Cracking in Concrete
Part I: Causes
Part II: Effects

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Overview

- Part I: Why does concrete crack?
  - What is a crack?
  - What are the causes?
  - How do we know the cause?

- Part 2: What are the effects of cracking on performance?
  - Influence of crack width on permeability
  - Case study

"Shibboleth" by Doris Salcedo

What is a crack?

- You know one when you see one, right?

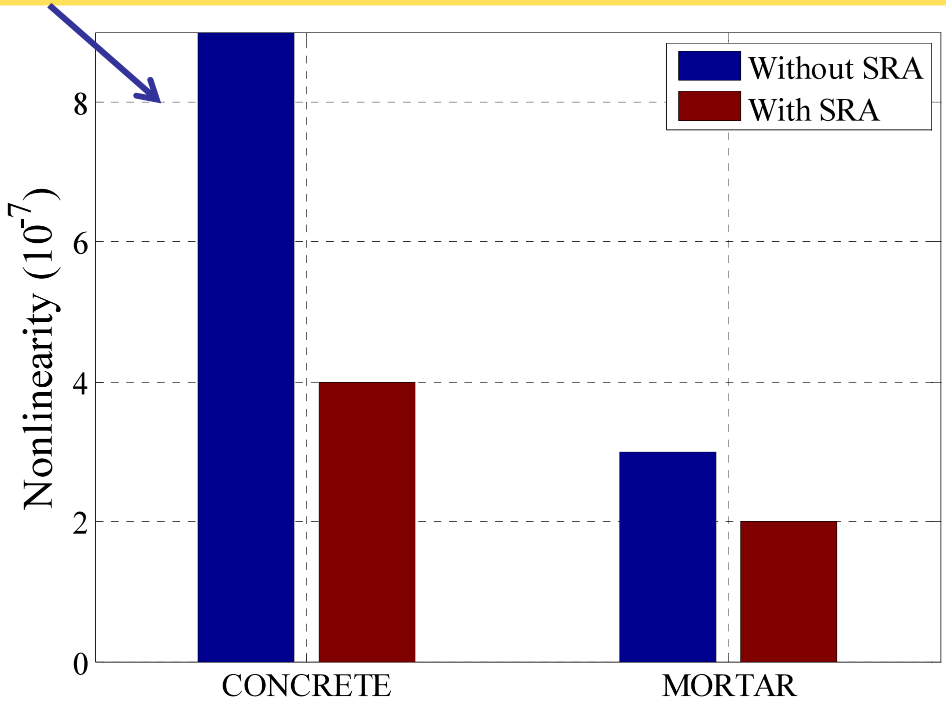

Even 10m underwater…

What is a crack?

- You know one when you see one, right?

Or do you???

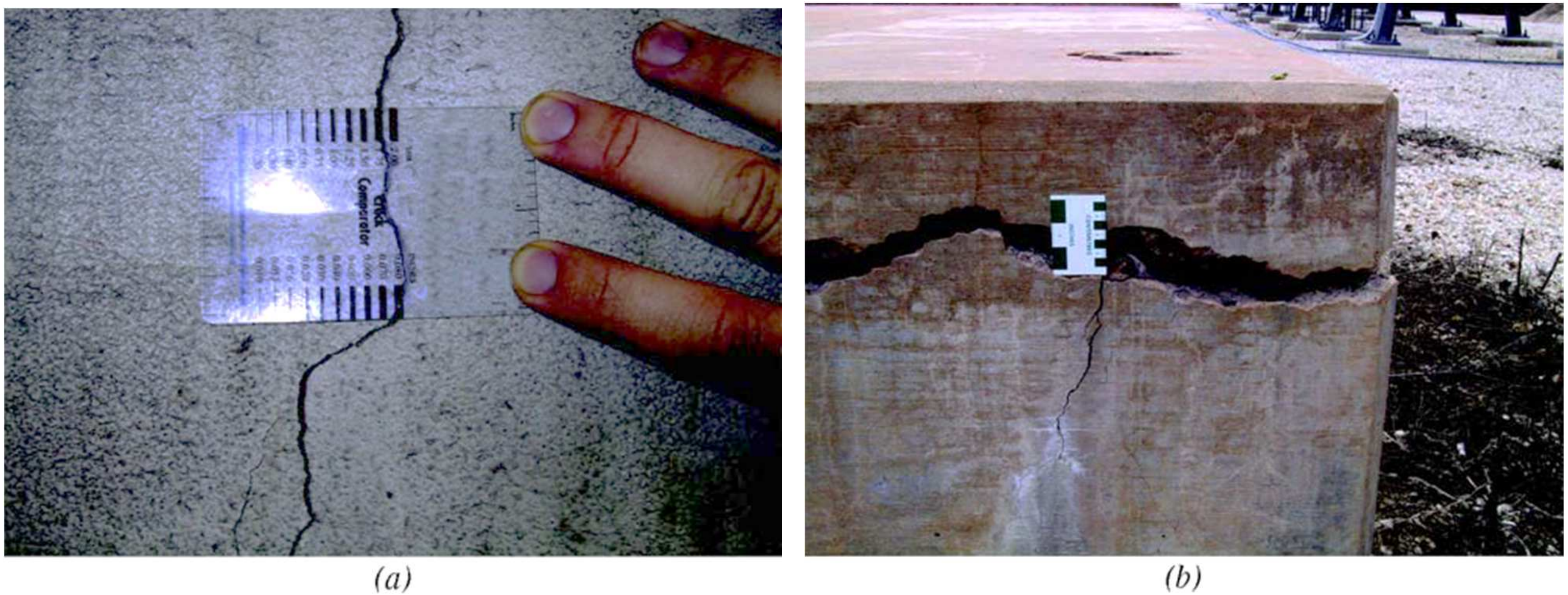
material nonlinearity α degree of microcracking



ACI Definition: Cracking

- *Crack*—a complete or incomplete separation, of either concrete or masonry, into two or more parts produced by breaking or fracturing. (ACI 201.1R-08)

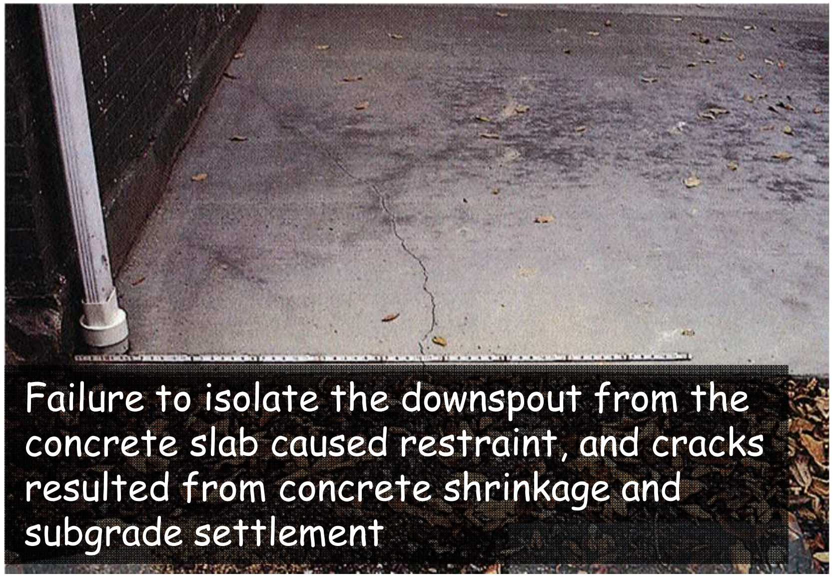
Report width & <u>type,</u> if possible


(a) (b)

Cracking decreases load carrying capacity, decreases stiffness, and increases permeability.

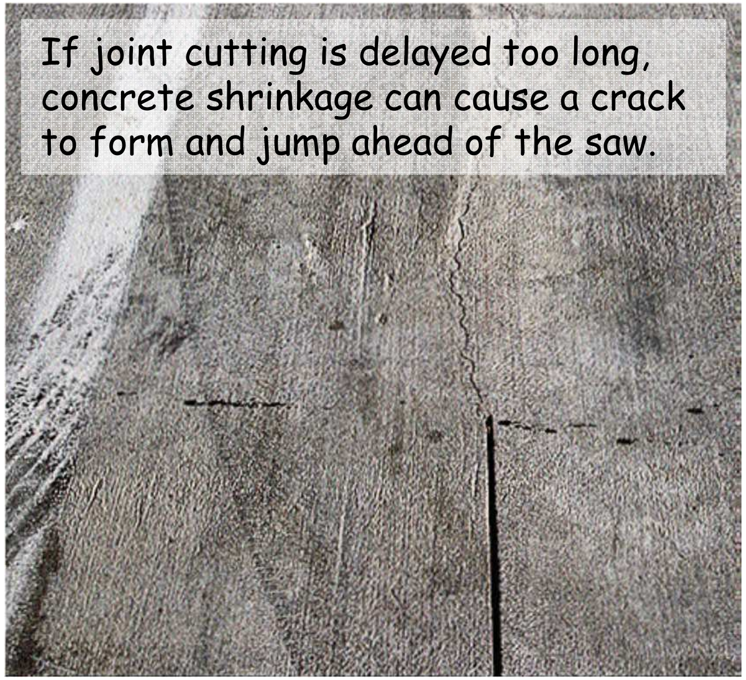
Why does concrete crack?

- Materials, mix proportions, construction practices, design, detailing, site conditions, etc., etc., etc.



Failure to isolate the downspout from the concrete slab caused restraint, and cracks resulted from concrete shrinkage and subgrade settlement

Combination of reactive aggregate mineralogy with exposure to alkalis and moisture led to ASR expansion and cracking



If joint cutting is delayed too long, concrete shrinkage can cause a crack to form and jump ahead of the saw.

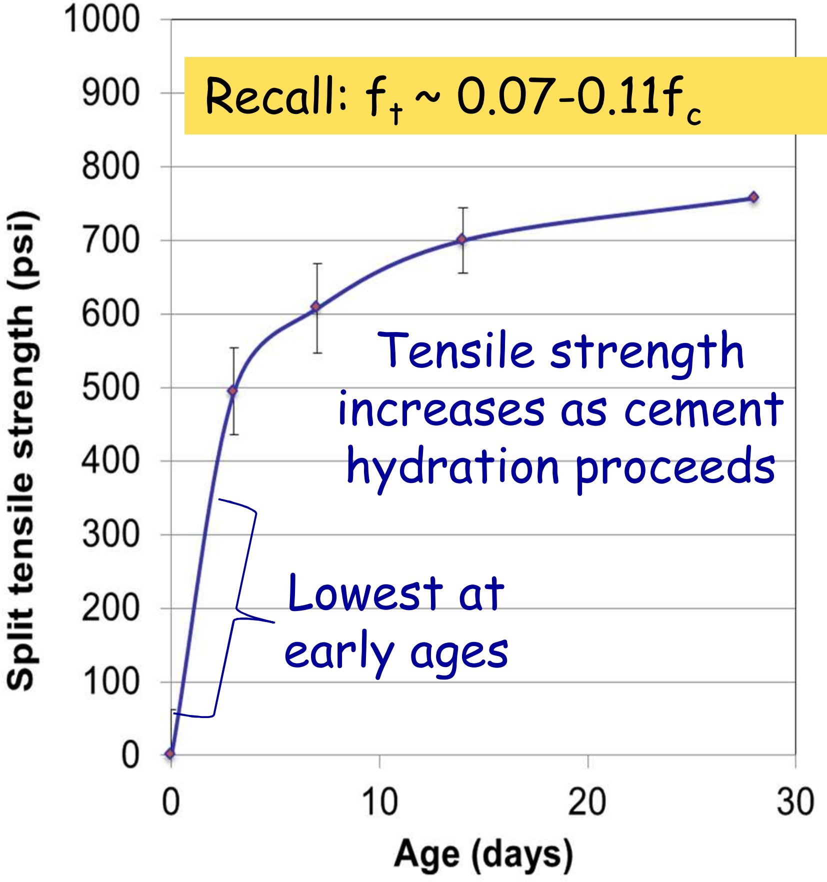
Cracking and crack growth can result from combination of sources

ACI 201.1R-08

Why does concrete crack?

While a simplification, it can be helpful to understand if we consider that concrete will crack when either tensile strength (f_t) or tensile strain capacity (d_t) are exceeded:

$$\sigma_t > f_t \text{ or } \varepsilon_t > d_t$$

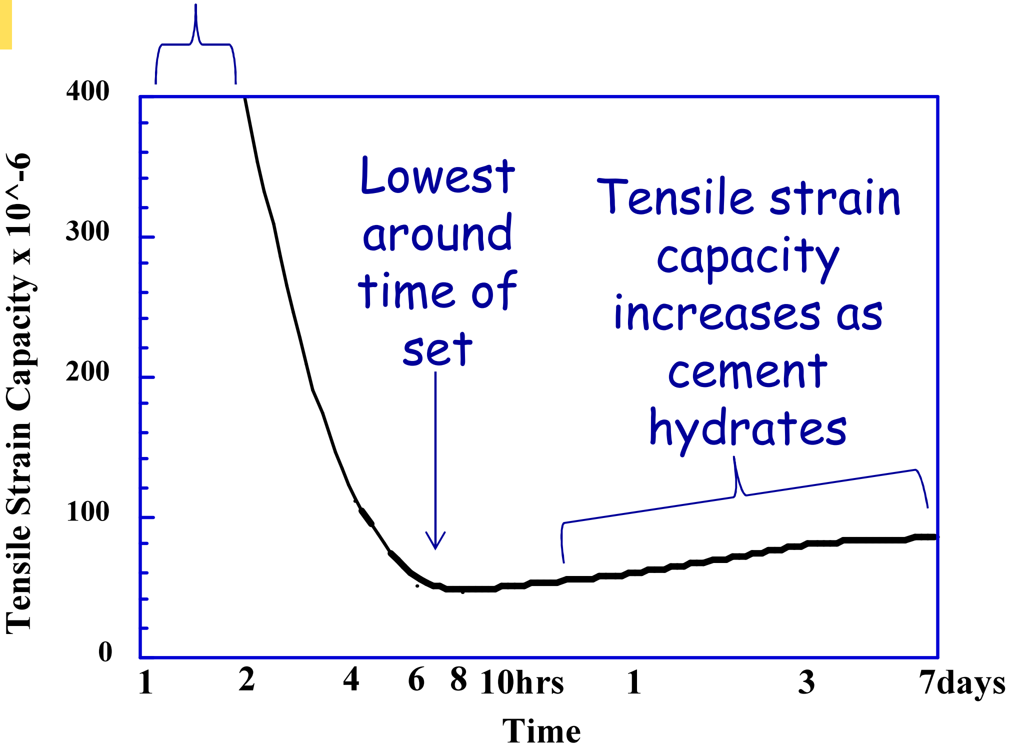


Recall: $f_t \sim 0.07\text{-}0.11 f_c$

Tensile strength increases as cement hydration proceeds

Lowest at early ages

When fluid or plastic, capable of large deformations



Lowest around time of set

Tensile strain capacity increases as cement hydrates

Weirig, H.J., *Beton*, 1981.

