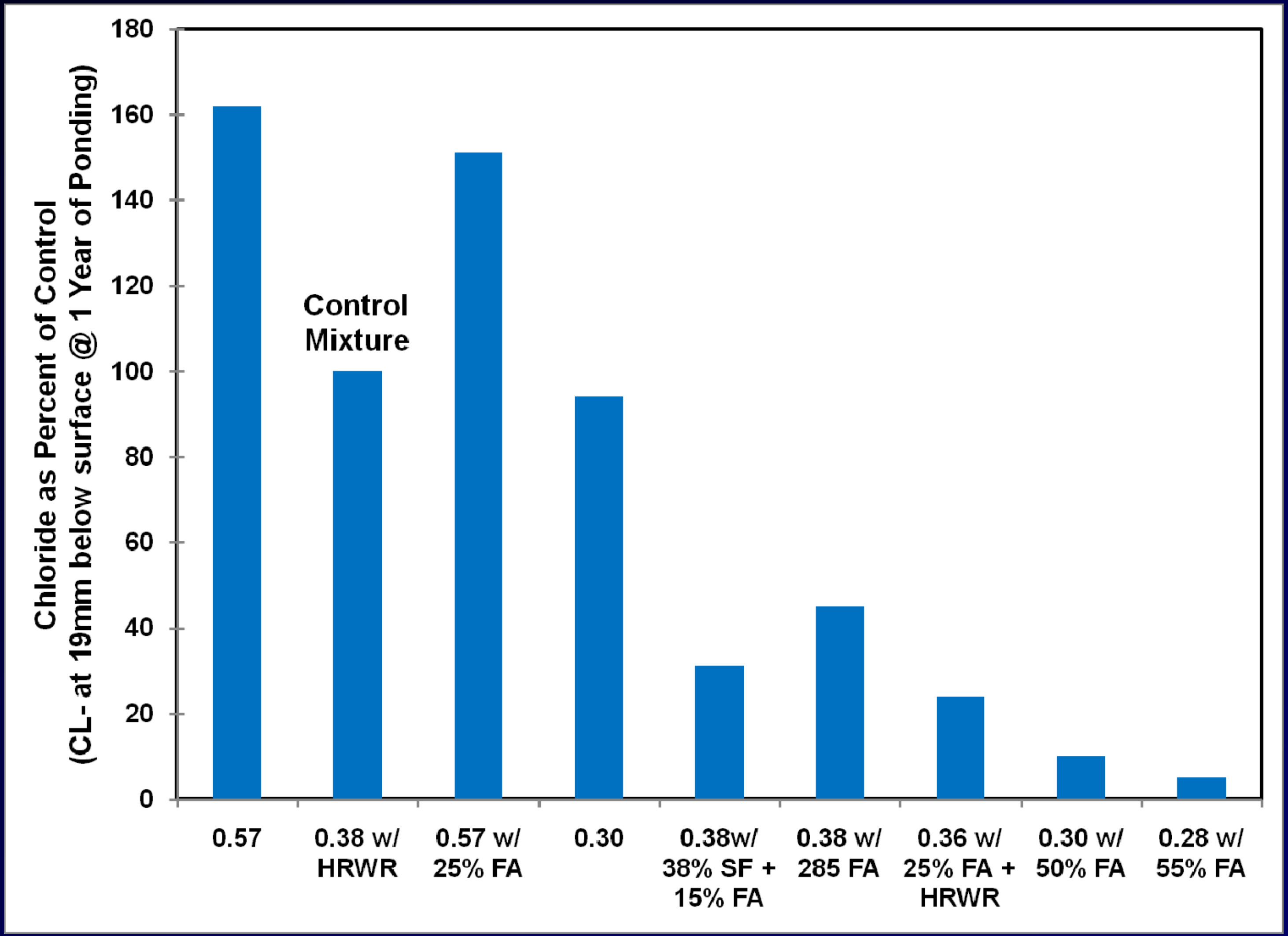
Corrosion of Uncoated Steel



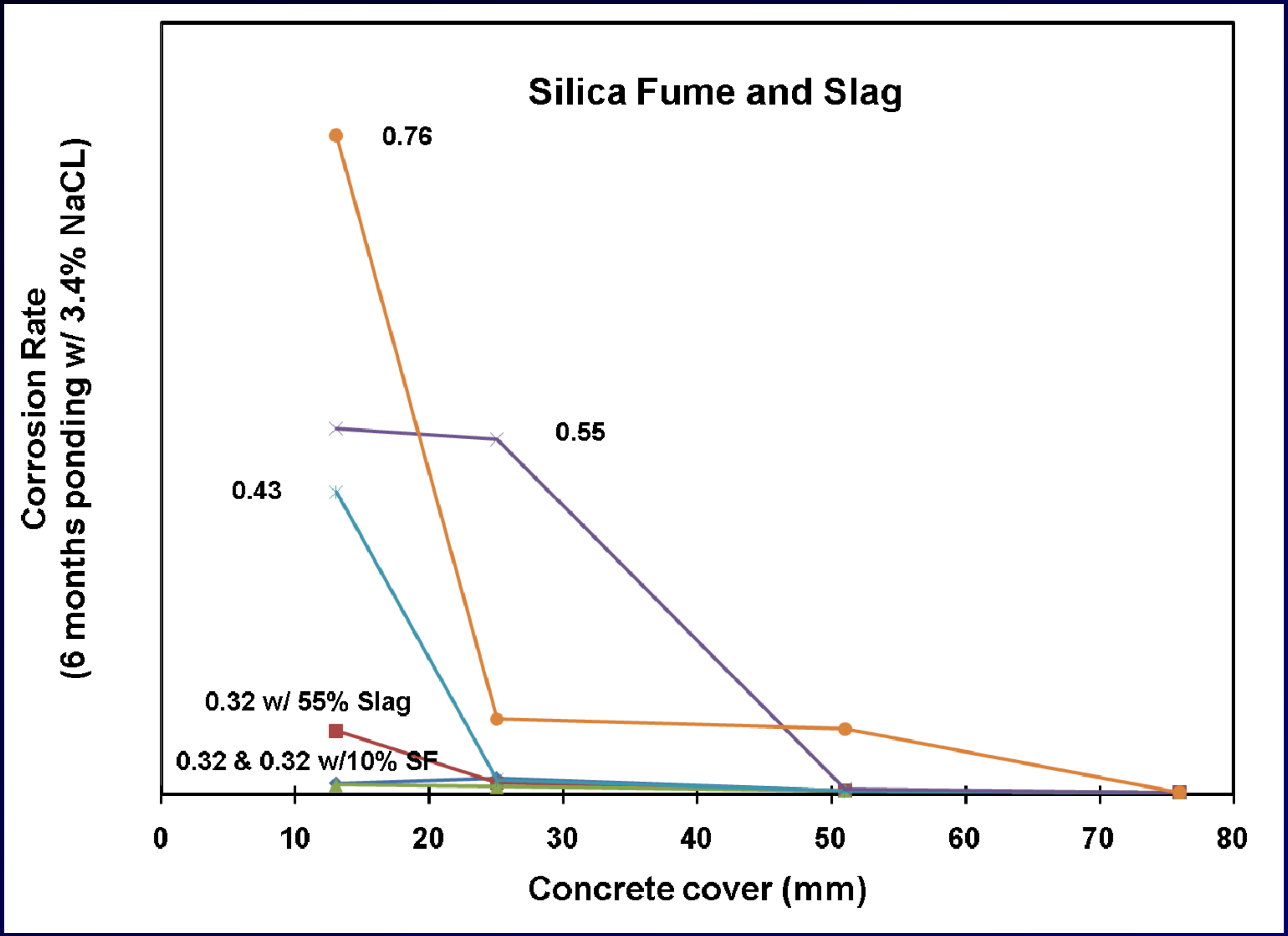
Diffusion

- Use supplemental cementitious materials
  - Fly ash
  - Silica fume
  - GGBFS
  - Natural pozzolans (Metakaolin)

