

Materials Related Distress of PCC



U.S. Department of Transportation
Federal Highway Administration

National Concrete Pavement
Technology Center



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Introduction

- Concrete pavements are inherently durable, having a history of exceptional long-term performance
- In some instances, pavement service life has been adversely affected by the concrete's inability to maintain its integrity in the environment in which it was placed
- These distress manifestations are categorized as materials-related distress (MRD)

What is Materials-Related Distress?

- MRD is commonly associated with the “durability” of the concrete
- Durability is not an intrinsic material property
 - Concrete that is durable in one application may rapidly deteriorate if placed in another application
 - “Durability” can not be measured directly. Potential durability can be inferred
- It is not related to loading, although loading can exacerbate the distress

MRD Manifestations

- Fine pattern cracking
 - Isolated to joints or over entire surface
 - Progressive in nature, getting worse over time
 - Degradation such as spalling or scaling
 - Often accompanied by staining and/or exudate
 - Evidence of expansion is also common with some types of MRD
- 

Are These MRDs?




And This?



What About This One?



Important Considerations

- The concrete constituents, proportions, and construction all influence MRD
 - Water is needed for deleterious expansion to occur
 - Severe environments (e.g. freezing and thawing, deicer applications, high sulfate soils, etc.) are major contributors
 - Strength does not equal durability
- 

Materials Basics - Hardened Cement Paste (HCP)

- Combination of cement, supplementary cementitious materials (SCMs), water, and admixtures to form hydration products and entrained air
 - HCP provides cohesion to the concrete mixture
 - Comprised (primarily) of calcium silicate hydrate (CSH) and calcium hydroxide (CH)
 - CSH - provides strength and is desirable
 - CH - provides little strength and plays a role in many MRD mechanisms
 - CH is soluble in water; solubility maximum at 0 °C (32 °F)
 - Pozzolans (e.g., fly ash) consume CH and yield CSH

Materials Basics - Aggregates

- Natural gravel, quarried rock, and sand, or manufactured mineral filler (e.g., air-cooled blast furnace slag and manufactured sand)
 - 65 – 80 % volume of the concrete
 - Less expensive than components of the HCP
 - Provide the load-carrying capacity of concrete
 - Provide dimensional stability
 - Generally considered inert but not always the case
 - Aggregate quality significantly impacts concrete quality
 - Local sources used (shipping considerations) so poor quality is often accepted but needs to be mitigated

Mechanisms of MRD Common in Pavements

- **Physical Mechanisms**

- Freeze-thaw deterioration of hardened cement paste
- Deicer scaling/deterioration
- Freeze-thaw deterioration of aggregate

- **Chemical Mechanisms**

- Alkali–aggregate reactivity
 - Alkali–silica and alkali–carbonate reactivity
- Sulfate attack
 - External and internal sulfate attack
- Corrosion of embedded steel

Freeze-Thaw Deterioration of Hardened Cement Paste

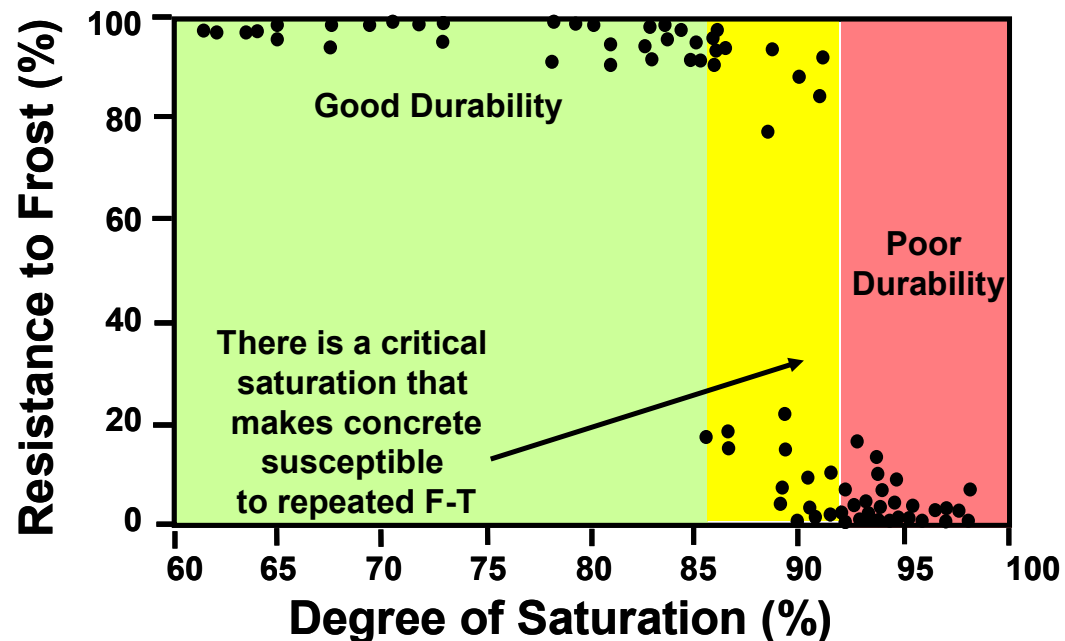
- Overview

- Deterioration of saturated HCP due to repeated freeze-thaw cycles
- Manifests as scaling, spalling, or map cracking
- Typically appears within 1 to 5 years after construction
- Prevented through the use of air entraining admixtures which create a protective air-void system