Why does concrete crack?

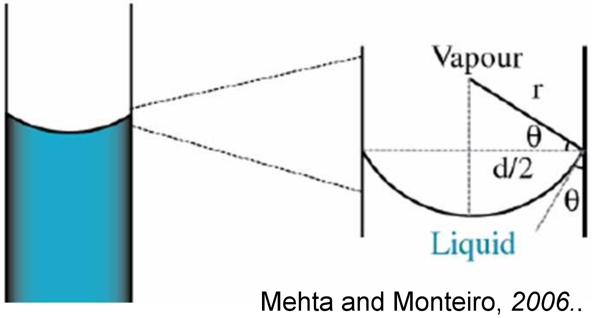
Tensile stresses or strains in concrete can result from

- External effects (e.g., thermal stresses, differential settlement)
- Shrinkage (e.g., plastic shrinkage, drying shrinkage)
- Expansion
- A combination of these

Shrinkage: Negative pressure (stress) developed in pores due to emptying

$$\sigma_{cap}=\gamma/r$$

σ_{cap} is the negative pore solution pressure
γ is the surface tension in the solution
r is the average radius of meniscus curvature

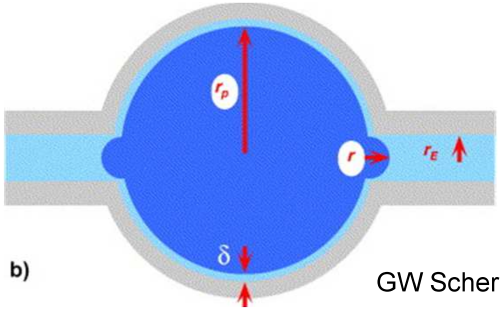


Mehta and Monteiro, *2006*..

Expansion: Stress due to crystallization in pores

$$\sigma_w=\gamma_{CL}/(r_p-\delta)$$

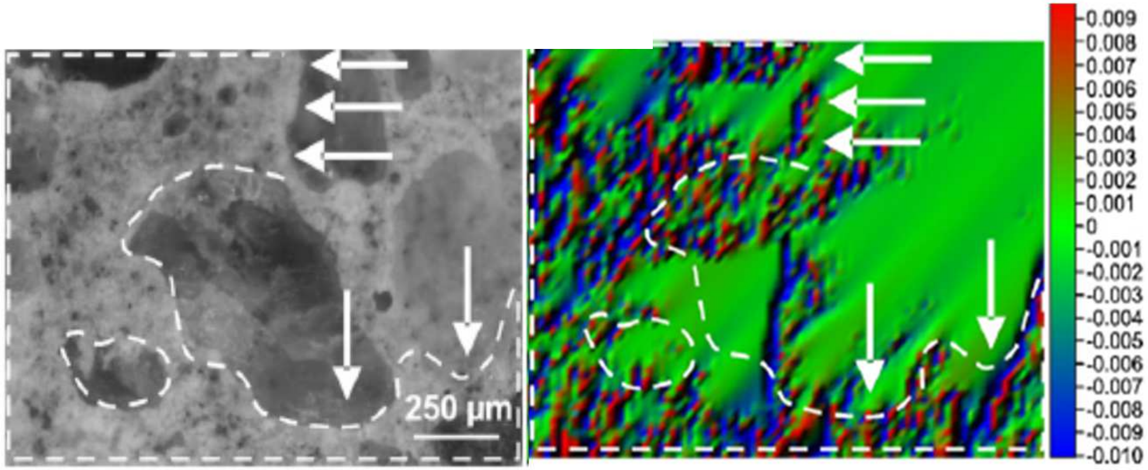
σ_w is the pressure on pore wall
γ_{CL} is the free energy between crystal and liquid
r is the pore radius
δ is the liquid film thickness between crystal and wall



GW Scherer, *CCR*, 2004.

Effect of Restraint

- Magnitude of tensile stress generated is related to degree of restraint
- Sources of restraint can be external or internal:
  - Connections to other structural elements
  - Subgrade
  - Formwork
  - Non-uniform deformation (curling, thermal effects)
  - Reinforcement
  - Aggregate



Localized restraint can lead to microcracking at aggregate-paste interface.

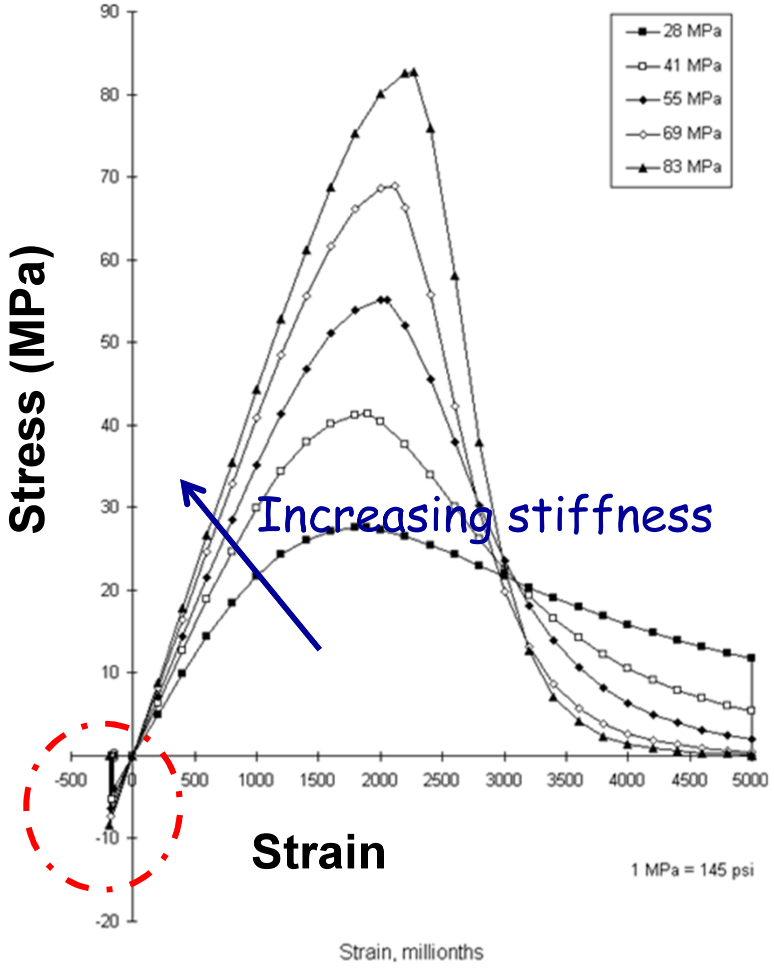
Lopez et al. , ACI Materials, *2004.*

Why does concrete crack?

- Concept of “Extensibility”
  - A material which is more resistant to cracking, through a combination of tensile strength, stiffness, and tensile strain capacity, is more extensible.
- Increasing stiffness, E, increases the magnitude of induced stress for a given strain:

$$\sigma = E\varepsilon$$

- E is greater
  - At later ages
  - For higher strength concrete



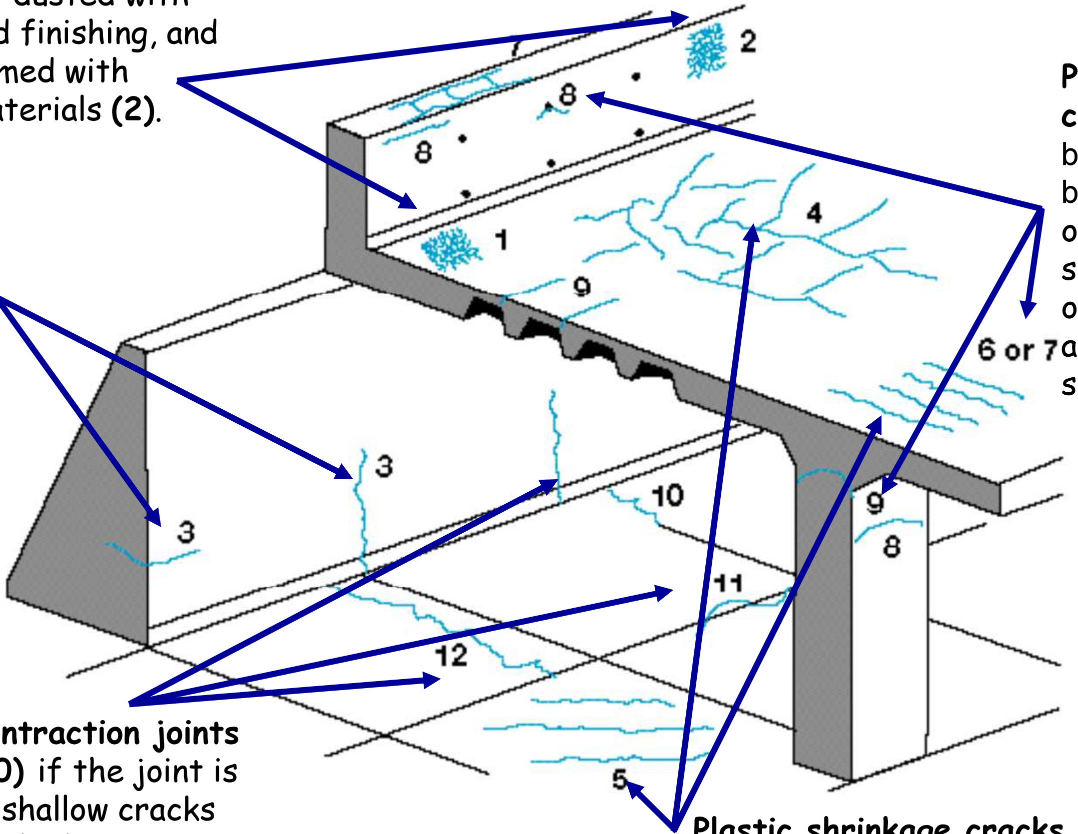
Increasing stiffness

1 MPa = 145 psi

Which is more extensible – NSC or HPC? Why?

How do we know the cause?

- While we often want to understand the underlying cause of cracking, cracks are better *initially* classified based upon appearance rather than source.



Crazing can occur at finished surfaces **(1)** that are overtroweled or dusted with cement to speed finishing, and at surfaces formed with impermeable materials **(2)**.

Cracks caused by restrained early thermal contraction (3) can occur in thick members when too much heat is generated or when the temperature change between the inside and face of the member is too high.

Plastic settlement cracks, caused by excess bleeding, and made worse by rapid early drying, can occur over **(7)** or at the side **(8)** of reinforcement or other embedments, and at changes in cross section thickness **(9)**.

Cracks due to ineffective contraction joints can jump ahead of the saw **(10)** if the joint is cut too late. If the cut is too shallow cracks may not occur within the joint **(11)**. Contraction joints are less effective in crack control when reinforcement continues through the joint **(12)**.

Plastic shrinkage cracks occur due to rapid early drying of the concrete surface and low rates of bleeding: elevated slabs **(4)**, slabs on grade **(5)**, and over reinforcement **(6)**.

Halvorsen, G.T., "Troubleshooting Concrete Cracking during Construction", *Concrete Construction*, Oct. 1993, p. 700-710.

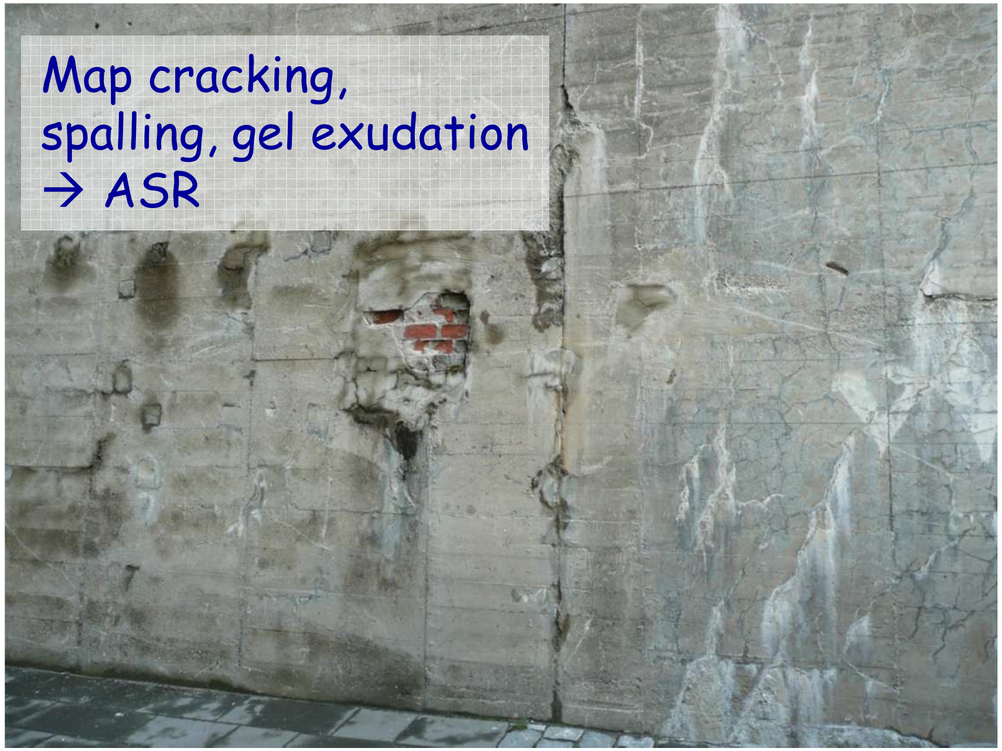
How do we know the cause?