Diffusion - Fly Ash



Diffusion - SF & GGBSF



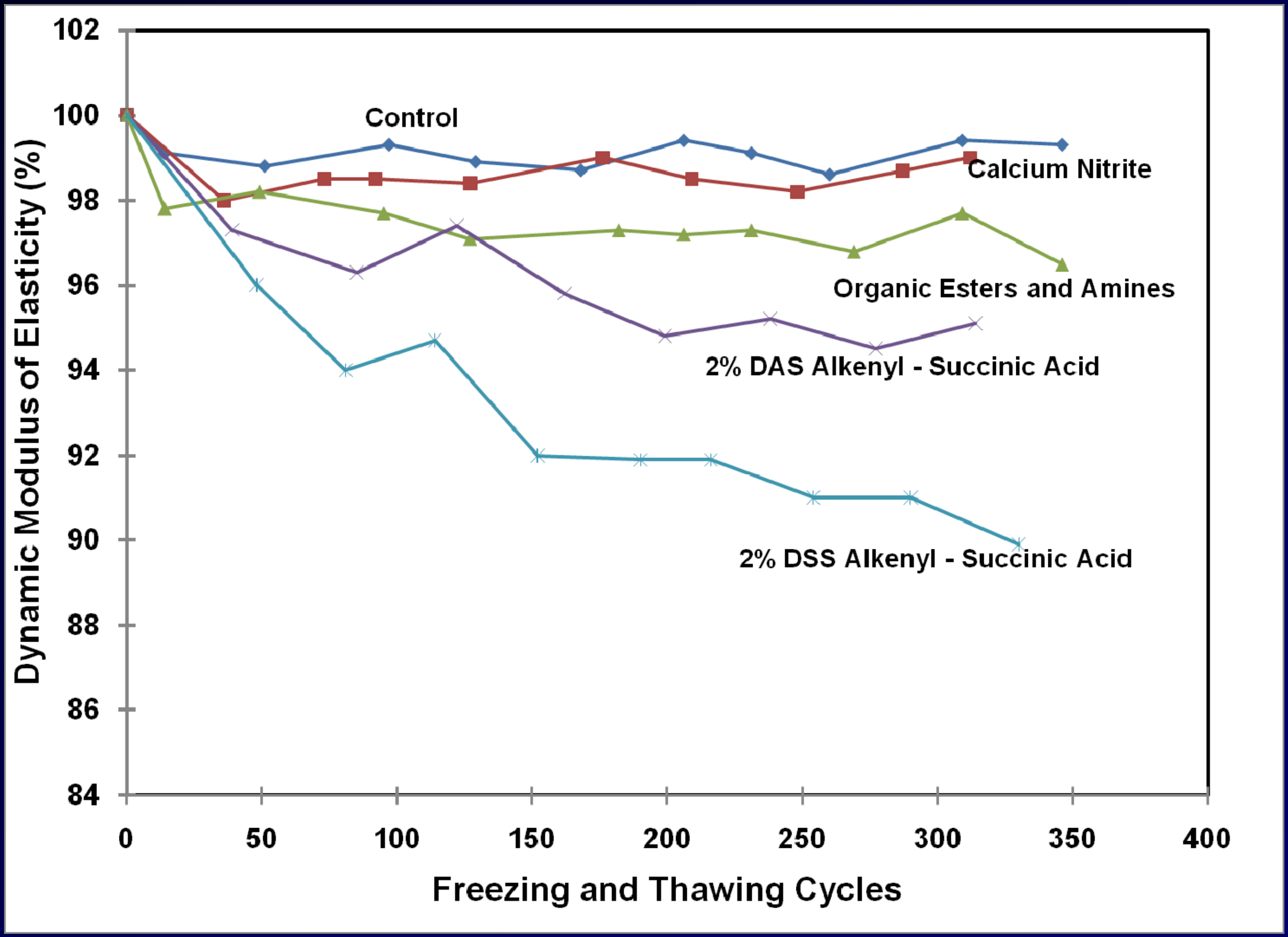
Corrosion Inhibitor Types

- Calcium Nitrite
- Organic Esters and amines
- Amino alcohol
- Alkenly-succinic acids

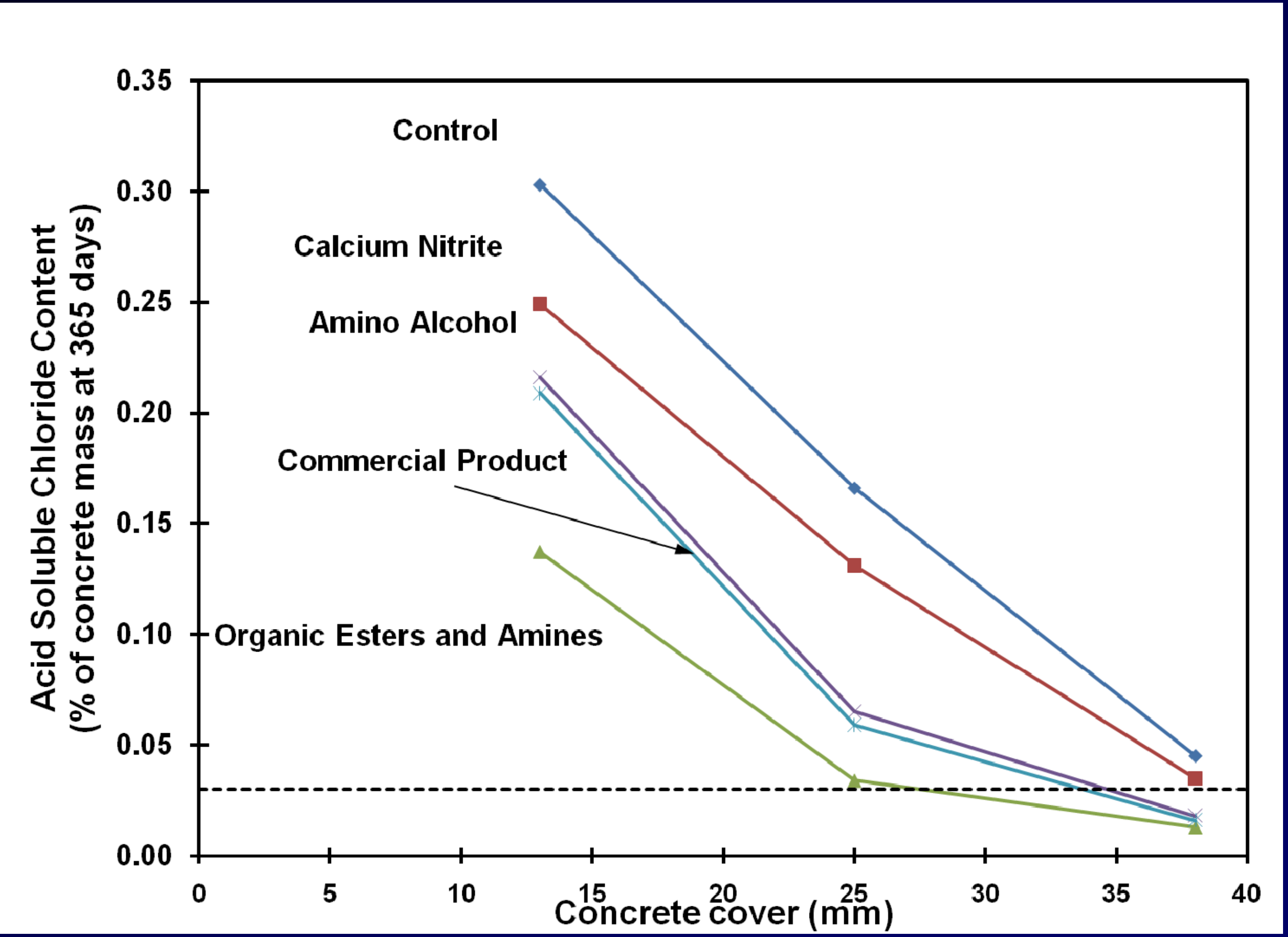
Corrosion Inhibitors

- Consequences of using inhibitors
  - Influence on freezing and thawing resistance
  - Influence on inhibiting corrosion – uncracked concrete