Freeze-Thaw Deterioration of Hardened Cement Paste

- Mechanism

- Results when the HCP becomes “critically saturated” and concrete undergoes F-T cycles
- The expansion of ice causes tensile forces that crack concrete



Freeze-Thaw Deterioration of Hardened Cement Paste

- Prevention

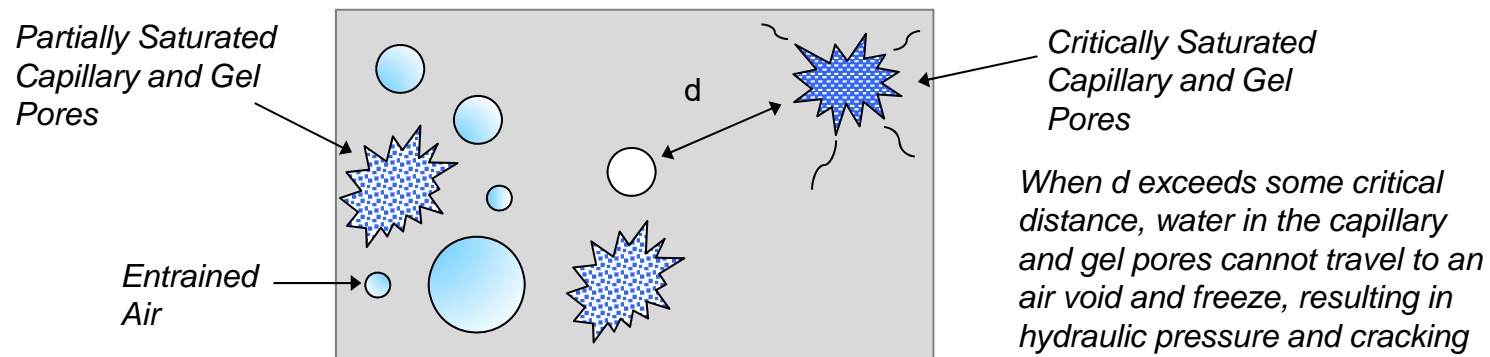
- Entrained air-void system

- Delays the time to critical saturation

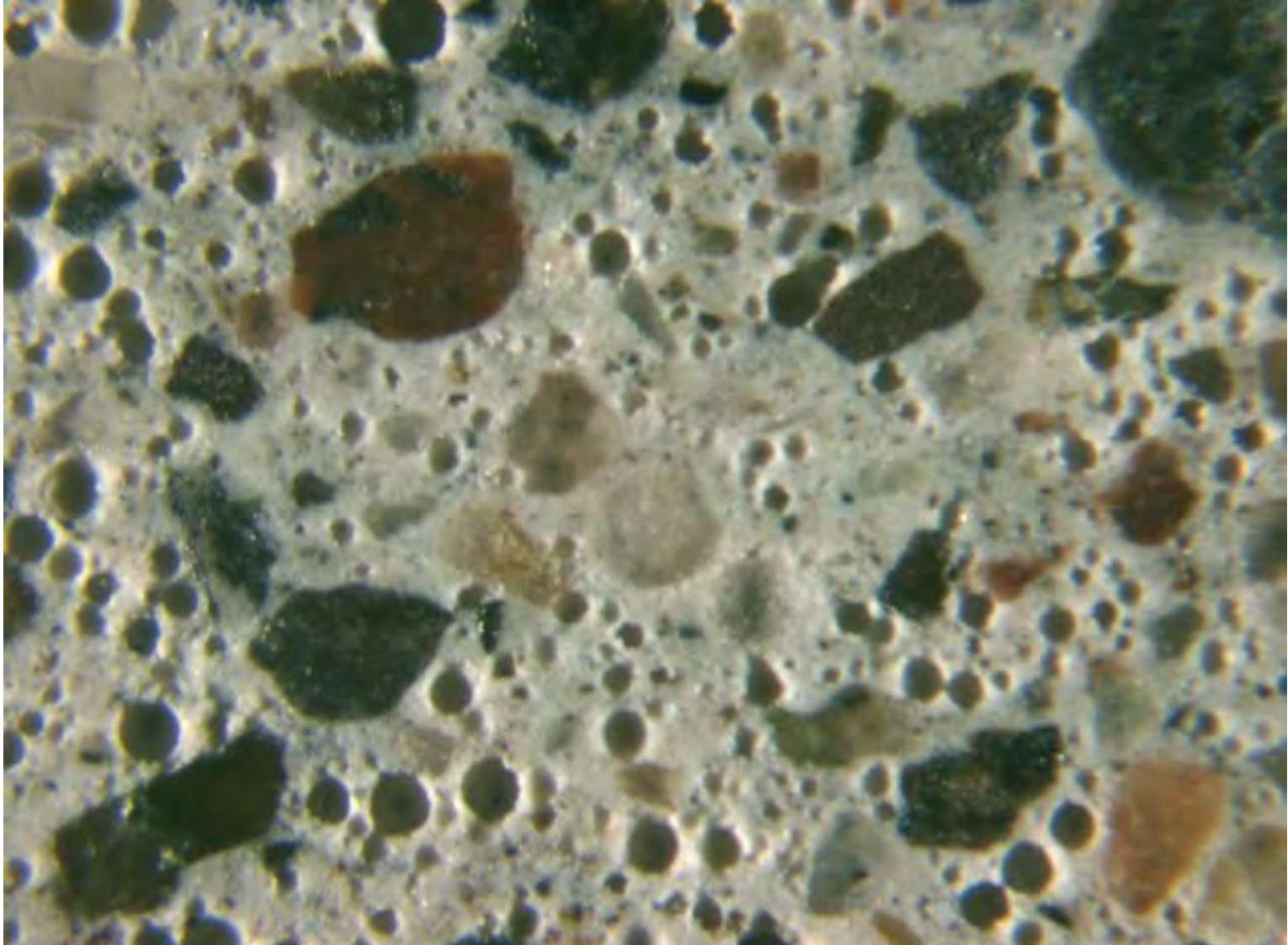
- Provides space for ice formation

- Allows for water movement (minimizing hydraulic pressure)

- Volume and spacing of voids critical




Air-Void System



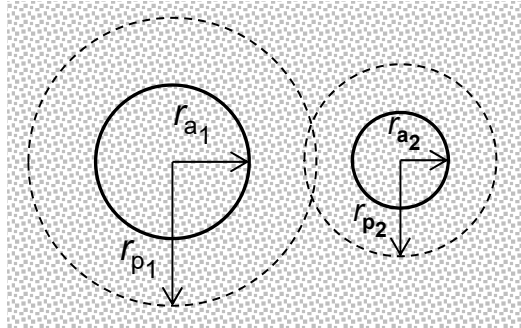
Air-Void System

- Testing

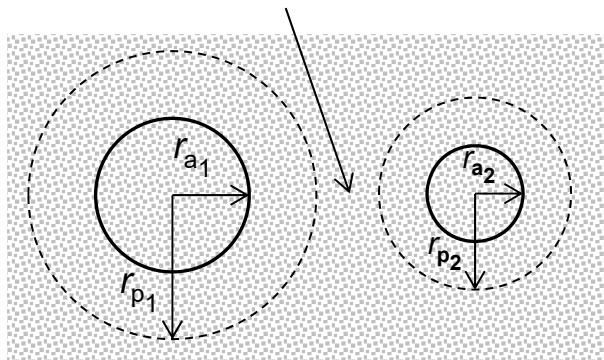
- ASTM C231 (pressure meter), ASTM C173 (roller meter), and ASTM C138 (unit weight bucket) all measure **ONLY** the air content (A)
 - Air content is the volumetric air content, typically 4 – 8 % volume by specification
 - For QC purposes it is sufficient to measure the volume of air
 - To fully establish F-T durability other air-void system (such as spacing factor) parameters are more important
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Air-Void System

- F-T durability requires adequate air void system



unprotected paste



r_{a_n} = radius of air void n

r_{p_n} = radius of FT protection

➤ Spacing Factor (\bar{L}):

- Approximates the constant distance from the surface of each air void surface, which would encompass some large fraction of the paste[†].
- Maximum: less than 0.2 mm (0.008 in.) (ACI 201)

➤ Specific Surface (α):

- Surface-to-Volume Ratio
- Defines the surface area associated with a unit volume of void space – smaller voids (i.e., more voids per unit volume) result in a higher specific surface
- Minimum: 24 mm²/mm³ (600 in.²/in.³)

➤ Air Content (A)

- Measured on hardened & fresh concrete
- L and α assumed proportional to A in fresh concrete

[†] Snyder, K., N. Natesaiyer and K. Hover (2001). The Stereological and Statistical Properties of Entrained Air Voids in Concrete: A Mathematical Basis for Air Void System Characterization. Materials Science of Concrete. S. Mindess and J. Skalny. Westerville, OH USA., American Ceramic Society. VI: 129-214.