- While we often want to understand the underlying cause of cracking, cracks are better *initially* classified based upon appearance rather than source.
  - *Craze cracks*—fine random cracks or fissures in a surface of plaster, cement paste, mortar, or concrete; can be due to shrinkage or expansion or a combination (shrinkage at top, expansion below)

ACI 201.1R08

How do we know the cause?

- Cracks are initially better classified based upon appearance rather than source.
- Use construction records, petrography, other methods to determine underlying cause(s).



Map cracking, spalling, gel exudation → ASR

Fine cracking pattern could be related to shrinkage? ASR?

How do we know the cause?

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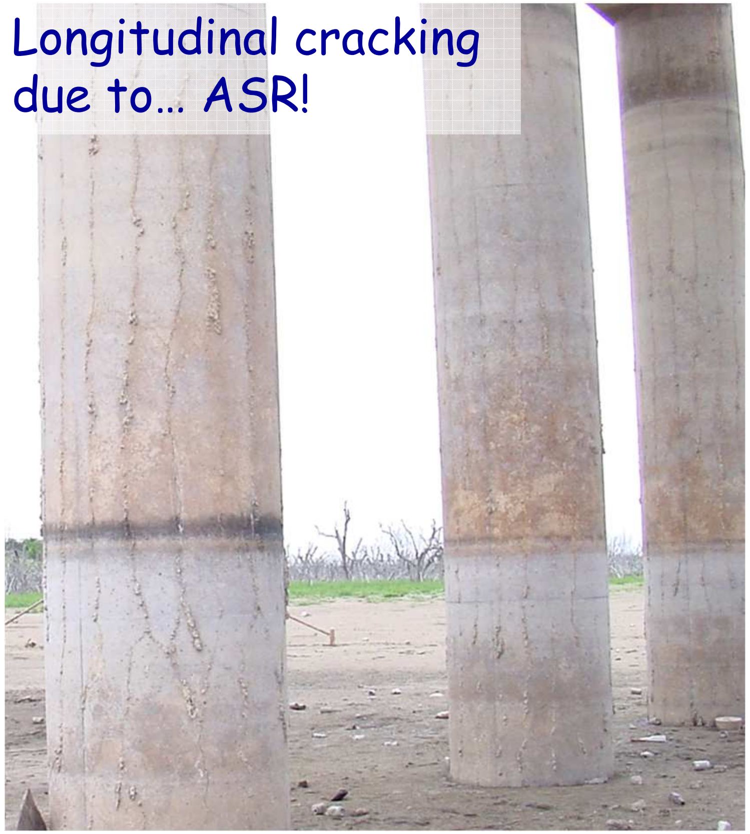

Longitudinal cracking due to… ASR!

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  - Influence of crack width on permeability
  - Case study

What are effects of cracking?

- Decreased load carrying capacity
  - Greater effect on tensile and flexural strength
  - Typically less effect on compressive strength
- Decreased stiffness
- Increased permeability

Same as "hydraulic conductivity"

Permeability – measure of the bulk rate of fluid flow through a porous material (e.g., concrete, cement paste, mortar) under an applied pressure

Pressure can be generated from
-external water (dams, tunnels)
- absorption processes can produce pressure differentials

Permeability

Some typical values for permeability (m/s):

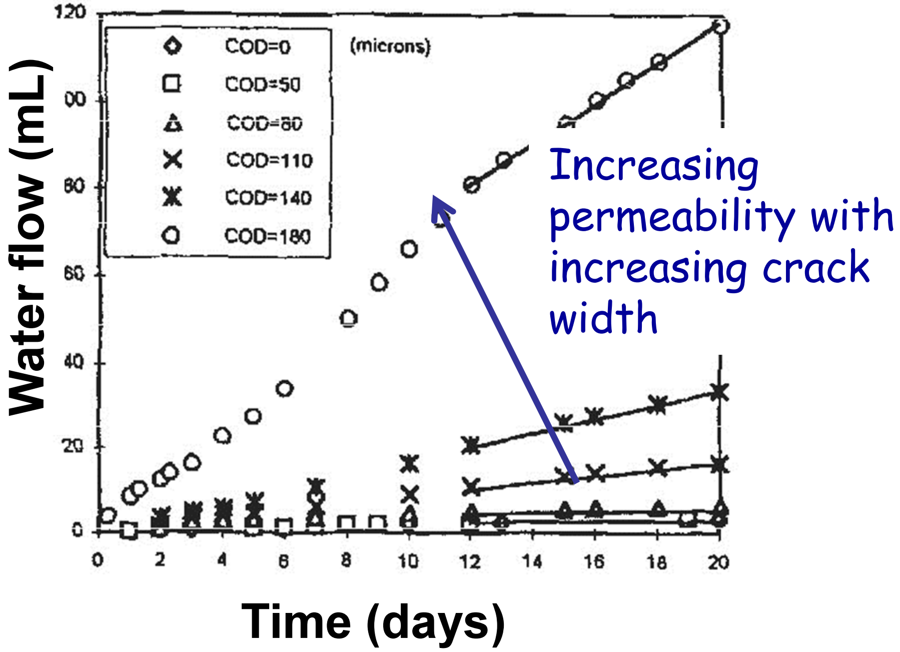
Plastic cement paste	$1x10^{-6} - 10^{-7}$
Mature, good quality concrete	$1-30x10^{-12}$
Hardened cement paste, kept moist (for w/c 0.30-0.70)	$0.1-120x10^{-14}$
High performance concrete	$1x10^{-15}$
Coarse aggregate	$1.7x10^{-10}-3.5x10^{-15}$

Why is the permeability in normal strength concrete so much larger than in paste or aggregate?

Permeability: Influence of Cracking

- Cracks <50-100μm wide have little effect on permeability
- With 300-400μm cracks, permeability **increased by 8 orders of magnitude** compared to uncracked concrete

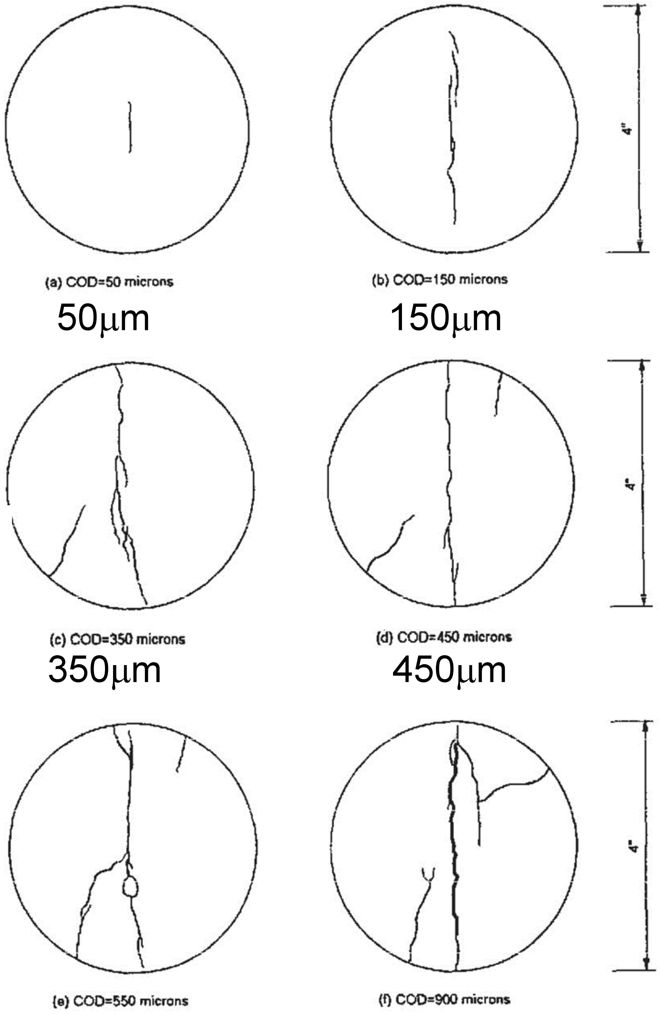
Concrete permeability with varying crack widths, 0-180μm



Increasing permeability with increasing crack width

source: Wang et al., CCR, 1997

How big is 100 μm?



(a) COD=50 microns
50μm

(b) COD=150 microns
150μm

(c) COD=350 microns
350μm

(d) COD=450 microns
450μm

(e) COD=550 microns
550μm

(f) COD=900 microns
950μm

FIG. 6. Crack patterns.

Permeability: Influence of Cracking

- Permeability is faster through larger crack widths and at higher temperature

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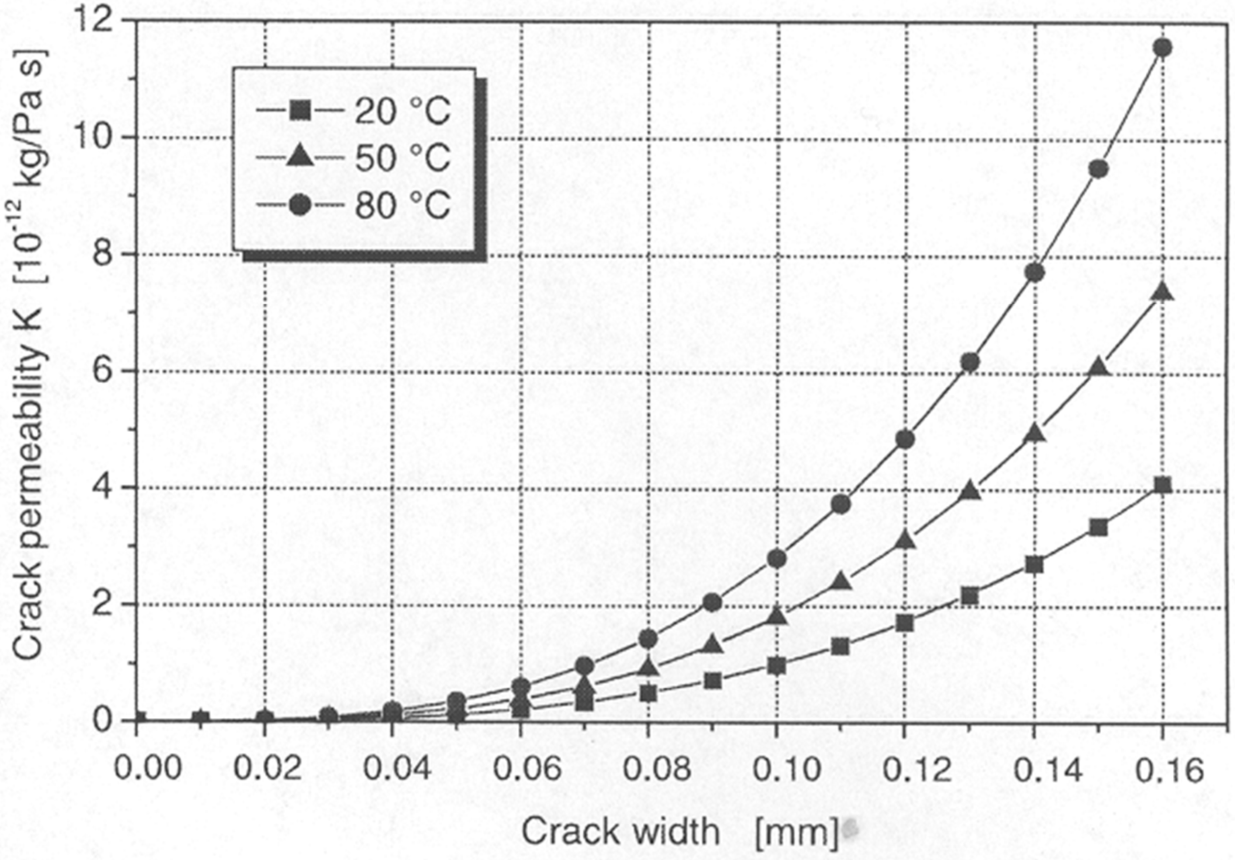


Fig. 7. Representation of the dependency of *K* of Eq. (4.3) on crack width and temperature.

Reinhardt and Jooss,
CCR, 2003.

Permeability: Influence of Cracking

- Guidance for designers?
  - Considering concrete deterioration due to cracking, in **versions prior to 1999**, AC1 Building Code (AC1 318 Commentary, Section 10.6) limited crack widths by limiting the distribution of flexural reinforcement in reinforced concrete design.
  - The Code limitations were based on crack widths of **0.016 in. (400 μm) for interior exposure and 0.013 in. (330 μm) for exterior exposure**
  - These were arbitrary numerical values based on past experience.

Permeability: Influence of Cracking

- Guidance for designers?
- Current versions of ACI 318 Sec. 10.6 include these (vague) caveats:

"Crack widths in structures are highly variable. In (previous) codes, provisions were given for the distribution of reinforcement… (for) a maximum crack width of 0.016 in. The current provisions for spacing are intended to limit surface cracks to a width that is **generally acceptable in practice, but may vary widely in a given structure.**"

"Provisions (for flexural reinforcement) are **not sufficient for structures subject to very aggressive exposure or designed to be watertight**. For such structures, special investigations and precautions are required."

"The role of cracks in the corrosion of reinforcement is controversial. Research shows that corrosion is not clearly correlated with crack surface width… for this reason, the former distinction between interior and exterior exposure has been eliminated."