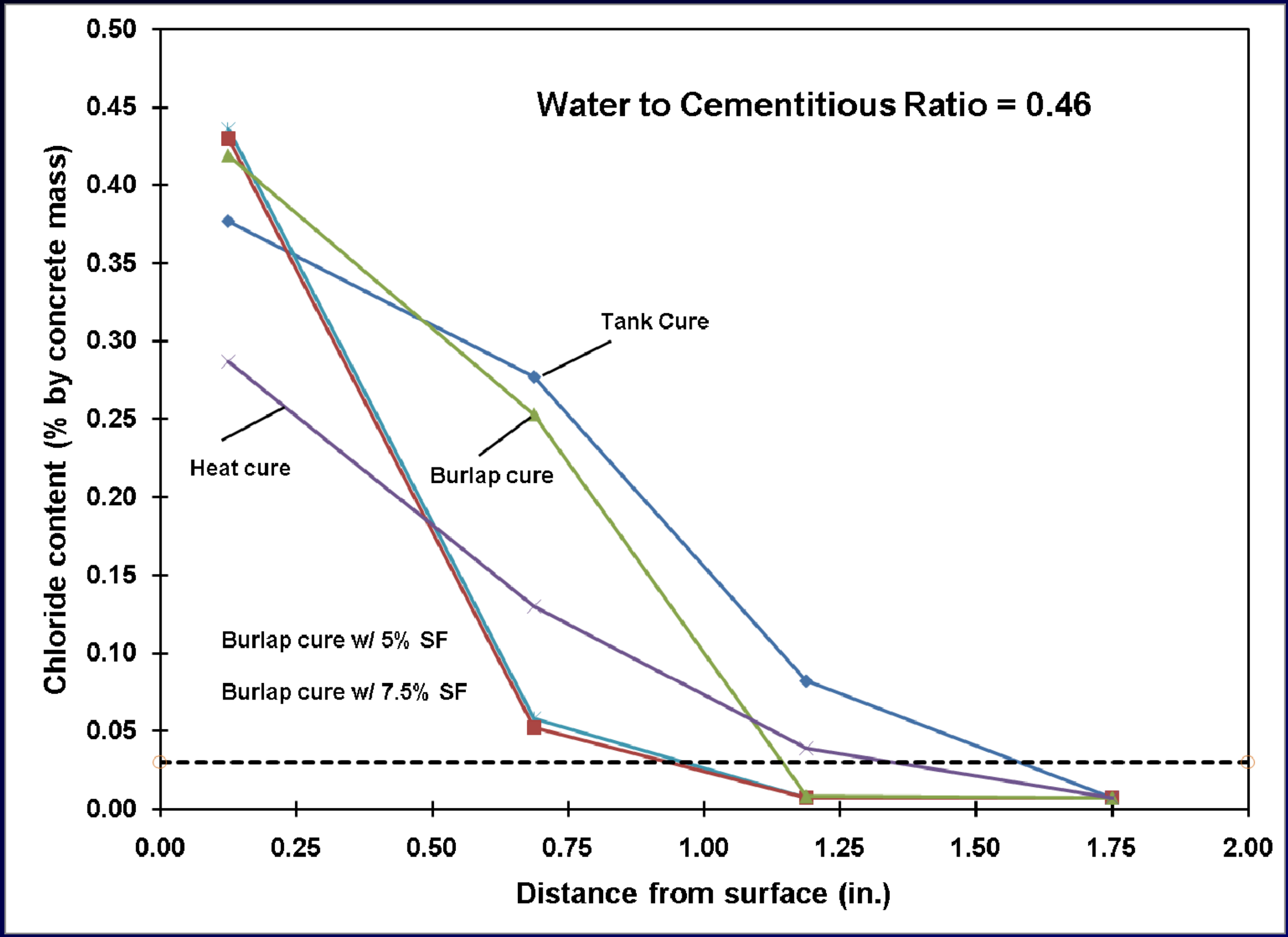
Corrosion Inhibitors – Freezing/Thawing



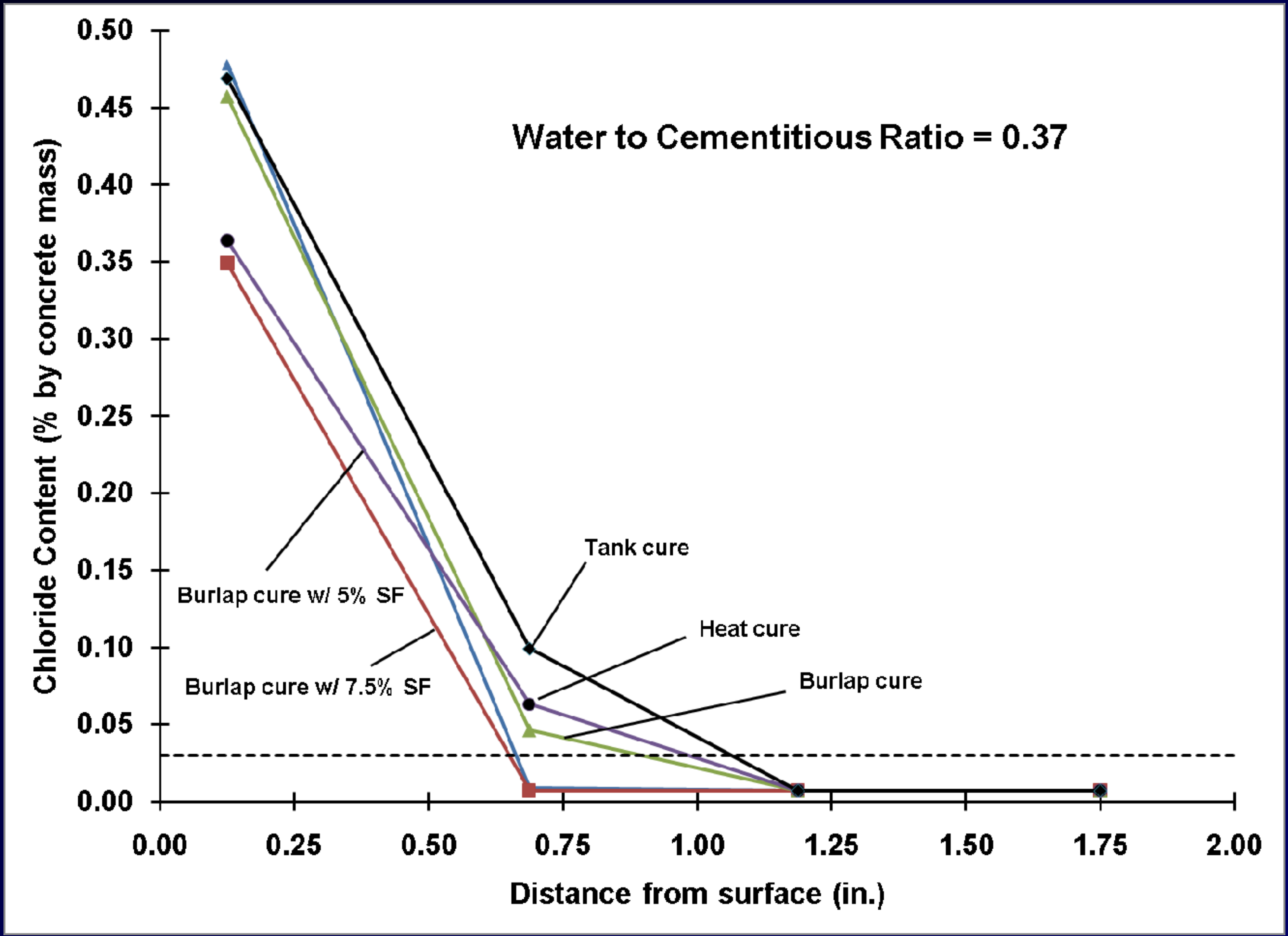
Corrosion Inhibitors – Chloride Ingress



Corrosion and Chloride Ingress



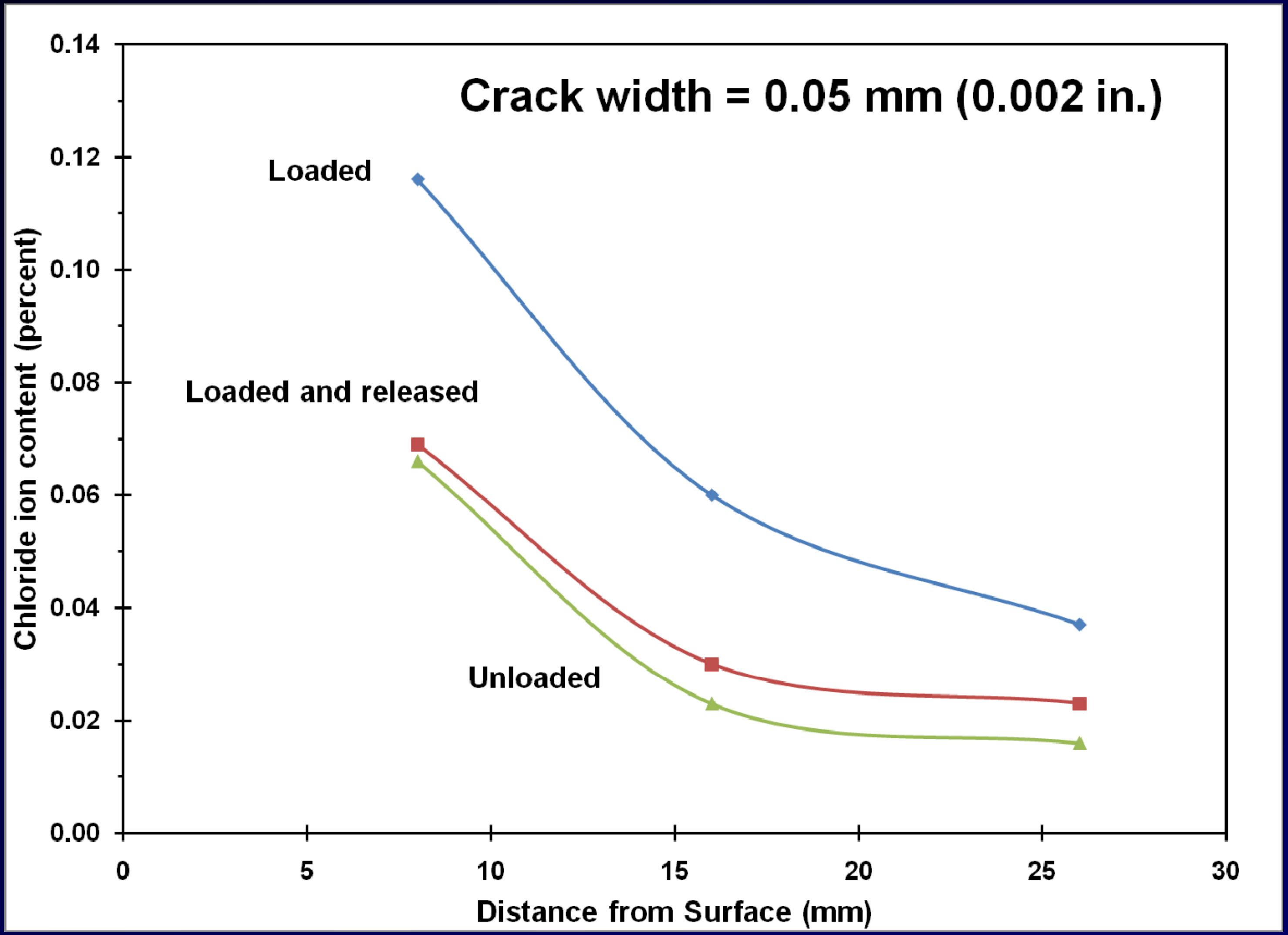
Corrosion and Chloride Ingress



Cracking

- Cracking exists in reinforced concrete structures

Cracking - Width



ACI 318 Code

- ACI 318 Chapter 4 – Durability Requirements
  - Exposure Categories and Classes
    - Freezing and thawing (F)
    - Sulfate (S)
    - Low permeability (P)
    - Corrosion protection of steel reinforcing (C)

Exposure Categories and Classes - Freezing and Thawing

- Exposure category F
  - Exterior concrete
  - Exposed to freezing and thawing
  - Possible exposure to deicing chemicals
- Four Classes
  - F0 – Not exposed to freezing and thawing (f-t)
  - F1 – Occasionally exposed to moisture and f-t
  - F2 – Exposed to f-t and continuous contact with moisture before freezing
  - F3 - Continuous contact with moisture, f-t, and deicing chemicals

Exposure Categories and Classes - Sulfate Attack

- Exposure category S
  - Concrete in contact with soil or water containing deleterious amounts of soluble sulfate
- Four Classes
  - S0 – Very low exposure
  - S1 – Structural member in contact with soluble sulfate (moderate) [seawater]
  - S2 – Structural member in contact with soluble sulfate (severe)
  - S3 - Structural member in contact with soluble sulfate : high sulfate content (very severe)

Exposure Categories and Classes - Concrete Permeability

- Exposure category P
  - Concrete in contact with water where low permeability is needed
- Two Classes
  - P0 – No specific permeability needed