Air-Void System

- Testing
 - To measure spacing factor, specific surface, and other air-void system parameters, it is necessary to analyze hardened concrete using ASTM C457
 - Requires special equipment and skilled operator (petrographer)
 - Because only hardened concrete can be analyzed, can only be used as a QA tool
 - AASHTO TP 118 (SAM meter) is an emerging technique that measures a combined parameter (SAM number) on fresh concrete that correlates to F-T performance in a manner similar to ASTM C457

Air-Void System


- Testing
 - Measurement of F-T performance of a concrete mixture is measured using ASTM C666 *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing*
 - Measures the loss in dynamic modulus after undergoing up to 300 cycles of freezing (either in air or water) and thawing (in water)
 - Test is severe and does not always correlate with field performance, but serves as a mixture screening test
 - Performed as part of mixture design, not as part of a QC/QA program (typically)

Deicer Scaling



Deicer Scaling/Deterioration

- Overview

- Deicer chemicals can amplify paste freeze-thaw deterioration and may also chemically react with or degrade hydrated paste constituents
 - Manifests as scaling, spalling, or map cracking with possible staining near joints
 - Typically appears within 1 to 5 years after construction
 - Prevented through the use of air entraining admixtures and a relatively low water-to-cement ratio
 - Minimize finishing, which can reduce air content at surface
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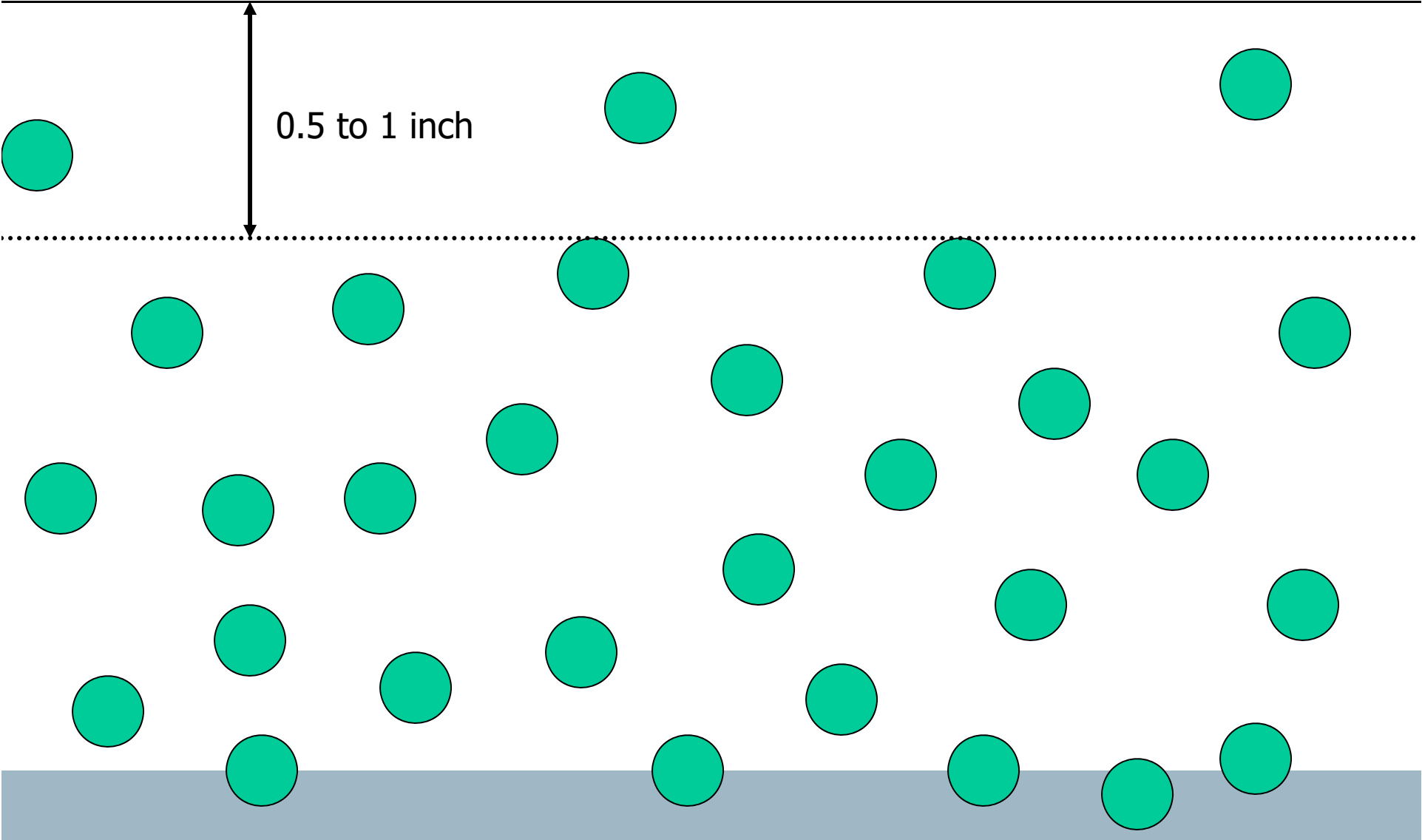
Deicer Scaling/Deterioration

- Mechanism

- Not well understood
- Current research indicates scaling is due to tensile forces developed in the surface layer of concrete due to expansion of the ice layer[†]
- The expansive forces of the ice are at a maximum when the solution freezing on the surface contains ~3% dissolved salt, and the type of salt is not a factor[†]
- Often seen when the concrete is over finished, working the air out of the surface layer

[†] Valenza, J. J., and G. W. Scherer. 2007. A Review of Salt Scaling: II. Mechanisms, *Cement and Concrete Research*. 37(7), 1022-1034.