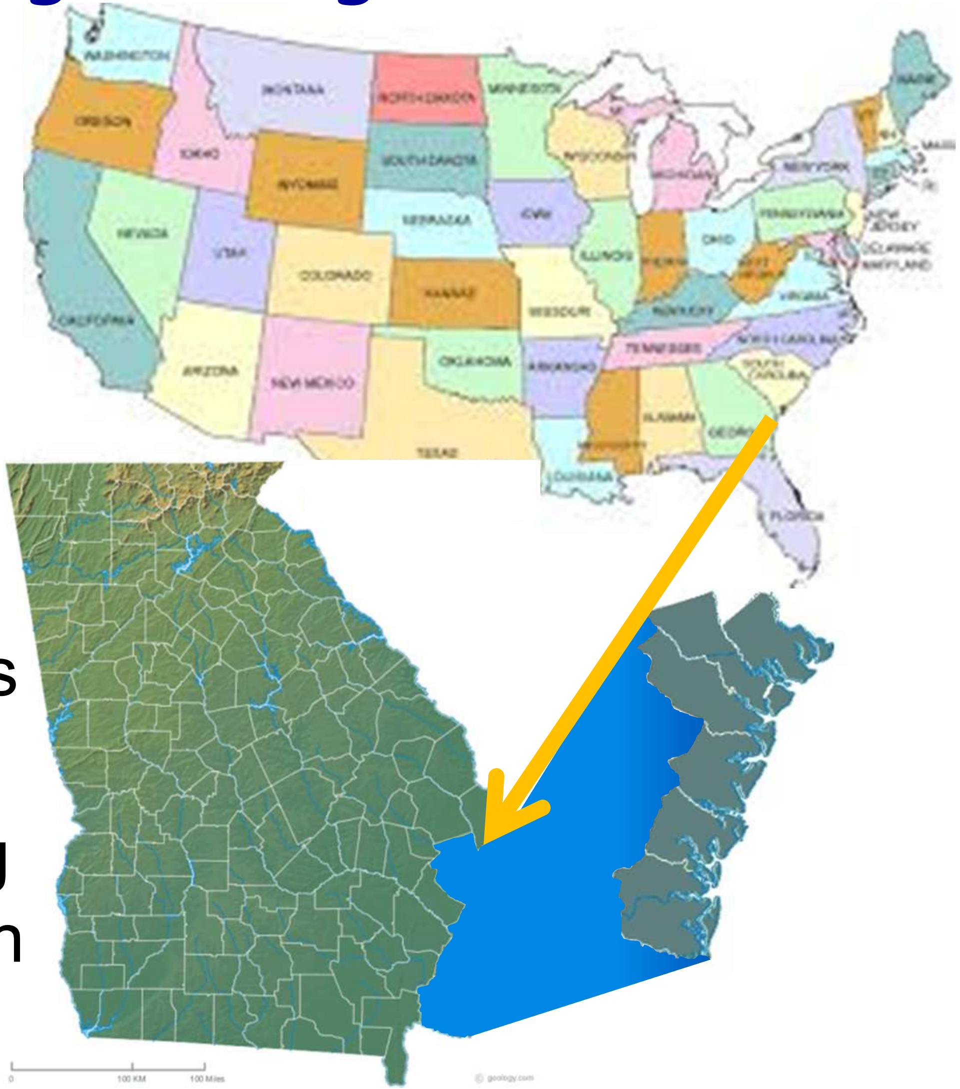
-"Although a number of studies have been conducted, clear experimental evidence is not available regarding the crack width beyond which corrosion danger exists."

Case study

- Illustrate effects of multi-scale cracking on performance

Assessment of Georgia Bridges

- Bridges with concrete substructures over bodies of water along coastal Georgia assessed for deterioration
- Interviewed maintenance engineers and inspection teams
- Develop understanding of durability concerns in concrete bridges

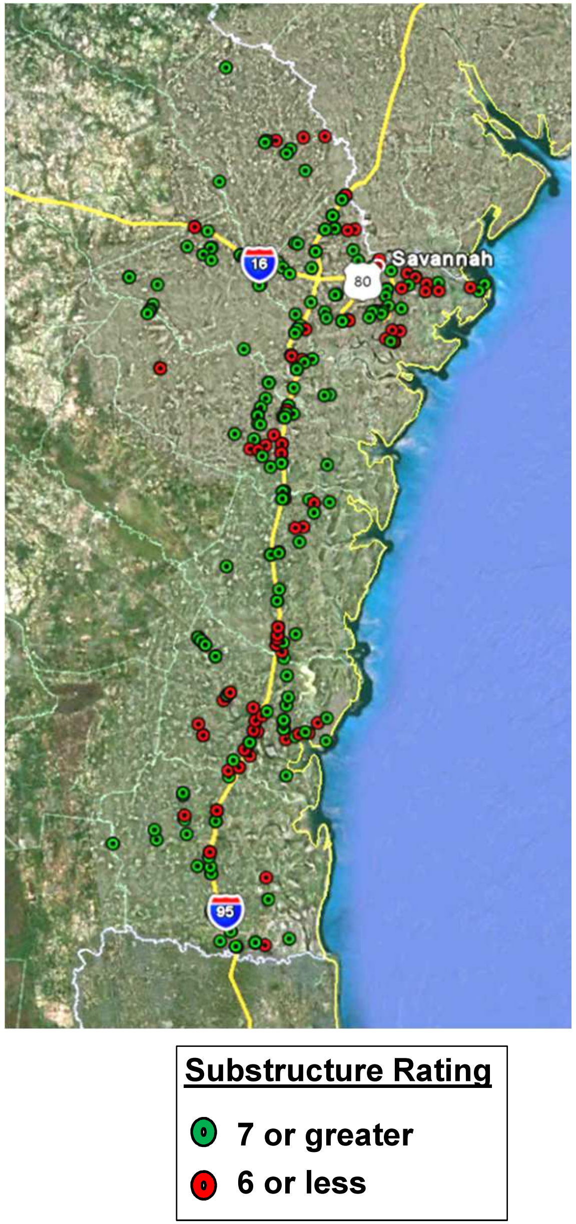


Counties: Effingham, Chatham, Bryan, Liberty, McIntosh, Glenn, Camden

Assessment of Coastal Georgia Bridges

- Results cataloged according to NBIS substructure damage state:

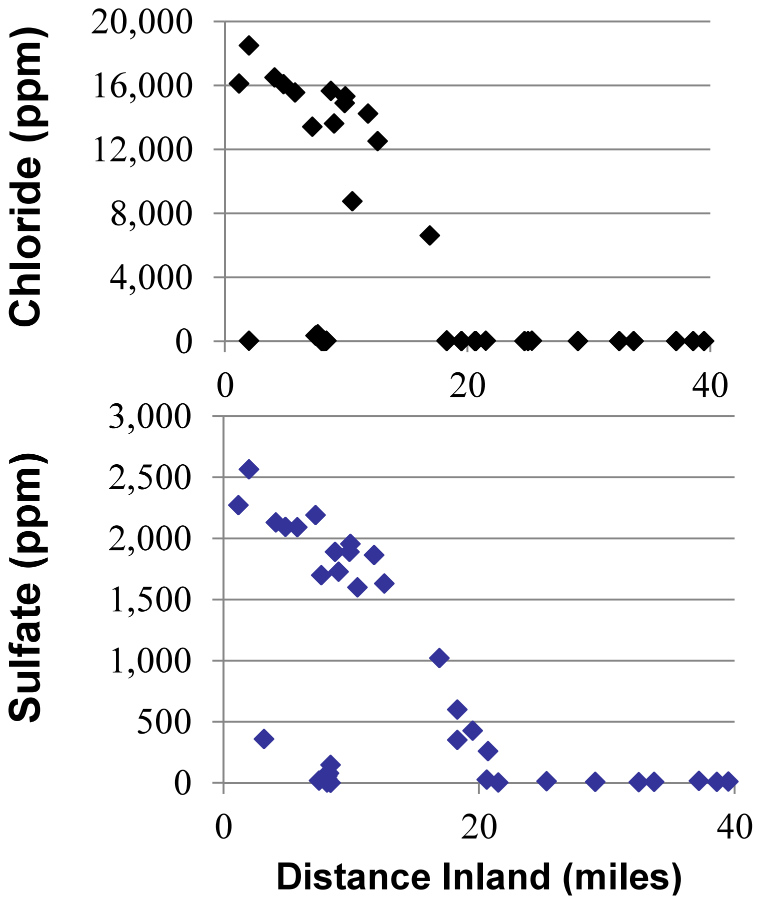
Code	Condition	Description	No.
9	Excellent	--	**205**
8	Very Good	No problems noted.	
7	Good	Some minor problems.	
6	Satisfactory	Structural elements show some minor deterioration.	**51**
5	Fair	All primary structural elements are sound but may have some minor section loss, cracking, spalling, scour.	**33**
4	Poor	Advanced section loss, deterioration, spalling or scour.	**1**
3	Serious	Loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.	**0**



Assessment of Coastal Georgia Bridges

Brackish water exposure

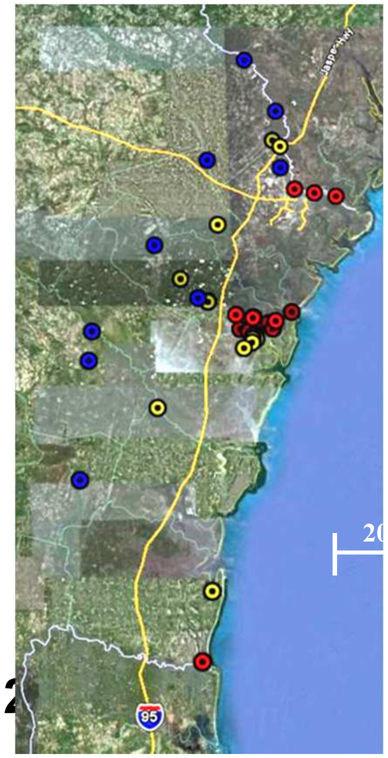
- Chlorides
- Sulfates
- pH~7.2



ACI 201.2 Sulfate Exposure Class

Exposure Class		SO_4 Content (ppm)
S0	Not Applicable	$SO_4 < 150$
S1	Moderate	$150 \leq SO_4 < 1,500$
S2	Severe	$1,500 \leq SO_4 < 10,000$
S3	Very Severe	$SO_4 > 10,000$

Sulfate Exposure Map



Assessment of Coastal Georgia Bridges

I-95 Turtle River Bridge

- Assessment focused on bridge substructures
- Exposure to chlorides, sulfates in submerged, splash, and tidal zones
- Exposure to carbonation

Inspection reports indicate much cracking, as well as spalling and other forms of damage in ~ 1/3 of coastal bridges

Reported Damage and Deterioration

Atmospheric zone damage patterns:

- Rust staining
- Cracking → spalling
- Cover delamination
- Exposed prestressing strands and rebar

Most common near splash zone, construction defects

US 80 at Lazeratto Creek Bridge

Ocean Highway at Riceboro Creek Bridge

Reported Damage and Deterioration

Splash and tidal zone damage patterns:

- Rust staining
- Cracking and spalling
- Cover delamination
- Exposed prestressing strands and rebar

I-95 at Savannah River

Harriett's Bluff Road at Deep Creek Bridge

US 17 at Back River Bridge

Reported Damage and Deterioration

Splash and tidal zone damage patterns:

- Surface abrasion due to wave and tidal action
- Particulates or debris suspended in flow
- Impact damage from boats, other objects

Island Expressway at Wilmington River Bridge

Harrell Highway at Buffalo Swamp

Houlihan Bridge

Reported Damage and Deterioration

Tidal and submerged zone damage patterns:

- Marine growth (oysters) in tidal zone
- Marine growth (barnacles, sponges) in submerged region

Marine growth can impede inspection, including diver inspection

Torra's Causeway at Little River

Reported Damage and Deterioration

Submerged zone damage patterns:

- Softening of concrete
- Surface cracking and spalling of cover concrete
- Efflorescence

Ocean Highway at Champney's River

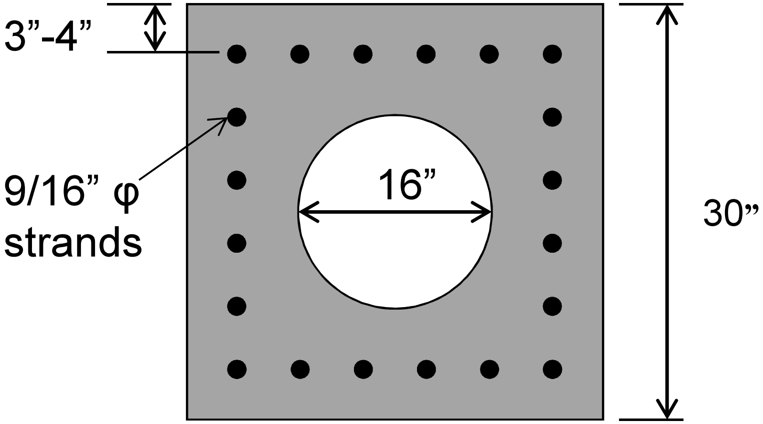
I-95 at Champneys River

Forensic Investigation

- 4 prestressed concrete piles extracted from Turtle River Bridge delivered to Georgia Tech Structures & Materials lab
- Concrete:
  - w/c ~0.50
  - Type I cement
  - No SCMs
  - Limestone coarse aggregate
  - Natural sand

What are causes of cracking and other damage?