  - P1 – Needed where water permeation into concrete might reduce durability [water tank]

Exposure Categories and Classes - Corrosion of Embedded Metals

- Exposure category C
  - Concrete that contains embedded reinforcing and prestressing steel requiring protection (protection by concrete)
- Three Classes
  - C0 – Concrete in dry environment
  - C1 – Exposed to moisture but no chlorides
  - C2 – Concrete exposed to moisture and chlorides (deicing chemicals, brackish water, seawater, seawater spray) [parking decks, bridge decks, piers]

ACI 318 Requirements

- Select concrete mixture based on exposure class

TABLE 4.3.1 — REQUIREMENTS FOR CONCRETE BY EXPOSURE CLASS

Exposure Class	Max. *w/cm**	Min. f'_c, psi	Additional minimum requirements			
			Air content			Limits on cementitious materials
F0	N/A	2500	N/A			N/A
F1	0.45	4500	Table 4.4.1			N/A
F2	0.45	4500	Table 4.4.1			N/A
F3	0.45	4500	Table 4.4.1			Table 4.4.2
			Cementitious materials†—types			Calcium chloride admixture
			ASTM C150	ASTM C595	ASTM C1157	
S0	N/A	2500	No Type restriction	No Type restriction	No Type restriction	No restriction
S1	0.50	4000	II‡	IP(MS), IS (<70) (MS)	MS	No restriction
S2	0.45	4500	V§	IP (HS) IS (<70) (HS)	HS	Not permitted
S3	0.45	4500	V + pozzolan or slag‖	IP (HS) + pozzolan or slag‖ or IS (<70) (HS) + pozzolan or slag‖	HS + pozzolan or slag‖	Not permitted
P0	N/A	2500	None			
P1	0.50	4000	None			
			Maximum water-soluble chloride ion (Cl^-) content in concrete, percent by weight of cement#			
			Reinforced concrete	Prestressed concrete	Related provisions	
C0	N/A	2500	1.00	0.06	None	
C1	N/A	2500	0.30	0.06	None	
C2	0.40	5000	0.15	0.06	7.7.6, 18.16**	