Impact of Poor Finishing



Deicer Scaling/Deterioration

- Prevention


- Do not over finish
- Good air-void system to begin with
- Avoid salts – especially at early ages (i.e., one year or less)
- Proper curing
- Penetrating sealers to reduce water ingress

Deicer Scaling/Deterioration

- Testing
 - Scaling performance of a concrete mixture is measured using *ASTM C672 Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals*
 - Assesses (by visual inspection only) the loss of material from the concrete surface after ponding dilute salt solution on the surface and exposing the samples to 50 cycles of F-T
 - Test is widely criticized for its subjectivity; modifications include measuring the mass loss from the sample
 - Test very susceptible to how specimens are finished

F-T Deterioration of Aggregate (D-cracking)

- Overview


- Caused by the fracturing or dilation of coarse aggregate under freeze-thaw cycling in a saturated state
 - Manifests as cracking and staining parallel to joints and cracks that may eventually spall
 - Commonly manifests within 10 to 15 years
 - Prevented through the use of non-susceptible aggregates or reduction in the top size of the coarse aggregate
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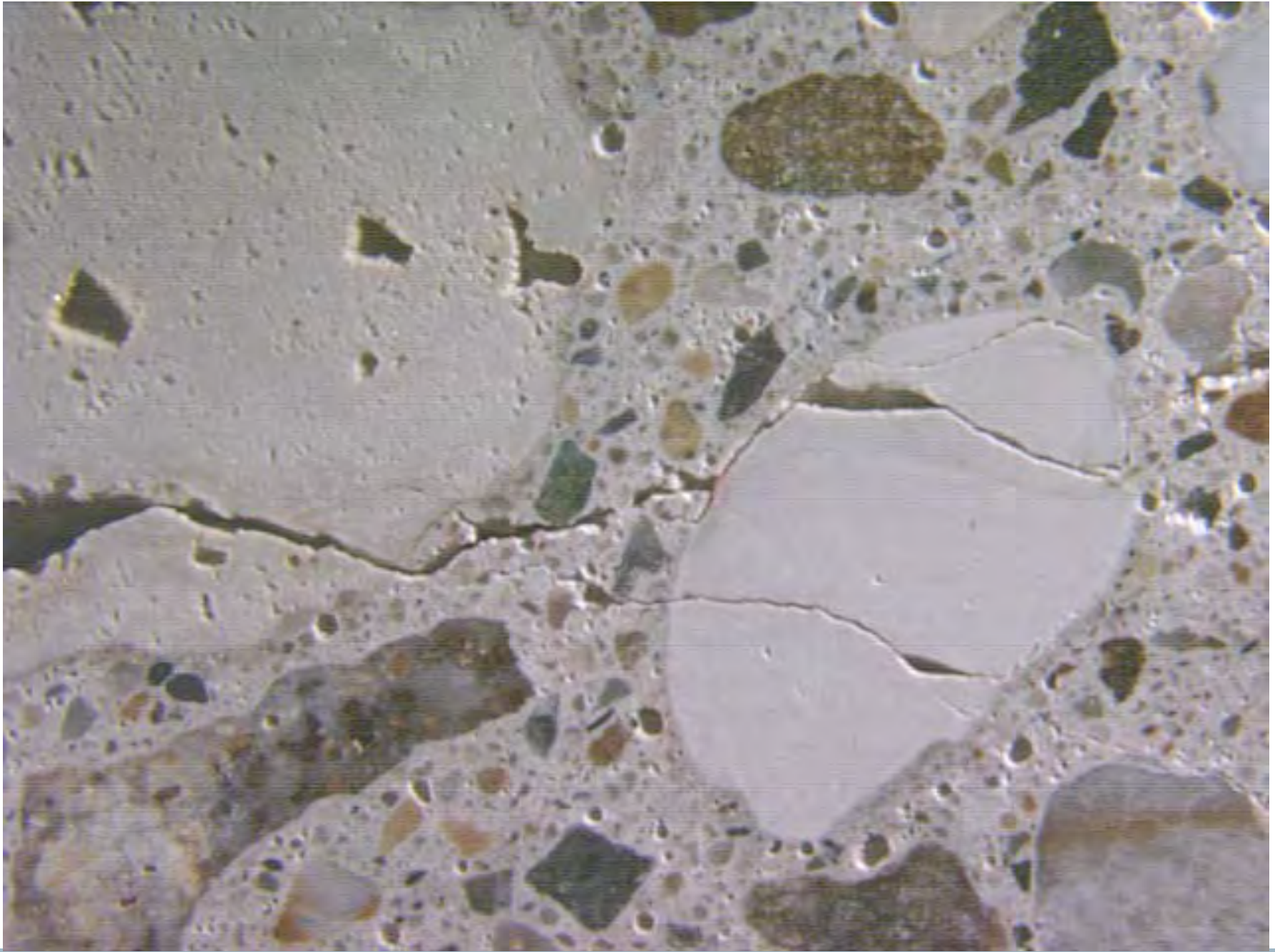
Aggregate Freeze-Thaw Deterioration