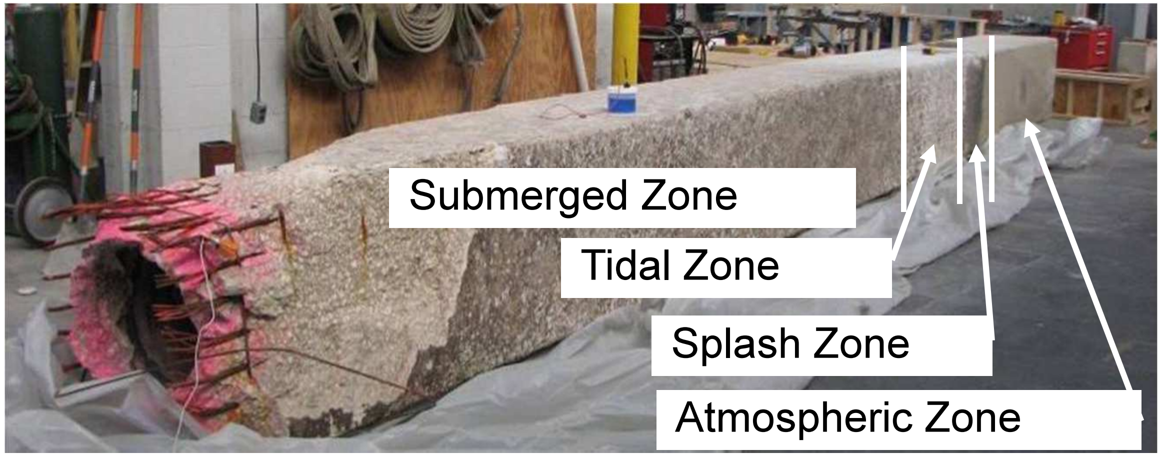
In service 32 years



Visual Survey of Damage

Damage found suggests:

- Physical deterioration
- Chemical attack
- Biodeterioration
- Corrosion



Submerged Zone

Tidal Zone

Splash Zone

Atmospheric Zone

Submerged zone:

- White discoloration/softening
- Boreholes/biological growth
- Spalling/longitudinal cracking

Tidal/splash zone:

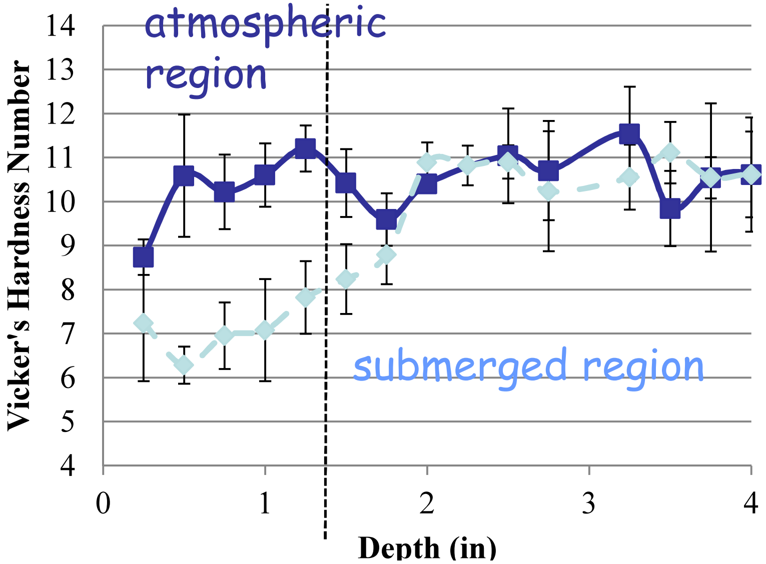
- Heavy oyster growth
- Longitudinal cracking at corners
- Spalling at corner strand
- Rust staining; reinforcement loss

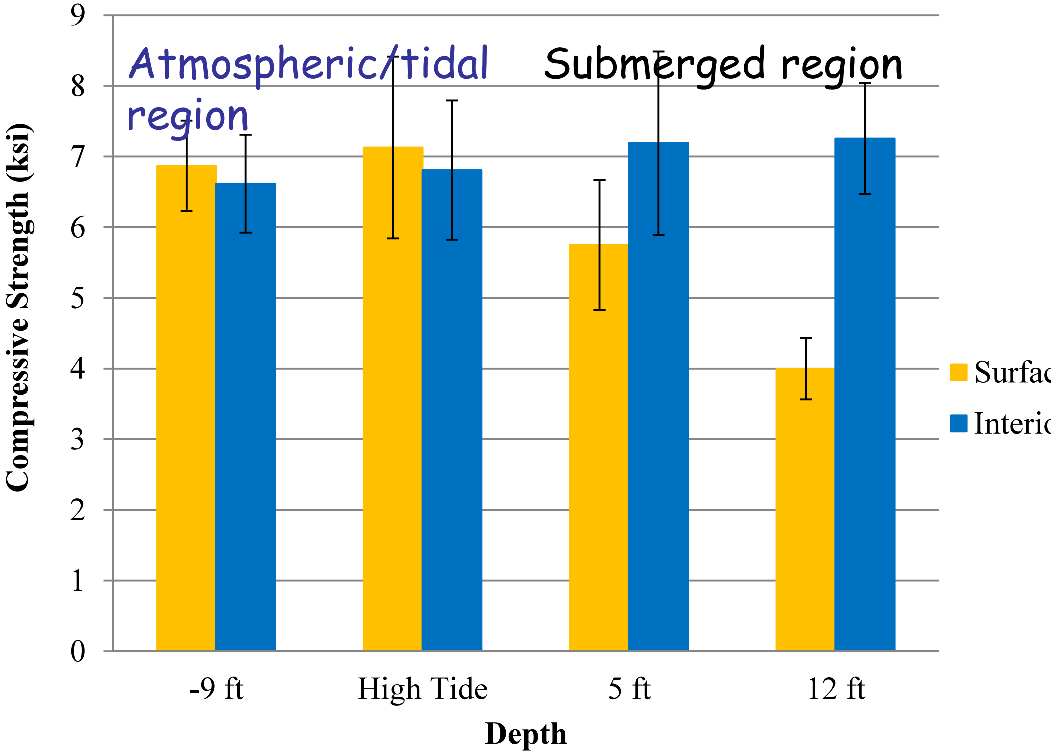
Atmospheric zone:

- Longitudinal cracking

Softening Near Surface

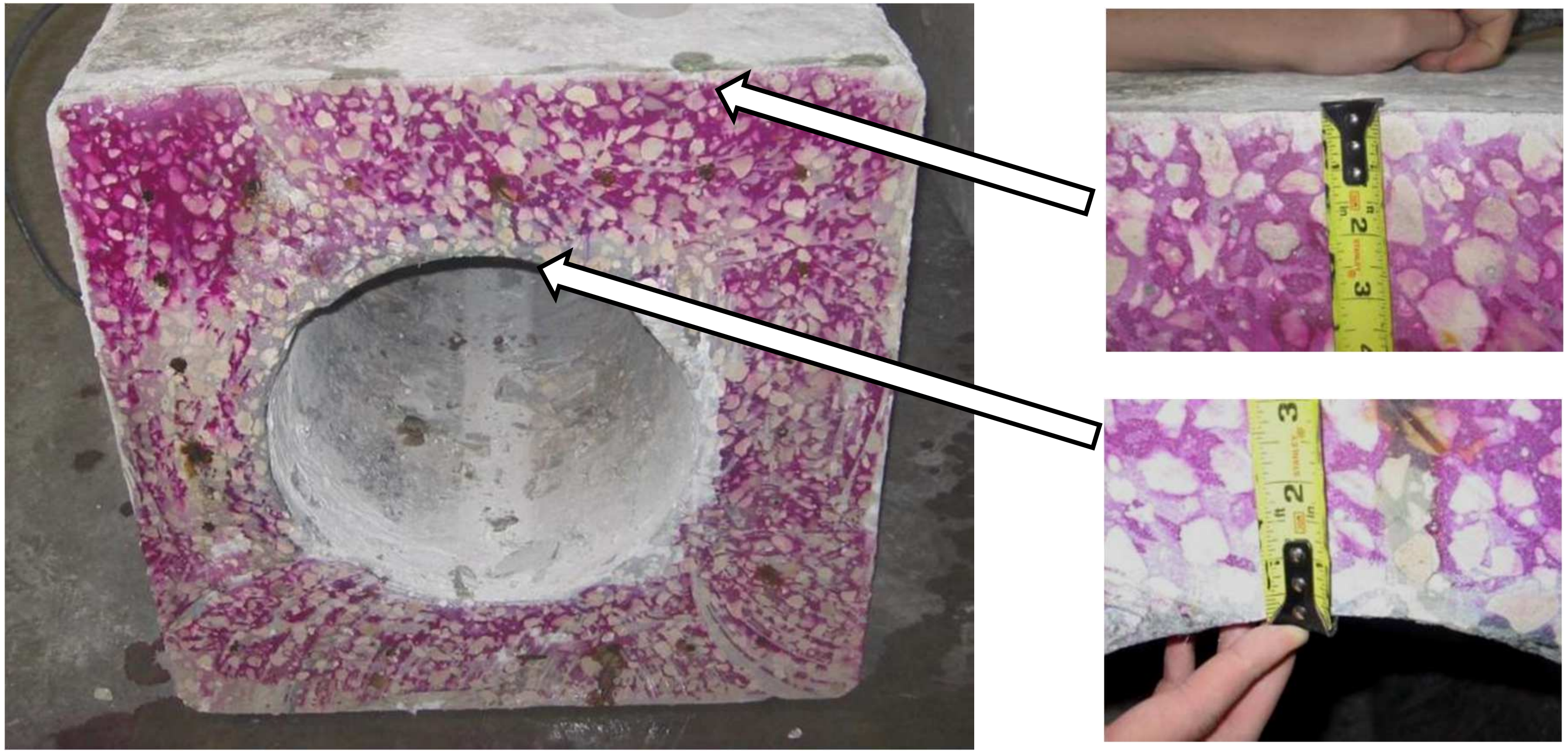
- Deterioration of hydrated cement paste
  - Loss of surface hardness → Chalky appearance
  - Greater loss of hardness and compressive strength near surface





Chemical Attack – Carbonation

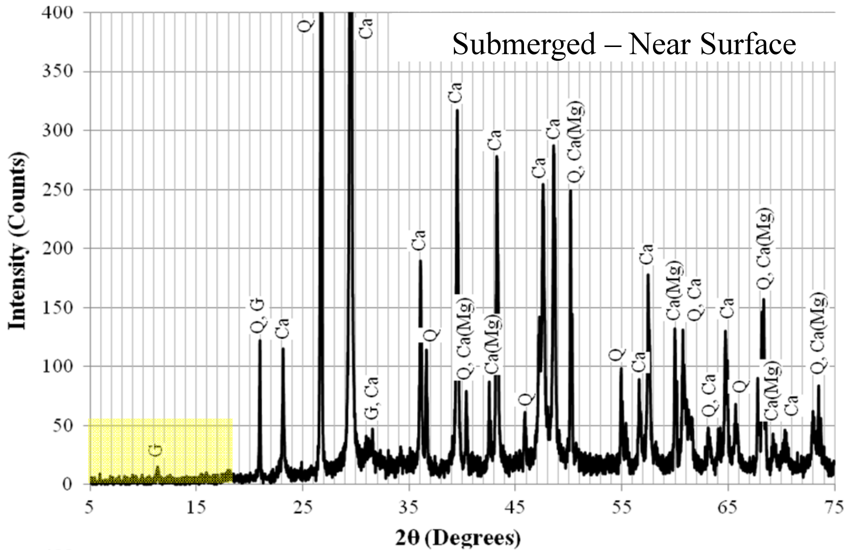
- Phenolphthalein pH indicator showed reduced pH of surface concrete in submerged and tidal regions
- Did not reach depth of reinforcement
- Could contribute to reduced strength in near-surface concrete

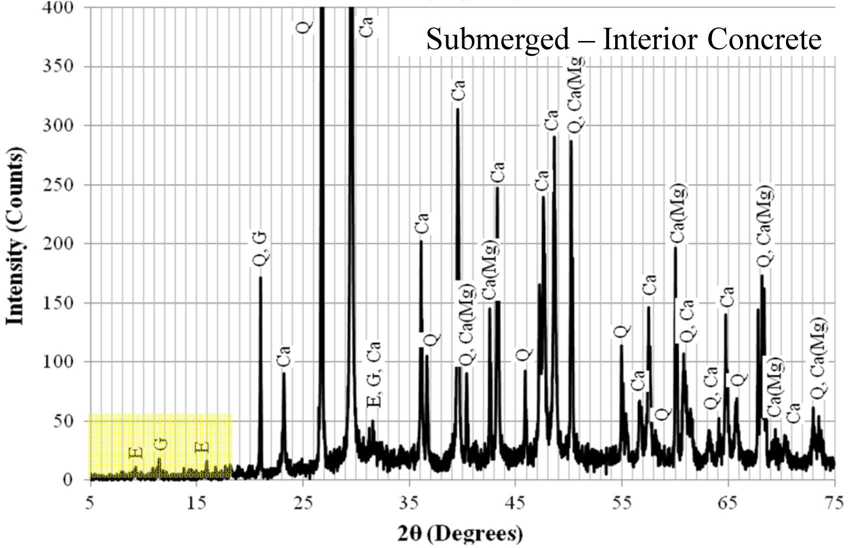


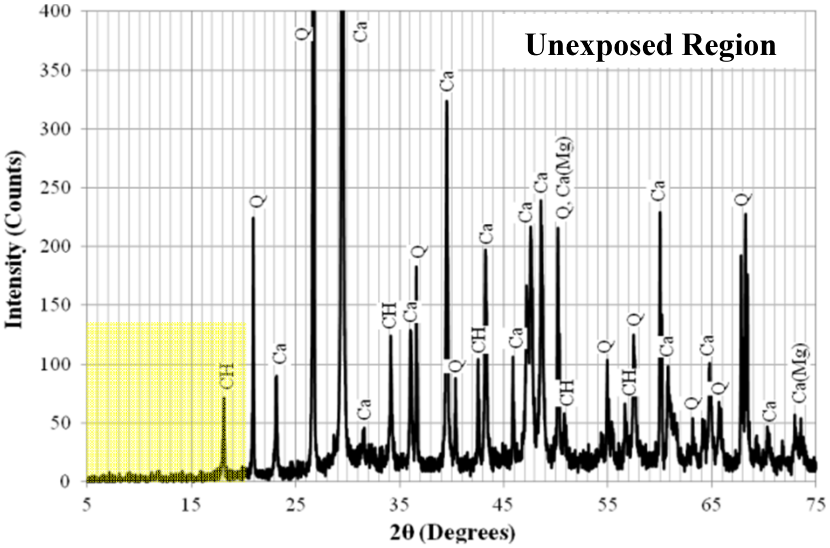
Carbonation rate of ~0.8mm/year in submerged region

Chemical Attack – Carbonation & Sulfate

- Compositional changes
  - Loss of portlandite
  - Alteration of C-S-H
  - Formation of ettringite
  - Formation of gypsum