Category F

- Maximum w/cm<0.45
- F0 Minimum f_c'>2500
- Minimum f_c' > 4500
- Entrained air content

Nominal maximum aggregate size, in.*	Air content, percent	
	Exposure Class F1	Exposure Classes F2 and F3
3/8	6	7.5
1/2	5.5	7
3/4	5	6
1	4.5	6
1-1/2	4.5	5.5
2†	4	5
3†	3.5	4.5

- For F3 use supplemental cementitious materials

Cementitious materials	Maximum percent of total cementitious materials by weight*
Fly ash or other pozzolans conforming to ASTM C618	25
Slag conforming to ASTM C989	50
Silica fume conforming to ASTM C1240	10
Total of fly ash or other pozzolans, slag, and silica fume	50†
Total of fly ash or other pozzolans and silica fume	35†

Category S

- Use sulfate resistant cement
  - Type II
  - Type V
- Maximum w/cm ratio
- Minimum f_c'
- No chlorides allowed for S2 and S3

			Cementitious materials[†]—types			Calcium chloride admixture
			ASTM C150	ASTM C595	ASTM C1157	
S0	N/A	2500	No Type restriction	No Type restriction	No Type restriction	No restriction
S1	0.50	4000	II[‡]	IP(MS), IS (<70) (MS)	MS	No restriction
S2	0.45	4500	V[§]	IP (HS) IS (<70) (HS)	HS	Not permitted
S3	0.45	4500	V + pozzolan or slag[ll]	IP (HS) + pozzolan or slag[ll] or IS (<70) (HS) + pozzolan or slag[ll]	HS + pozzolan or slag[ll]	Not permitted

Category P

- Minimal requirements
- Maximum w/cm ratio
  < 0.50
- Minimum f_c' > 4000

P0	N/A	2500	None
P1	0.50	4000	None

Category C

- Minimum f_c'> 5000 psi for severe exposure
- Maximum w/cm<0.40
- Control chlorides in mixture
- Control chloride exposure

			Maximum water-soluble chloride ion (Cl^-) content in concrete, percent by weight of cement[#]		Related provisions
			Reinforced concrete	Prestressed concrete	
C0	N/A	2500	1.00	0.06	None
C1	N/A	2500	0.30	0.06	
C2	0.40	5000	0.15	0.06	7.7.6, 18.16[**]

Construction type and condition	Chloride limit, percent by mass		
	Test method		
	Acid soluble	Water soluble	
	ASTM C1152	ASTM C1218	Soxhlet[*]
Prestressed concrete	0.08	0.06	0.06
Reinforced concrete wet in service	0.10	0.08	0.08
Reinforced concrete dry in service	0.20	0.15	0.15

[*]The Soxhlet test method is described in ACI 222.1.[4.8]

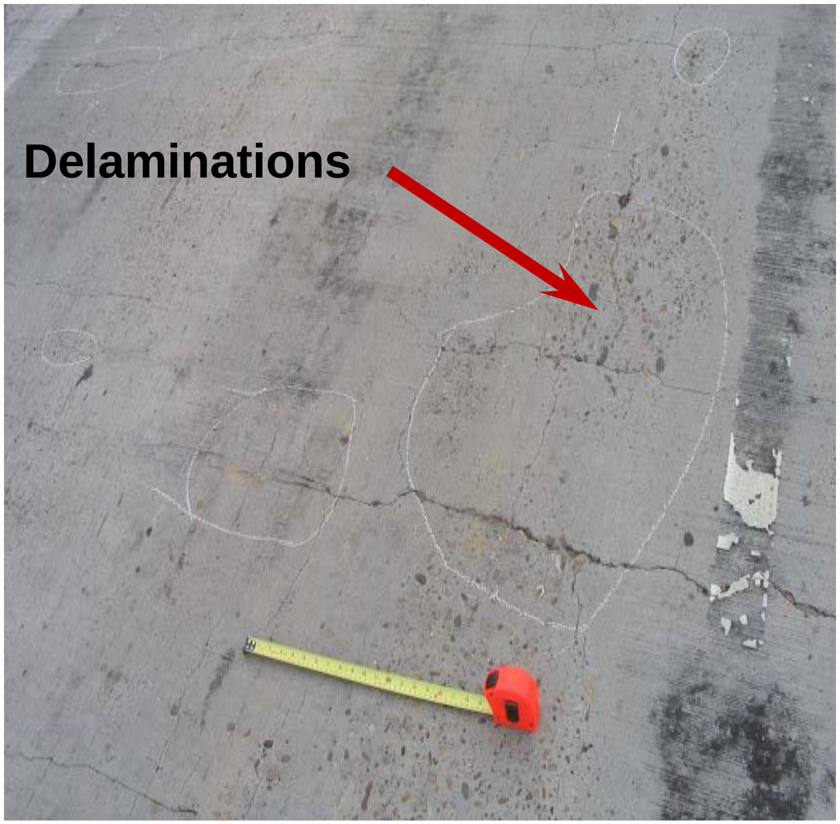
Summary Durable Concrete Structures

- Low w/cm concrete effective in controlling chloride ingress
- Supplementary cementitious can reduce chloride ingress rate
- Corrosion inhibitors can extend service life
- Heat curing below 160 ^{o}F can reduce permeability
- Air entrainment necessary in freezing environments

External Protection Schemes

- FHWA sponsored research 1992
- Objective
  - Find cost-effective coatings or alternate materials
  - Design life for infrastructure facilities: 75 to 100 years