F-T Deterioration of Aggregate

- Mechanism

- Aggregates are porous and absorb water
 - The rate of water absorption and the rate of water expulsion is a function of the pore size distribution of the aggregates
 - D-cracking aggregates have a pore size distribution that does not allow for rapid expulsion of water as a freezing front moves through an aggregate
 - The resulting hydrostatic pressure forces can exceed the tensile strength of the aggregate
- 



18.1 x 13.6 mm

Photo credit K. Peterson, University of Toronto

F-T Deterioration of Aggregate

- Prevention

- Avoid the use of susceptible aggregates

- D-cracking aggregates are best identified by experience

- When it is necessary to use susceptible aggregates, limit the aggregate top size

- A smaller aggregate particle diameter allows for more rapid expulsion of absorbed water



F-T Deterioration of Aggregate

- Testing

- Iowa Pore Index Test (IPIT)

- Measures the amount of water absorbed by aggregates under pressure (241 kPa, 35 psi) in a prescribed time

- Water absorbed 0-1 minutes \propto macropores (Primary Load)

- Water absorbed 1-15 minutes \propto micropores (Secondary Load)

- Secondary Load > 27 mL is associated with D-racking susceptible aggregates

- IPIT results are more representative of the parent rock because of the large sample volume used (9000 g)

- Variable/erroneous results for aggregates with rapid rates of early absorption

- No discernible trends in the results from gravels

F-T Deterioration of Aggregate

- Testing

- Washington Hydraulic Fracture

- Measures the amount of particle fracture that occurs after pressurizing aggregate (7930 kPa, 1150 psi) submerged in water

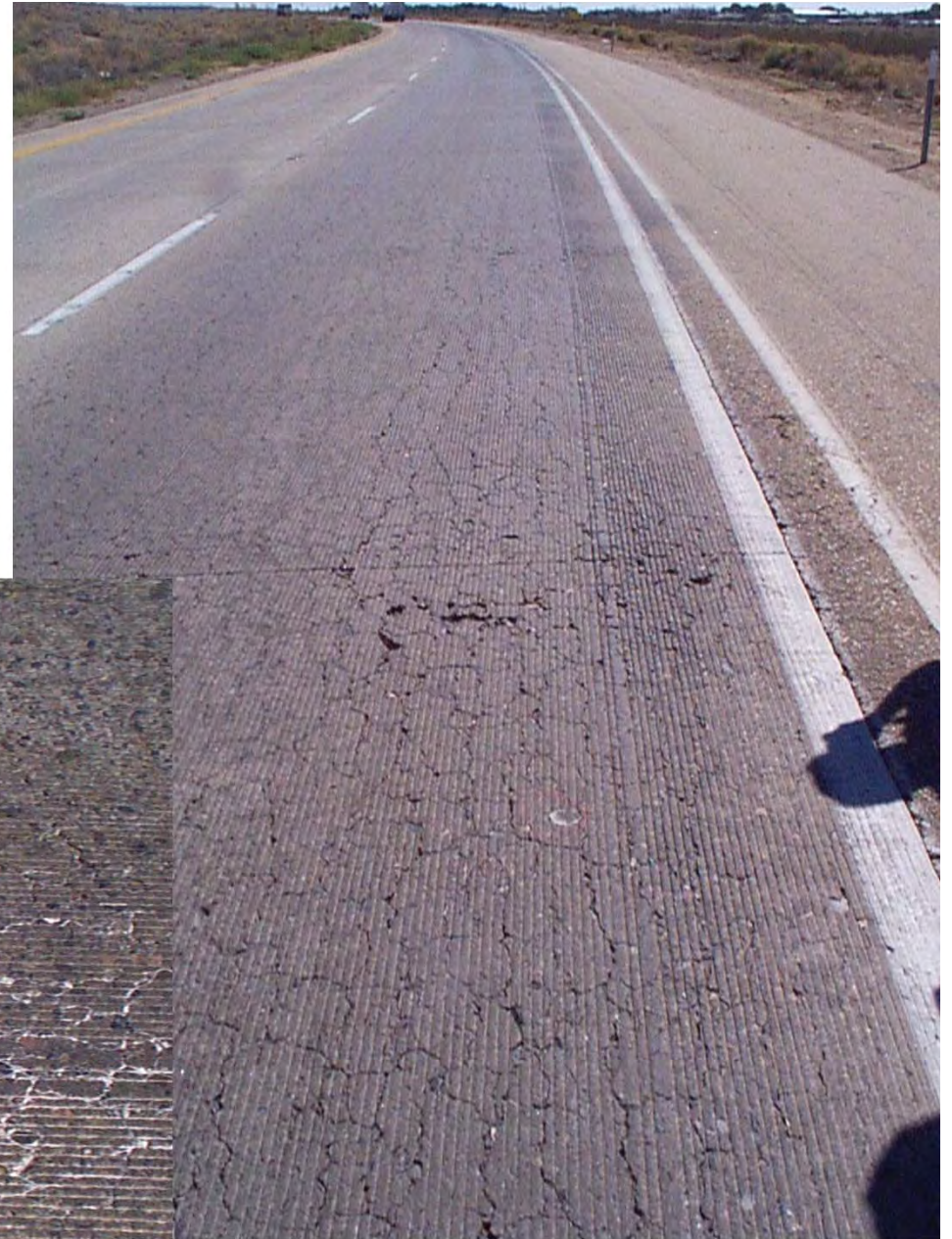
- Start with n particles retained on a 12.5 mm (1/2 inch) sieve. After 10 cycles of pressure and release, report the increase in the number of particles retained on a #4 sieve as a percentage of n (percent fracture)