Chemical Attack – Carbonation & Sulfate

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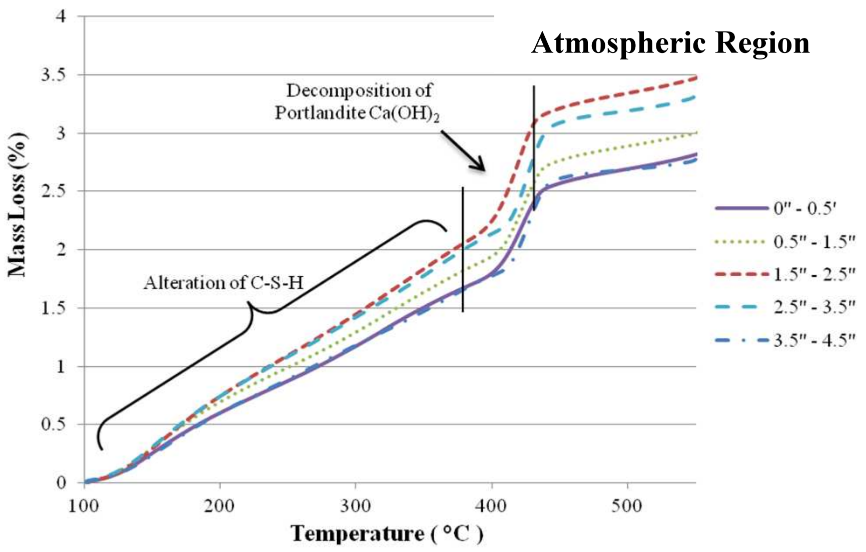
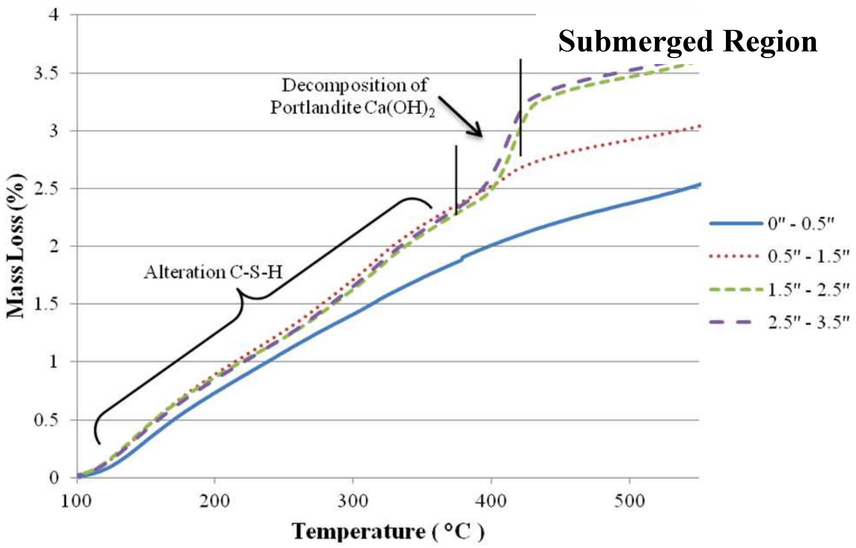


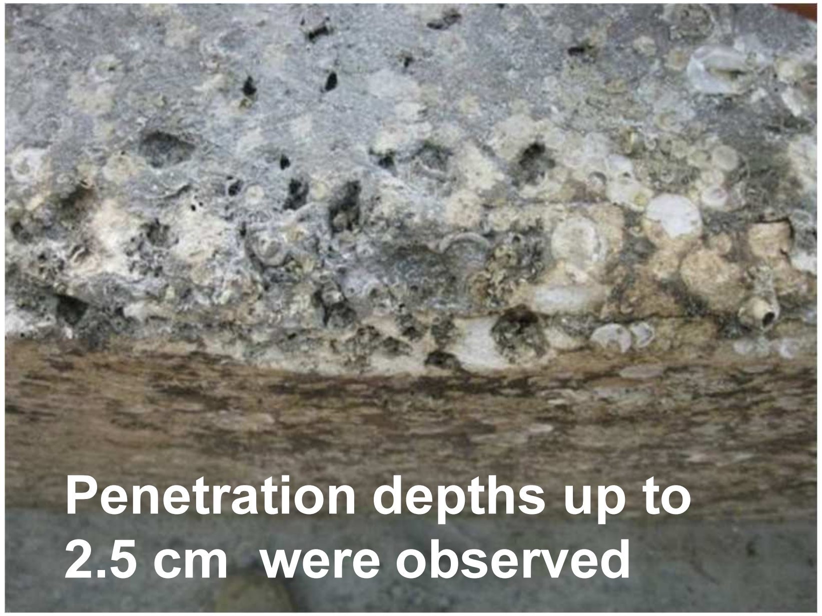


Combination of carbonation and sulfate attack can decrease strength and result in formation of expansive products → cracking, increased permeability

Biodeterioration

- Biodeterioration evident in submerged regions
- Attack isolated to porous Pleistocene limestone aggregates
  - 70% of cores taken had damage to aggregates
- May result in coupled bio/chemical deterioration

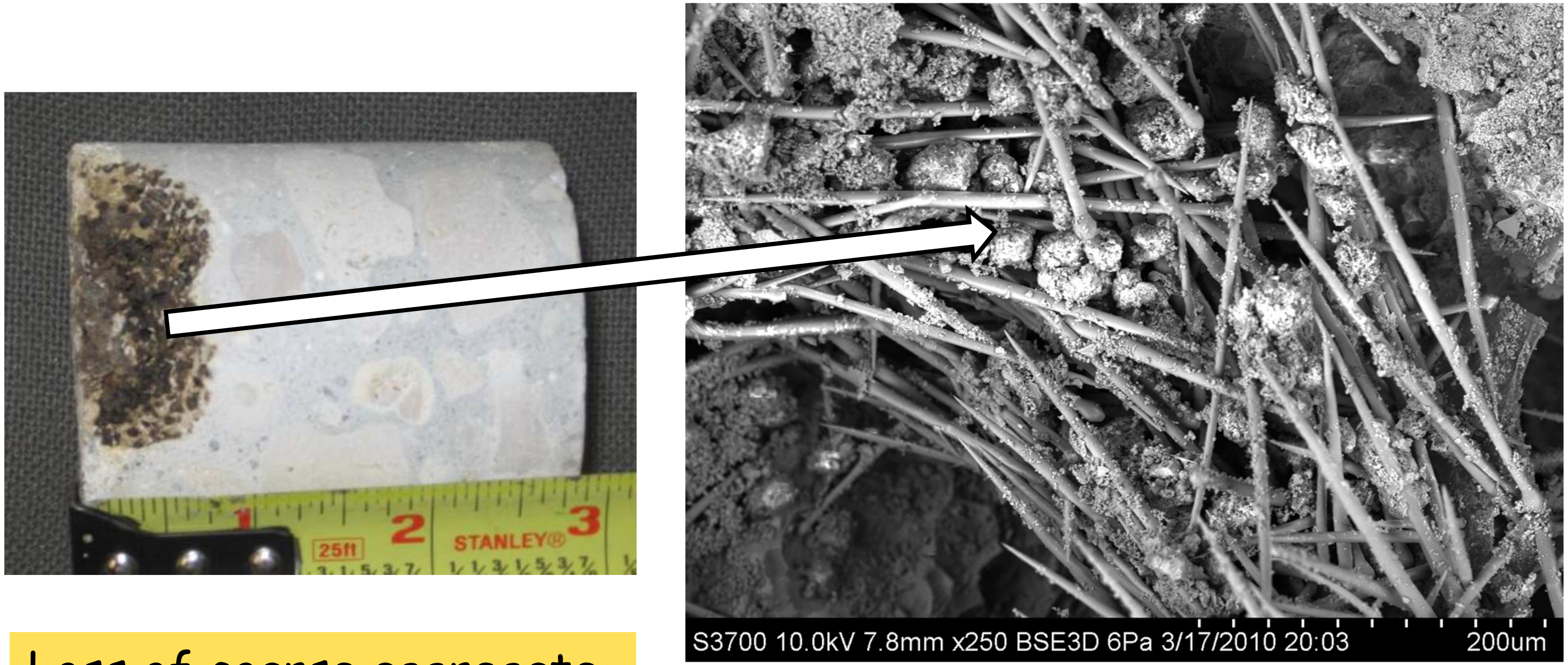
Bore holes along recently exposed surface



Penetration depths up to 2.5 cm were observed

Biodeterioration

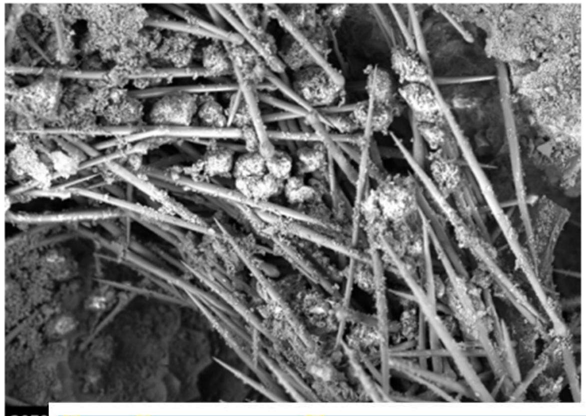
- Boreholes in aggregates examined by ESEM

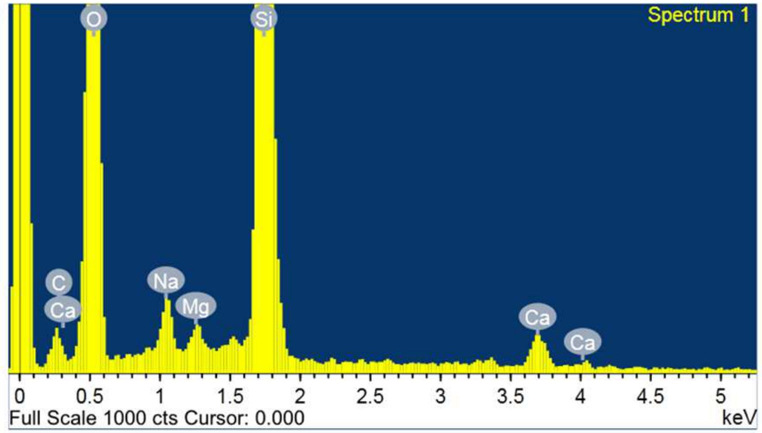


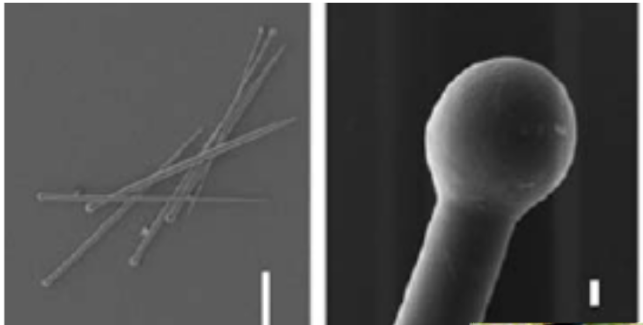
Loss of coarse aggregate by biodegradation clearly increases local permeability

Biodeterioration

- Deposits in boreholes found to be spicules; the skeletal structure of a boring sponge *Cliona*





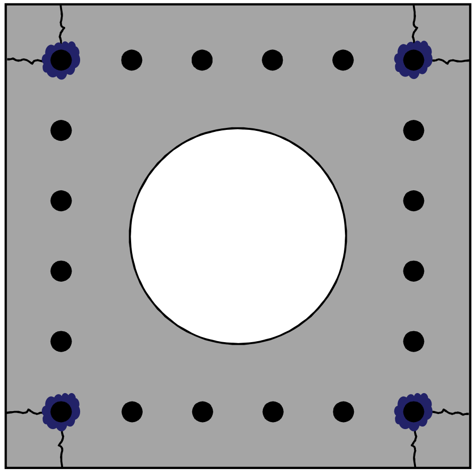


(Zea and Weil, 2003)

(Zea and Weil, 2003)

Chloride Induced Corrosion

- Extensive longitudinal cracking of concrete
  - Cracking most extensive at corners
  - 2-D flow of chlorides decreases time to corrosion
- Cracking linked to corrosion observed in splash zone

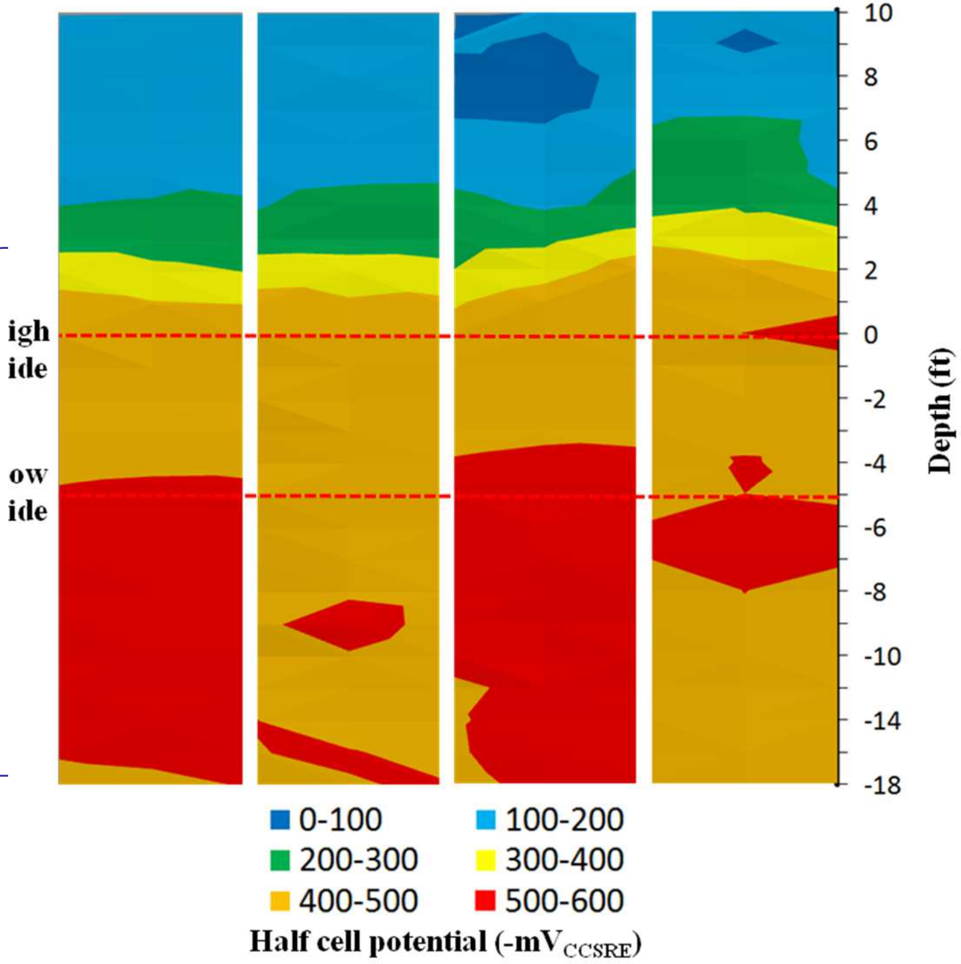


Chloride Induced Corrosion

Corrosion potential mapping

- > 350 mV 90% or greater probability of corrosion
- < 200 mV 10% or less probability of corrosion
- Does not indicate rate of corrosion