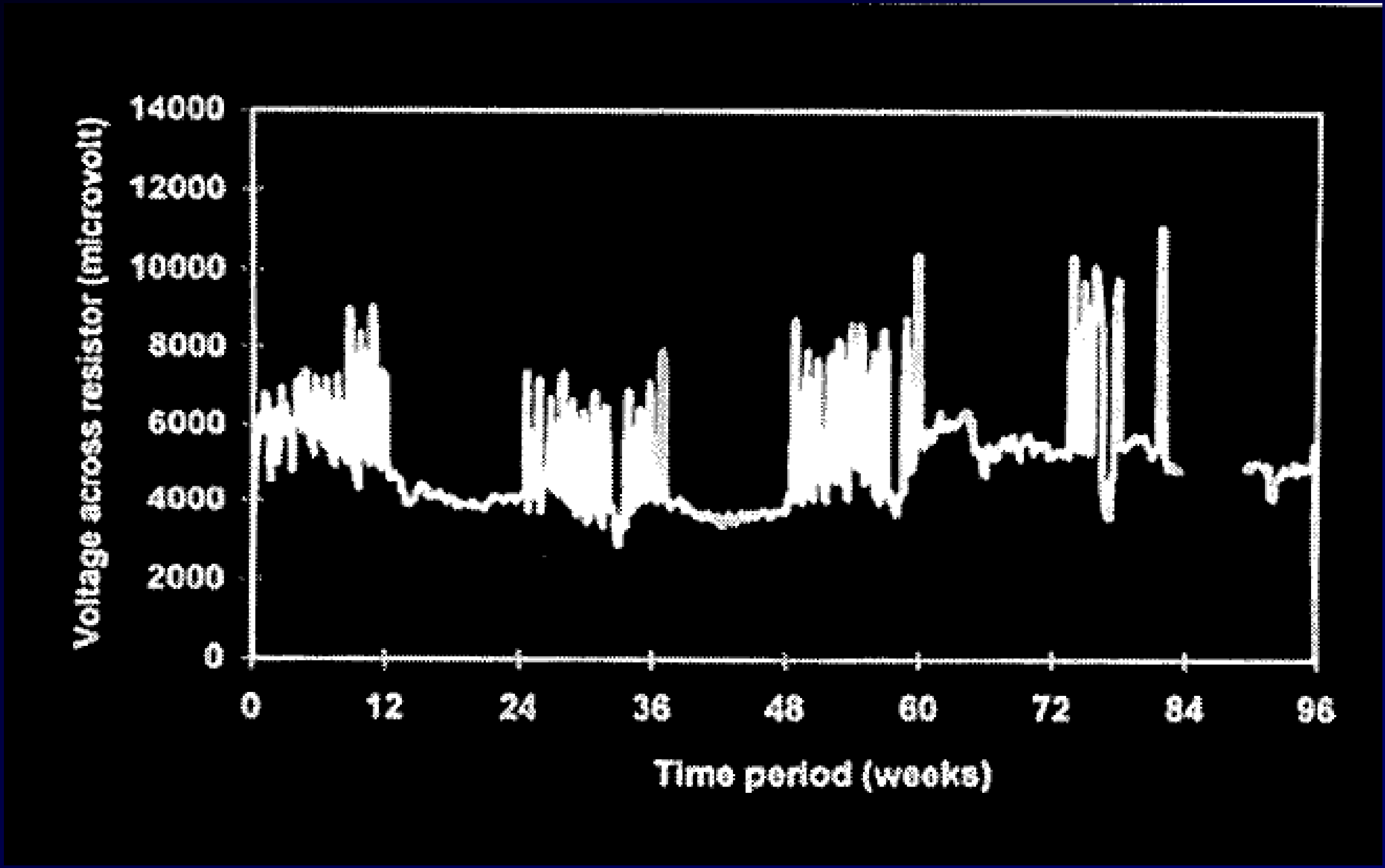
Corrosion of Reinforcing Bars



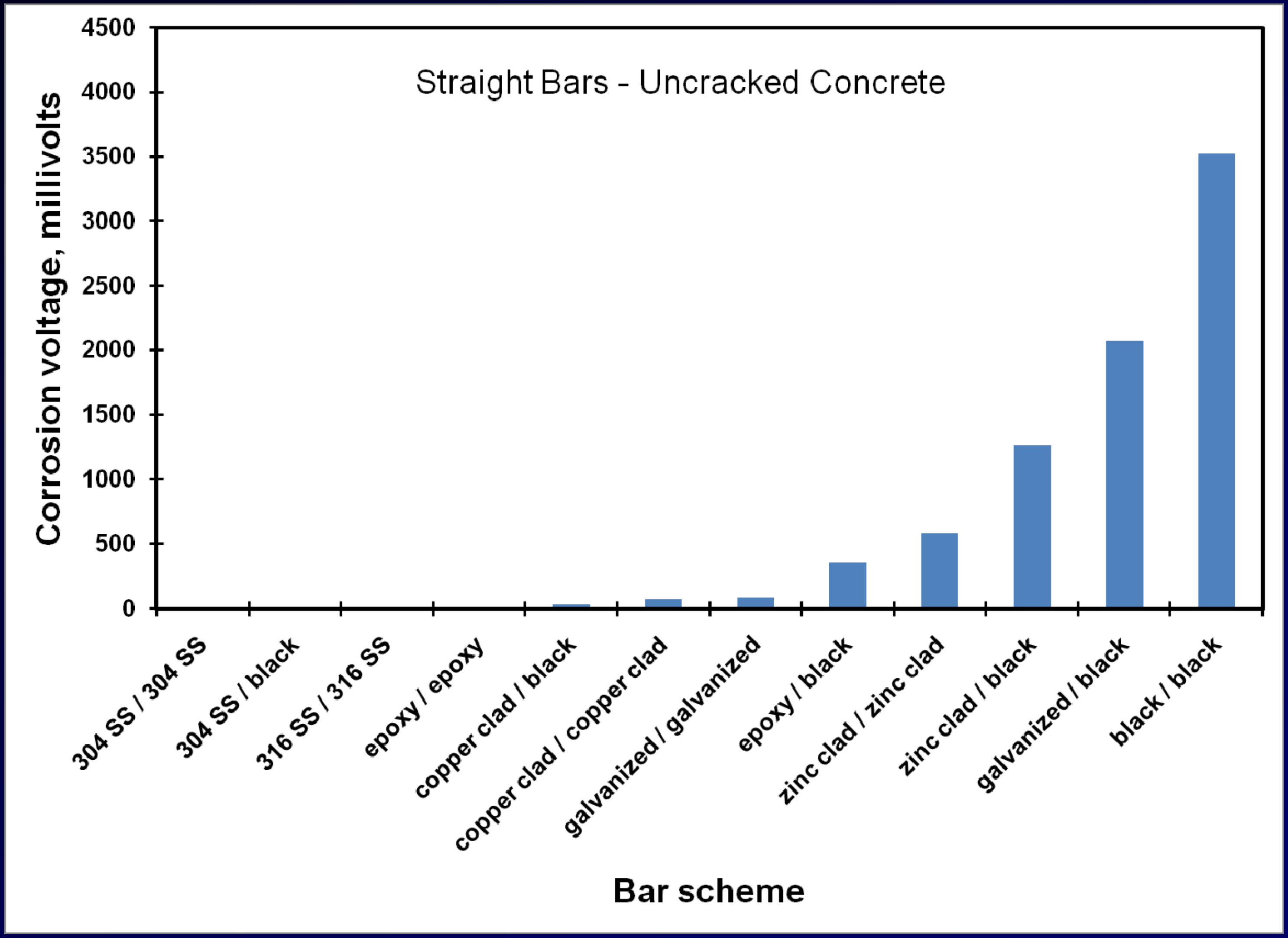
Alternate Reinforcing Bar Types

- ASTM A 615 / A 706 black
- Epoxy coated bars
  - Bendable
  - Nonbendable
- Galvanized bars
- Metallic-clad bars
  - Zinc
  - Copper
  - Stainless
- Metallic corrosion resistant bars (stainless)