- From these measurements determine the number of pressurization cycles required to create a percent fracture of 10% - low values indicate more D-cracking susceptibility

- Can identify aggregates likely to fail due to hydraulic pressures


- Does not simulate the confining effect of the HCP

Alkali-Silica Reactivity



Alkali-Silica Reactivity

- Overview

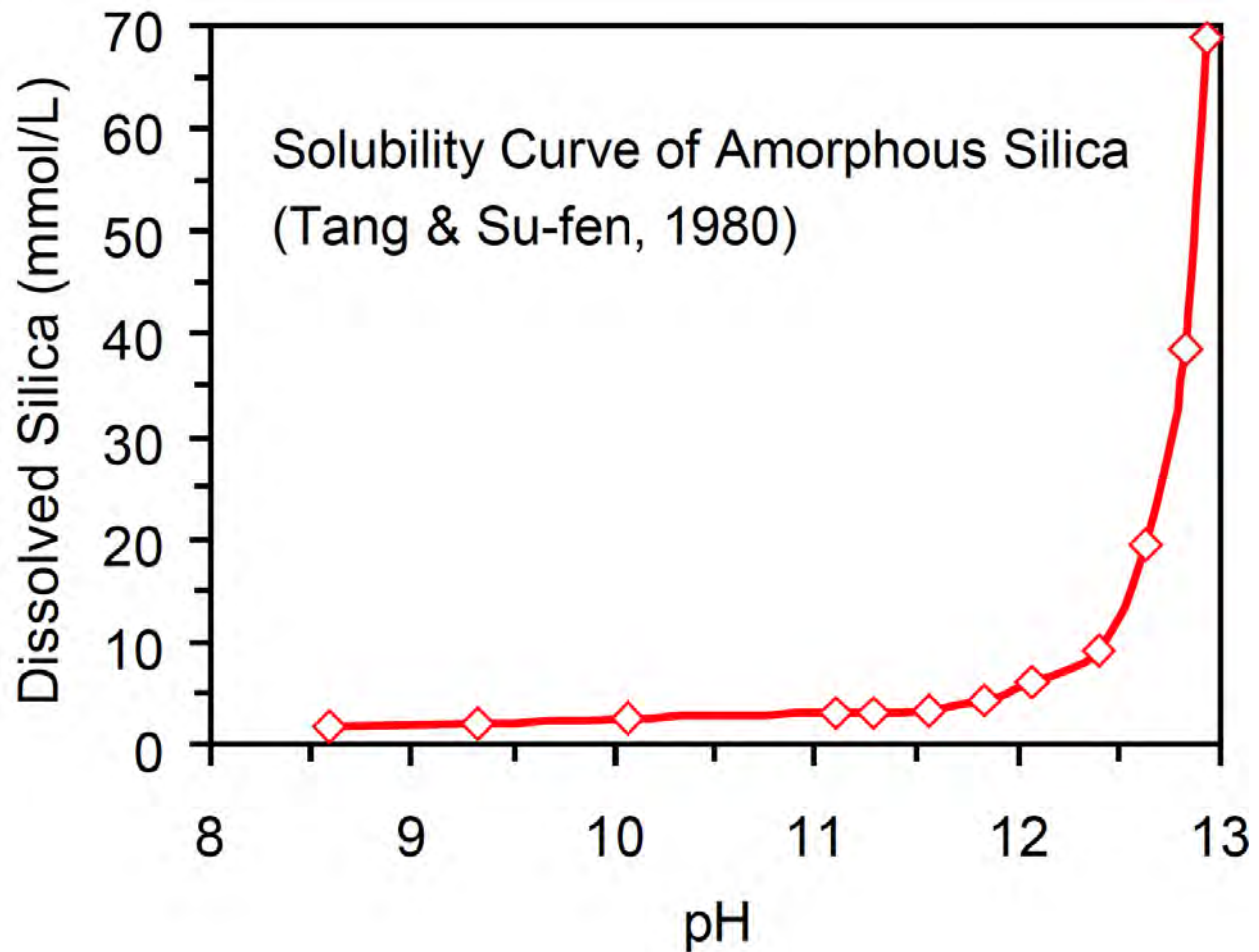
- Caused by a reaction between alkali hydroxides in the paste pore solution and reactive silica in aggregate that forms expansive reaction product
 - Manifests as map cracking over the entire slab area. Exudate is common, as is expansion related distress
 - Commonly occurs within 5 to 15 years
 - Prevented through the use of non-susceptible aggregates, limiting total mixture alkalinity, and addition of pozzolans
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Alkali-Silica Reactivity