Probability of corrosion greatest in splash, tidal and submerged zones

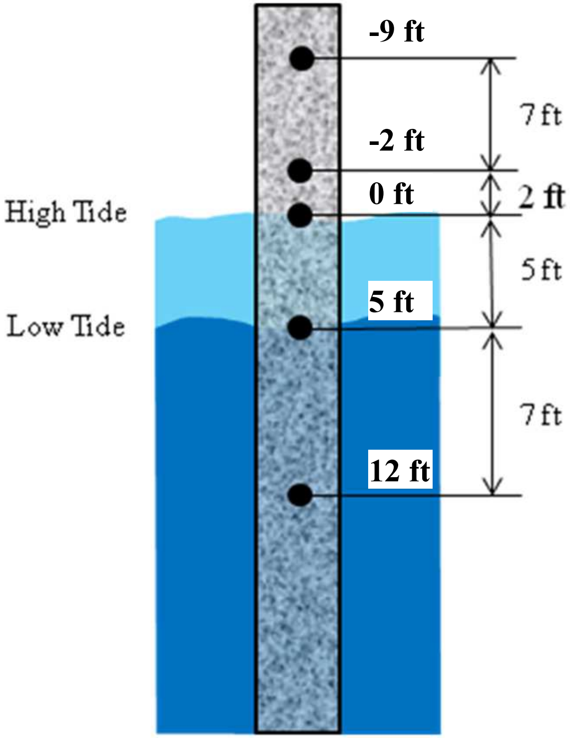


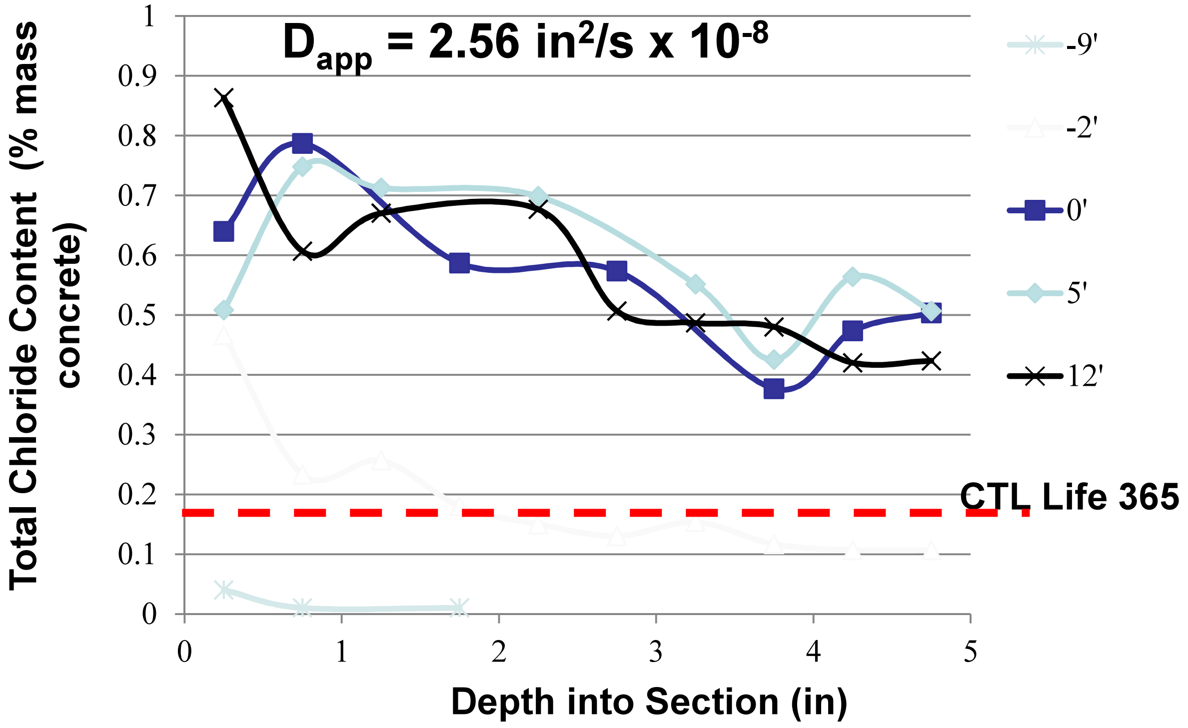
ASTM C879

Chloride Induced Corrosion

Chloride Ingress

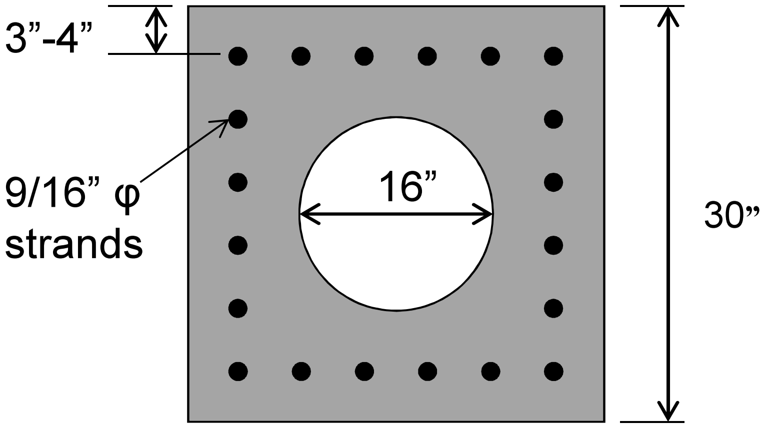
- Chloride profiles in atmospheric, splash, tidal, and submerged zones
- Shows chloride concentrations exceed threshold (CTL) at reinforcement depth

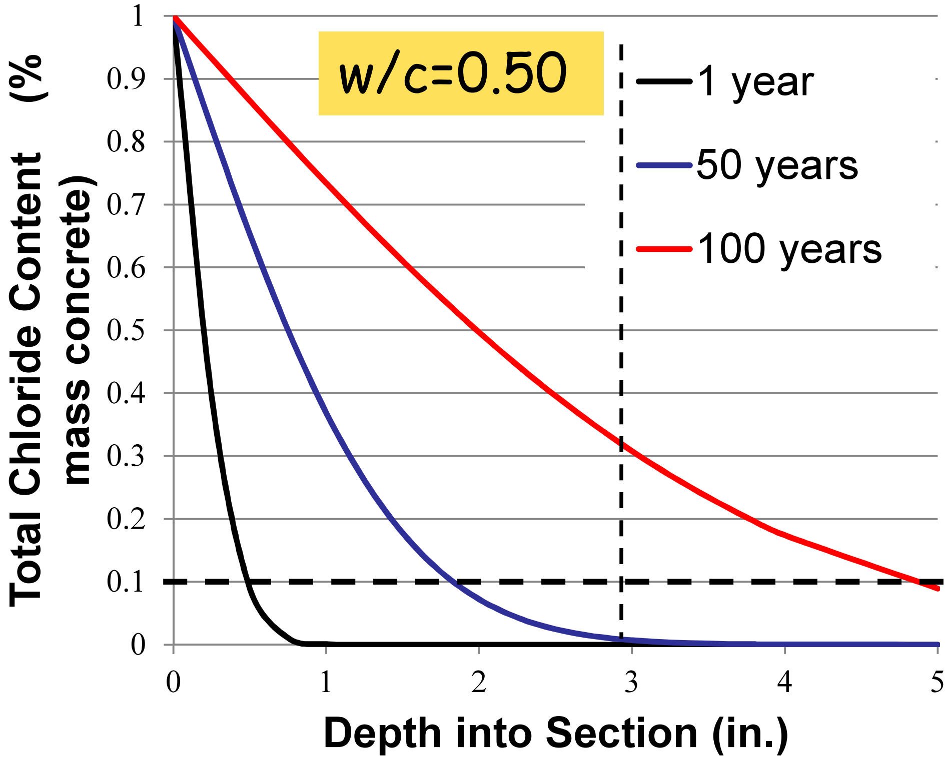




What is underlying cause for failure?

- Modeling suggests corrosion would not initiate for at least 50 years
- Why were piles removed after just 32 years of service?





Standard chloride modeling approaches do not account for cracking

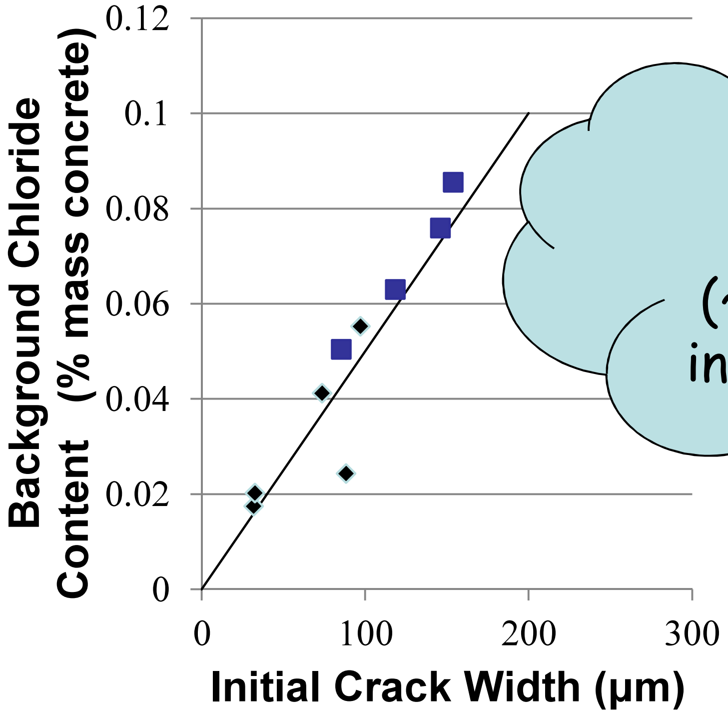
Multiple Underlying Causes

- Materials selection, mixture design
  - w/c=0.50
  - No SCMs
  - Type I cement
- Reinforcement design
  - Adequate cover
  - Corner strand most susceptible to environmental degradation
- Environmental conditions
  - Carbonation
  - Sulfate attack
  - Biodeterioration
  - Chloride-induced corrosion
- Other?

Decreased strength → cracking
Increased permeability →
increased degradation, cracking

Multiple Underlying Causes

- Construction practices
  - Overdriving of piles
  - Introduction of narrow cracks
  - “Fast path” for chloride, sulfate, carbonation ingress
  - Likely contributed to earlier than predicted failure



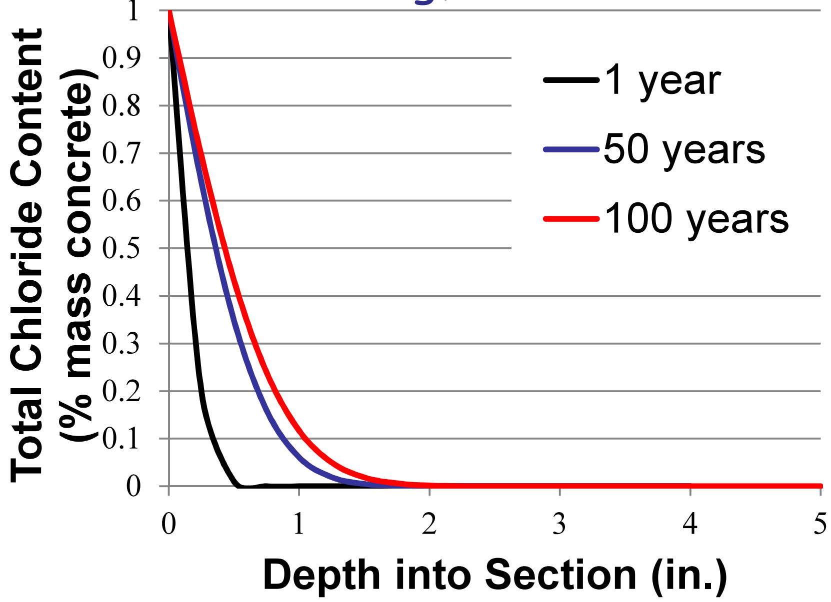
Even relatively narrow cracks (~200μm) lead to increased chloride content

(www.danbrownandassociates.com)

Remedies: New Construction

- Materials selection, mixture design
  - w/c=0.30-0.33
  - Sulfate resistant cement
  - Binary and ternary blends with SCMs for chloride and sulfate resistance
  - Avoid Pleistocene limestone coarse aggregate

Estimated Chloride Profiles: 50% slag, 5% metakaolin

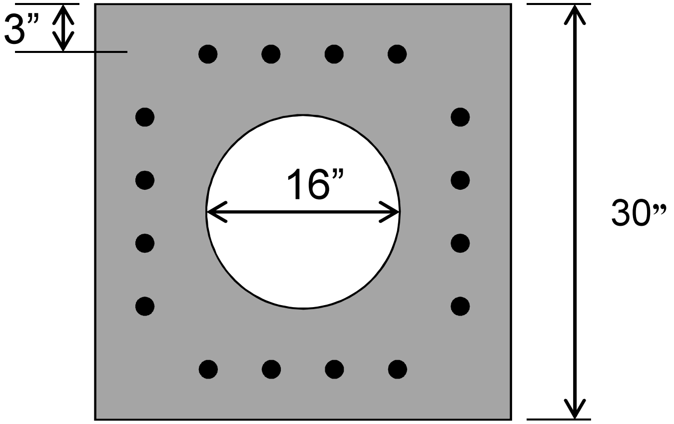


Variations in Sulfate Resistance with fly ash (F), slag (S), silica fume (SF), and metakaolin (MK)