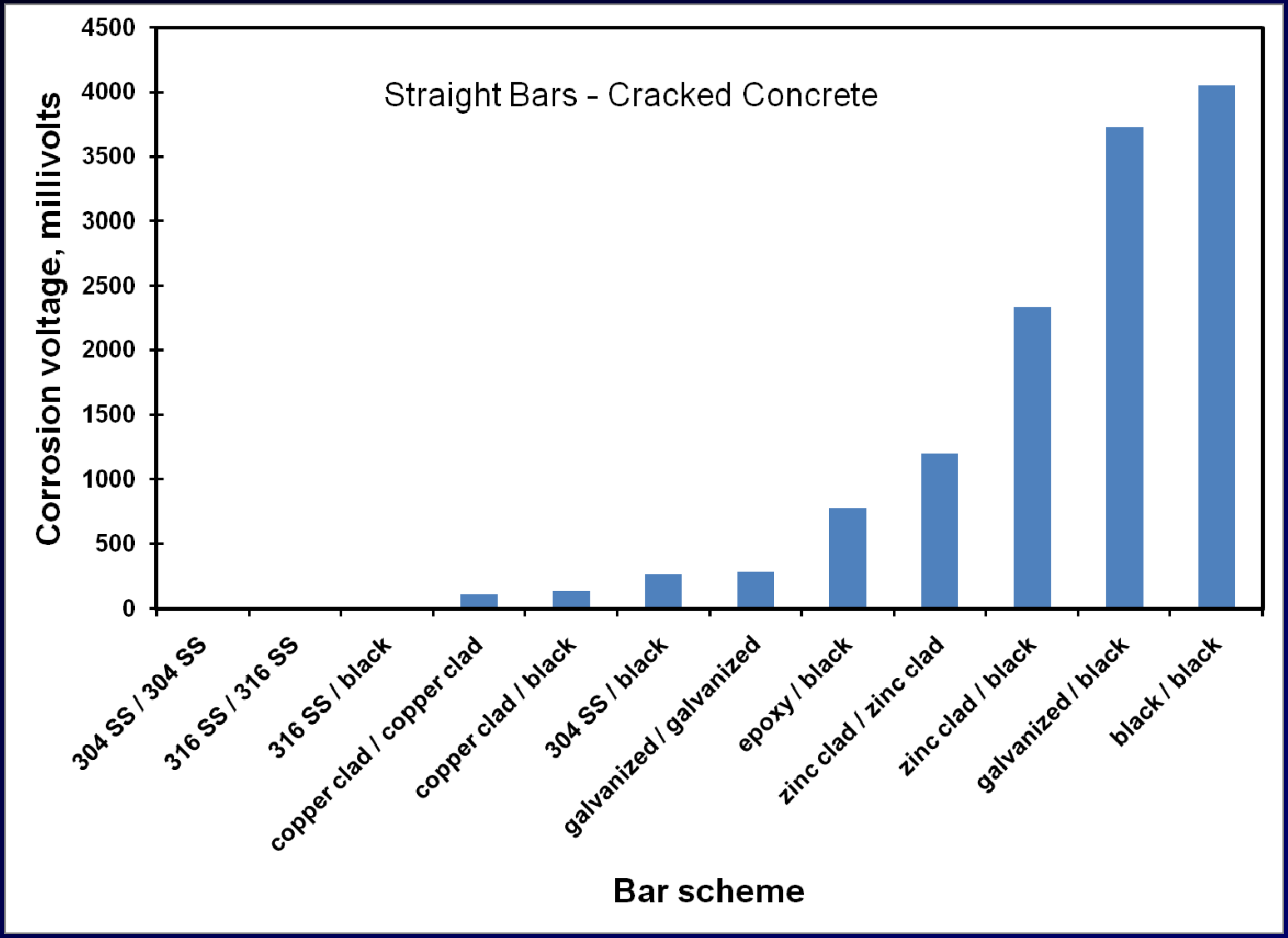
Wetting and Drying Regimes



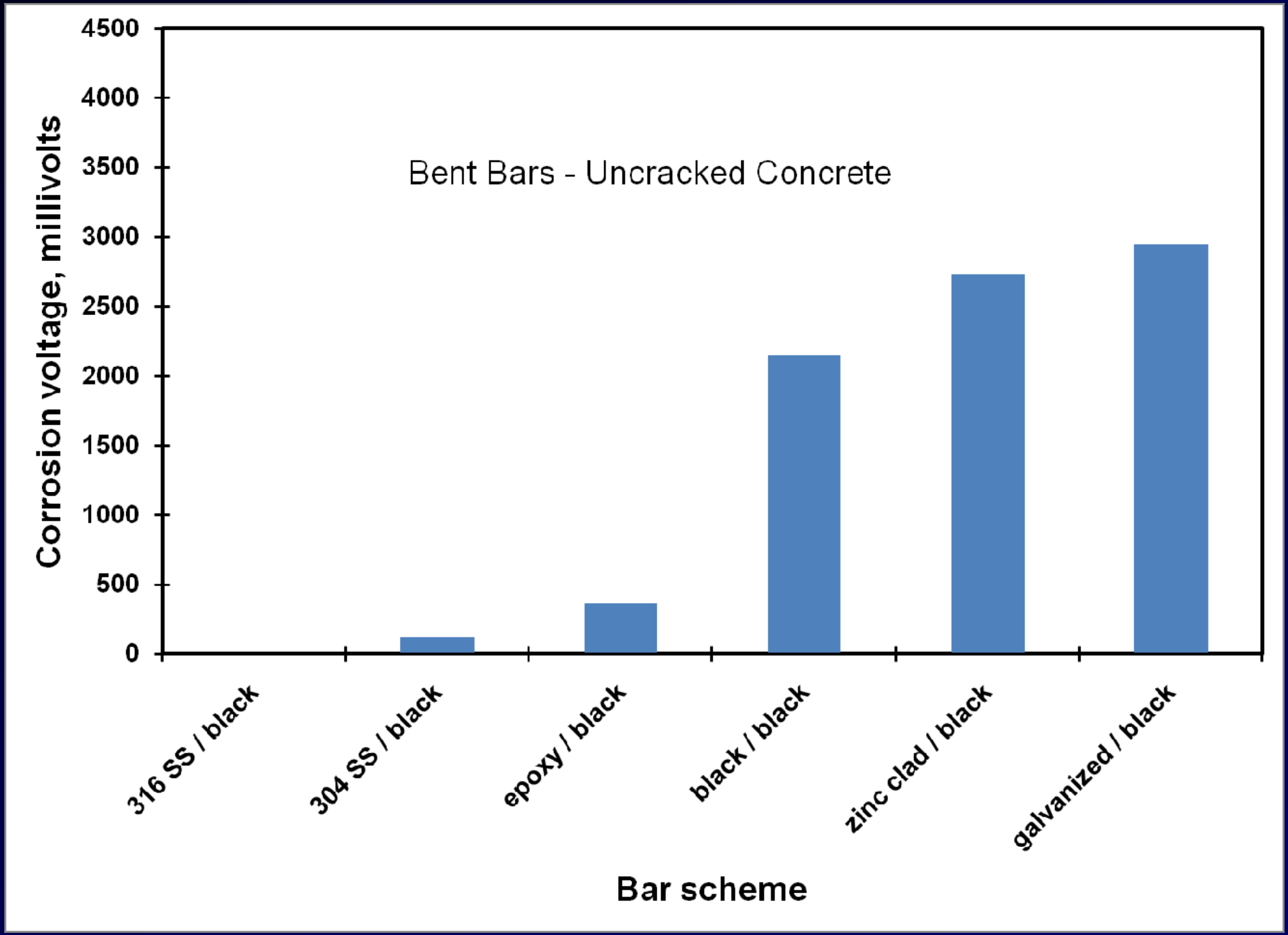
Effectiveness Ranking



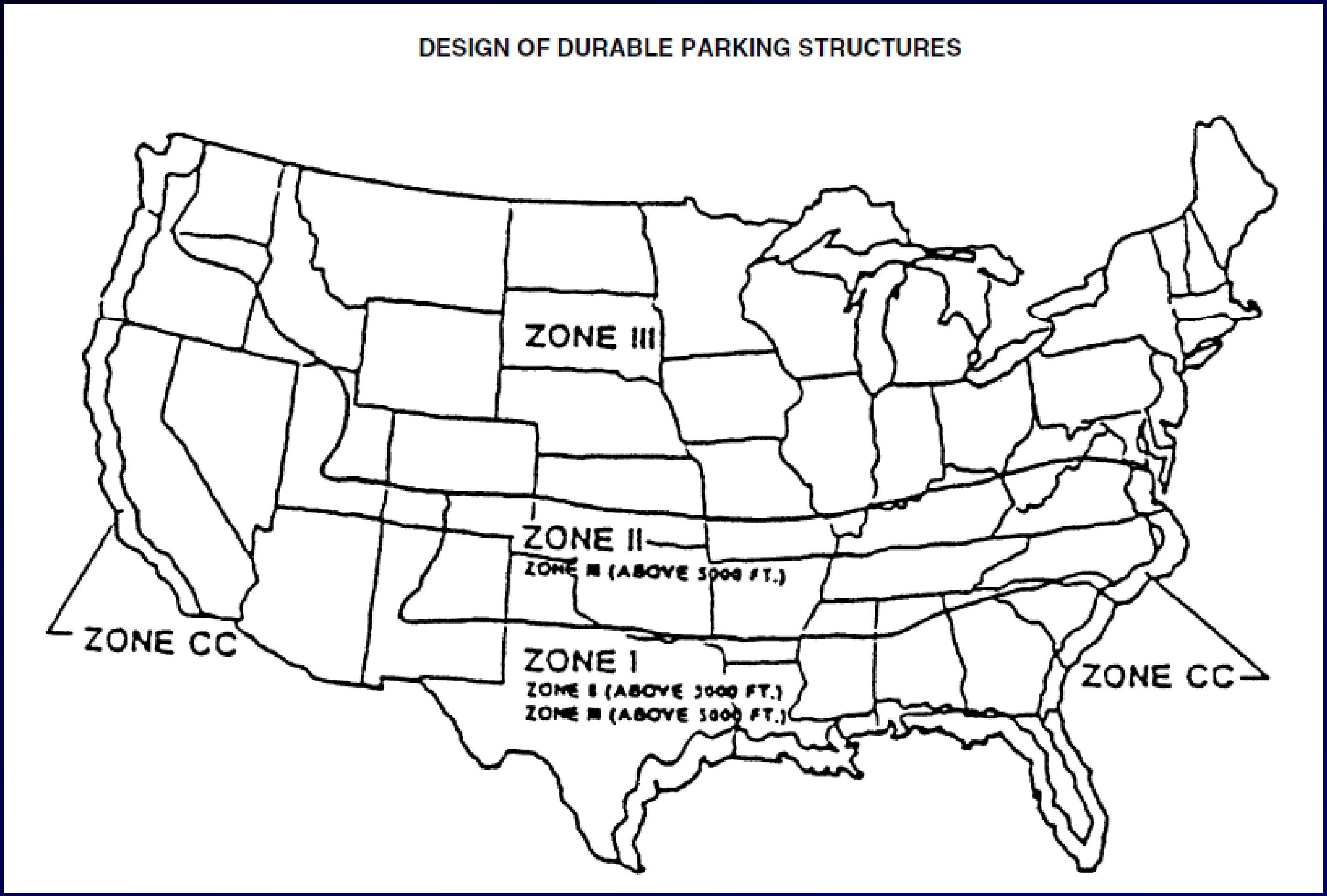
Effectiveness Ranking



Effectiveness Ranking



Zone Map for Parking Structures



ACI 362 – Precast Recommendations

Design element Note cracks and construction joints to be sealed to prevent leakage		Durability zone (refer to Fig. 3.1)		
		I	II/CC-I	III/CC-II
Concrete	Strength, psi	5000	5000	5500
	w/c, maximum	0.45	0.40	0.38
	Air, %[‡]	Not required	6-1/2 ± 2	6-1/2 ± 2
Reinforcement cover, in inches, and protection[§‖#] 2 in. cover recommended for No. 6 through No. 18 bars	Precast concrete: Top of flange	1-1/2	1-1/2	2[**]
	Precast concrete: TT, other sides	1-1/2	1-1/2[‖]	1-1/2[‖]
	Precast concrete: beam	1-1/2	1-1/2[‖]	1-1/2[‖]
	Precast concrete: column	1-1/2	1-1/2[‖]	1-1/2[‖]
	Walls (exterior face)	3/4	1-1/2[‖]	1-1/2[‖]
Precast concrete flange edge connectors[**]	1 in. minimum top cover	Liquid galvanized	Hot-dipped galvanized or stainless steel	Stainless steel