Mix	Strength Degradation Rating	ASTM C 1012 Rating	Overall Exposure Rating
Type II	S3	S2	S2
Type III	S2	S1	S1
Type V	S3	S2	S2
T3-F15	S1	S3	S1
F25	S3	S3	S3
F25-MK5	S3	S2	S2
F25-MK10	S3	S3	S3
F25-SF5	S3	S3	S3
F25-SF10	S2	S3	S2
S35-MK5	S2	S3	S2
S50-MK5	S3	S3	S3
S35-SF5	S3	S3	S3
S50-SF5	S1	S3	S1

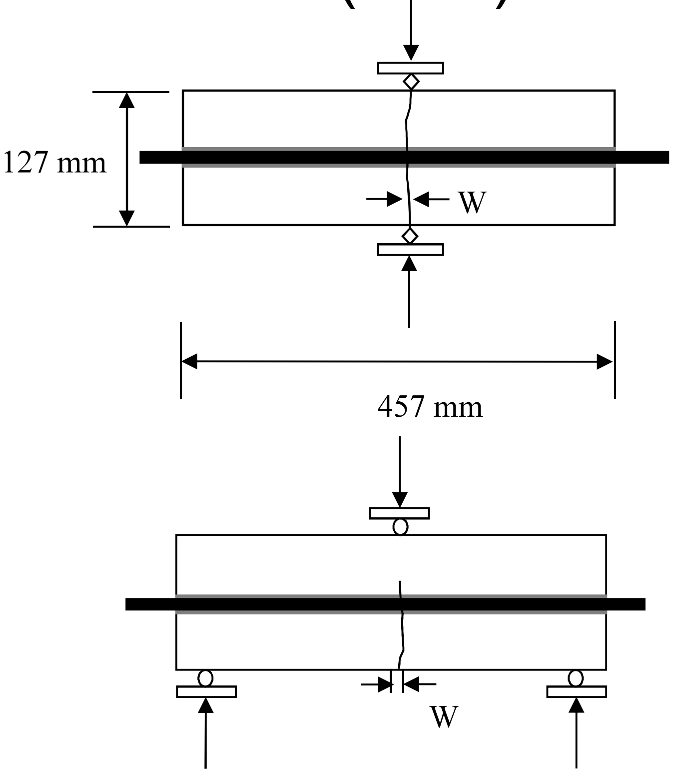
Remedies: New Construction

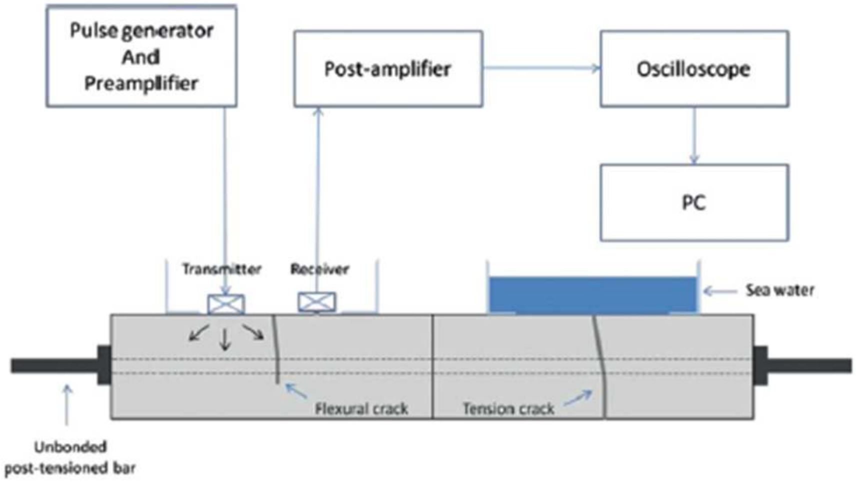
- Good curing practices
- Reinforcement design
  - Adequate cover
  - Eliminate corner strand
  - Corrosion resistant steel: high strength stainless strand (2205)
- Other?



Remedies: Self-Healing

- Produced concrete with narrow cracks through tensile and flexural loading
  - Examined ordinary concrete, binary, and ternary blends
  - Initial crack widths less than 200μm
- Monitored crack healing with diffuse ultrasound non-destructive evaluation (NDE) method





In et al, NDT&E, 2013

Remedies: Self-Healing

- Slag mixes showed fastest rate of crack filling
- Slag mixes showed most complete crack filling
- Fly ash mixes never filled completely

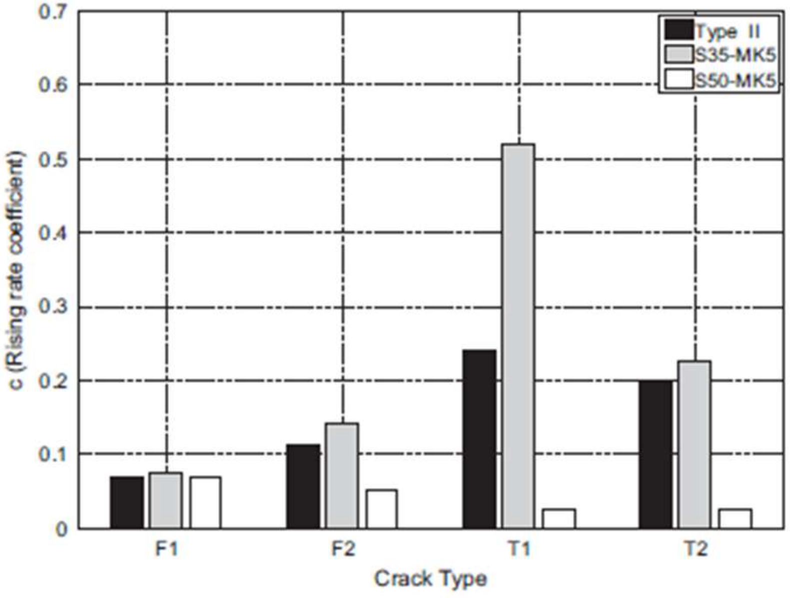
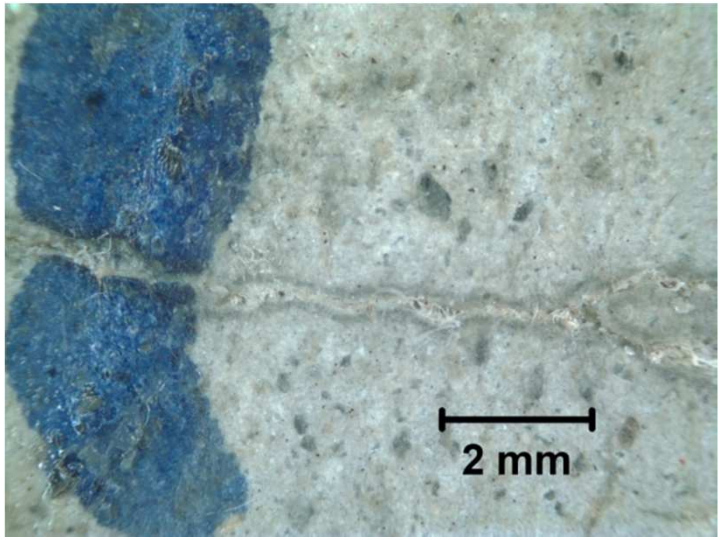
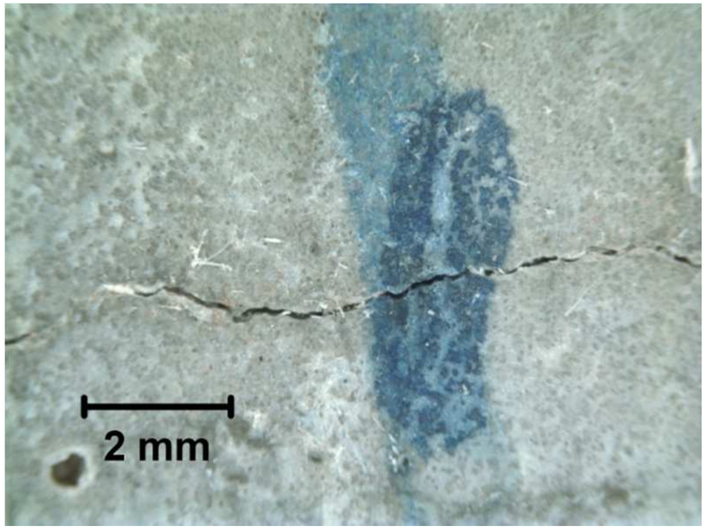


Fig. 9. Plot for "rate of healing" coefficient c vs. crack type in terms of mix composition.



S35-MK5 flexure crack specimen at 180 days



F25 flexure crack specimen at 180 days

In et al, NDT&E, 2013

Remedies: New Construction

Mix Design Recommendations for High Performance Marine Concrete

Mix Design	75 year Capability	100 year Capability
ACI 201		
T3-F15		
F25		
F25-MK5	🟩	
F25-MK10		
F25-SF5	🟩	
F25-SF10	🟩	
S35-MK5	🟩	
S50-MK5	🟩	🟩
S35-SF5	🟩	🟩
S50-SF5		

100 year service lives with slag-containing concrete, due in part to self-healing effects but also due to sulfate resistance and low Cl permeability

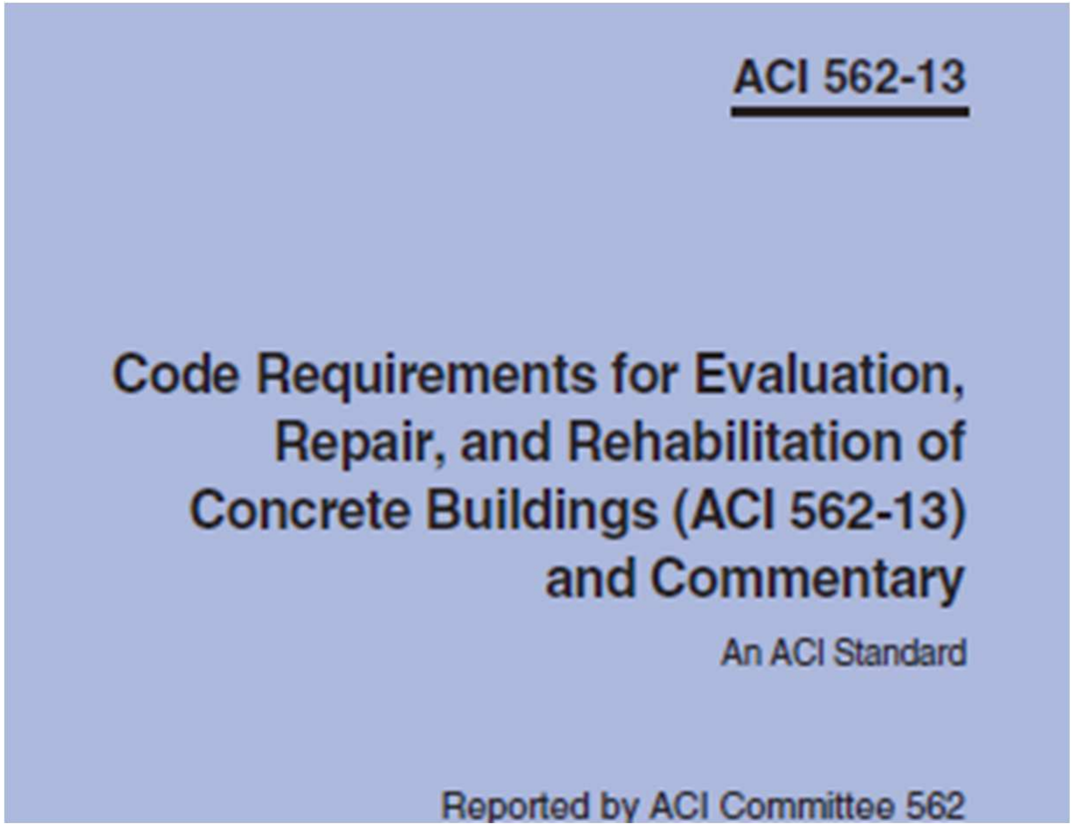
Remedies: Existing Structures

- ACI 224.1R07:

“Cracks need to be repaired if they reduce the strength, stiffness, or durability of the structure to an unacceptable level, or if the function of the structure is seriously impaired.”

- ACI 562-13

Concrete repair code



ACI 562-13

Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete Buildings (ACI 562-13) and Commentary

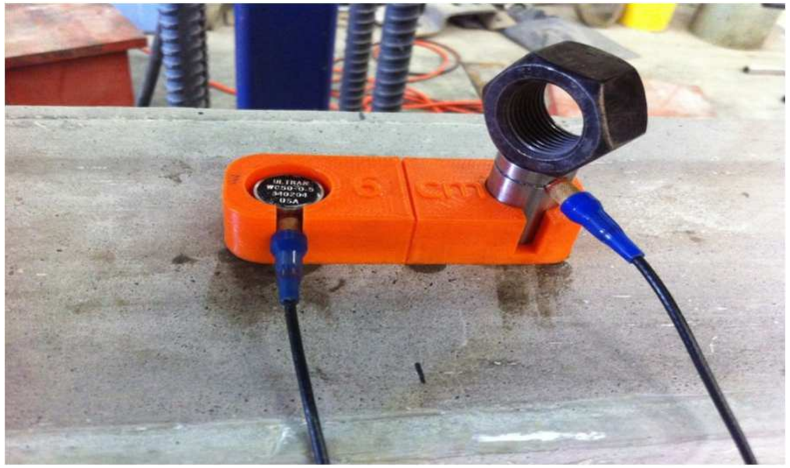
An ACI Standard

Reported by ACI Committee 562

Remedies: Existing Structures

- Non-destructive evaluation of crack *depth* needed
- Determine if crack extends through cover

Diffuse Ultrasound



Impact Echo

“Take Aways”

- Cracking can occur for a variety of reasons and can be macro or microscale
- Cracks which are visible will increase permeability
- Microcracks can also decrease durability
- Cracking can be due to multiple sources
  - Small cracks can grow larger, more connected
  - Chemical interactions with environment can lead to loss in strength → increases potential for cracking
- Practically, only very narrow cracks can be self-healed
- Must evaluate the environmental exposure conditions and desired service life to determine how to address cracking in existing structures