Precast concrete exposed plates	—	Rust-preventative paint	Epoxy-coated[††] or hot-dipped galvanized	Epoxy-coated[††] or hot-dipped galvanized
Sealer[‡‡]	—	Roof only	All floors and roof	All floors and roof

Parking Structure Design

- Effective use of protective measures
  - Good design measures
    - Drainage
    - Detailing for crack control
    - Proper cover
    - Proper finishing
    - Proper curing

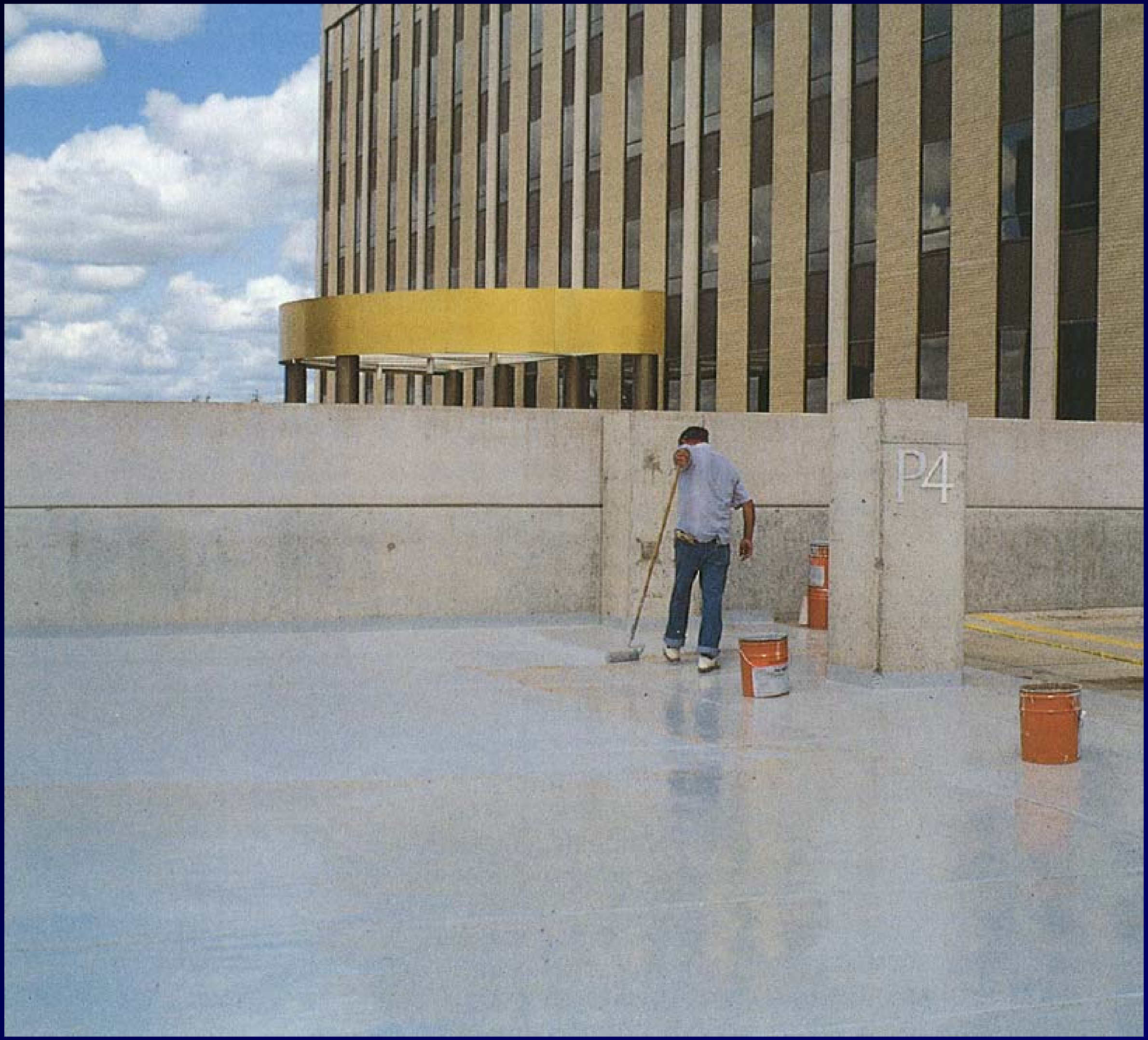
Parking Structure Design

- Effective use of protective measures
  - Internal measures
    - Air entrainment
    - Corrosion inhibitors
    - Reduced permeability
    - Coated or special reinforcing bars

Parking Structure Design

- Effective use of protective measures
  - External measures
    - Sealers
    - Protective coatings (membranes)

Traffic Bearing Membranes



Summary Durable Concrete Structures

- Alternate reinforcing bar schemes can extend service life
  - Need same type bar throughout
  - Epoxy coating effective
  - Stainless for long service life in cracked concrete
- Keep cover to 25 – 30 mm (1 – 1 ¼ in.)

Questions