- Mechanism

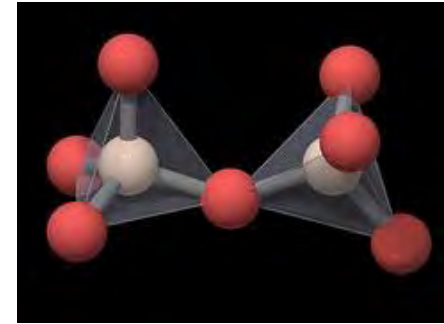
- In the presence of pore solution (i.e., H_2O , Na^+ , K^+ , Ca^{2+} , OH^- , and H_3SiO_4^- ions), reactive silica undergoes depolymerization, dissolution, and swelling
- Depends on pH of the solution, not on alkalis per se, although they control the pH
- The higher the pH, the more soluble the silica
- Attack is more aggressive when the silica is not crystalline (i.e., amorphous or crypto-crystalline) as in cherts or opaline shales

Alkali-Silica Reactivity



Tang, M.S. and Su-Fen, H. (1980), 'Effect Of $\text{Ca}(\text{OH})_2$ On Alkali-Silica Reaction', *Eighth International Congress of Cement Chemistry* (2; Paris, France), 94-99.

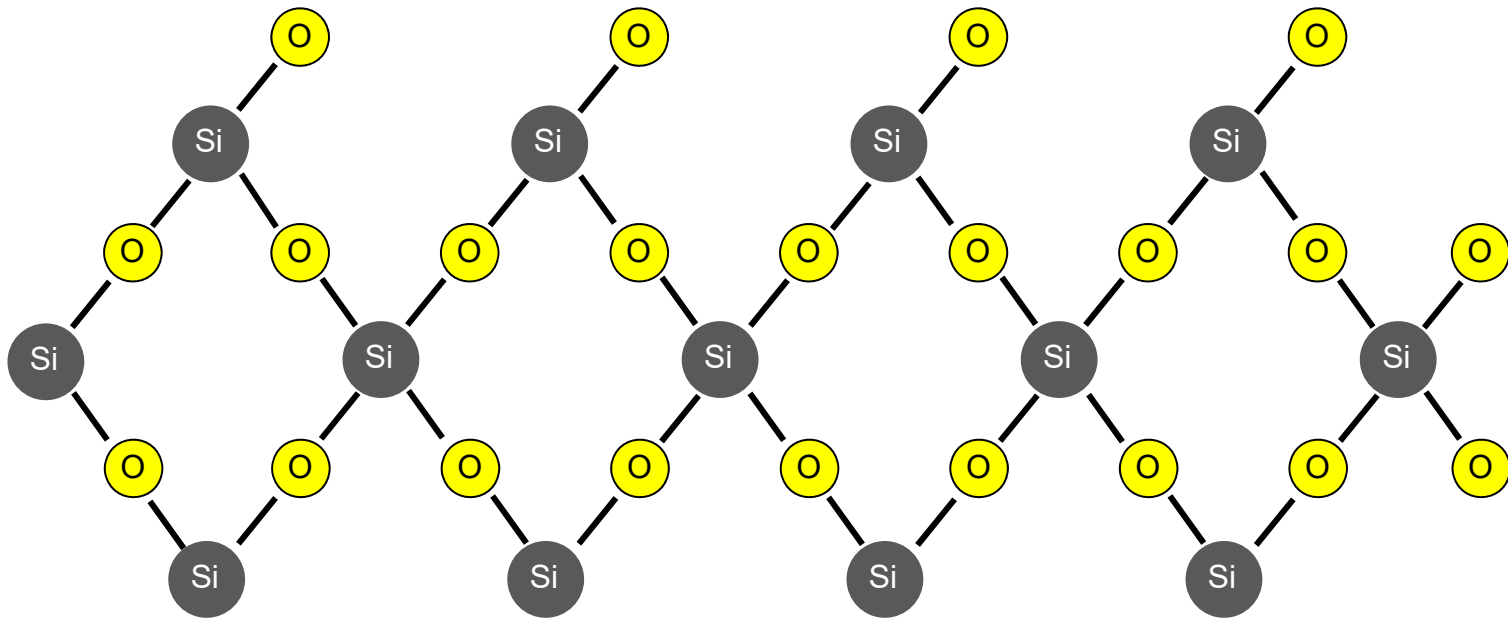
Alkali-Silica Reactivity



Silica tetrahedra forming siloxane bond[†]

- Mechanism

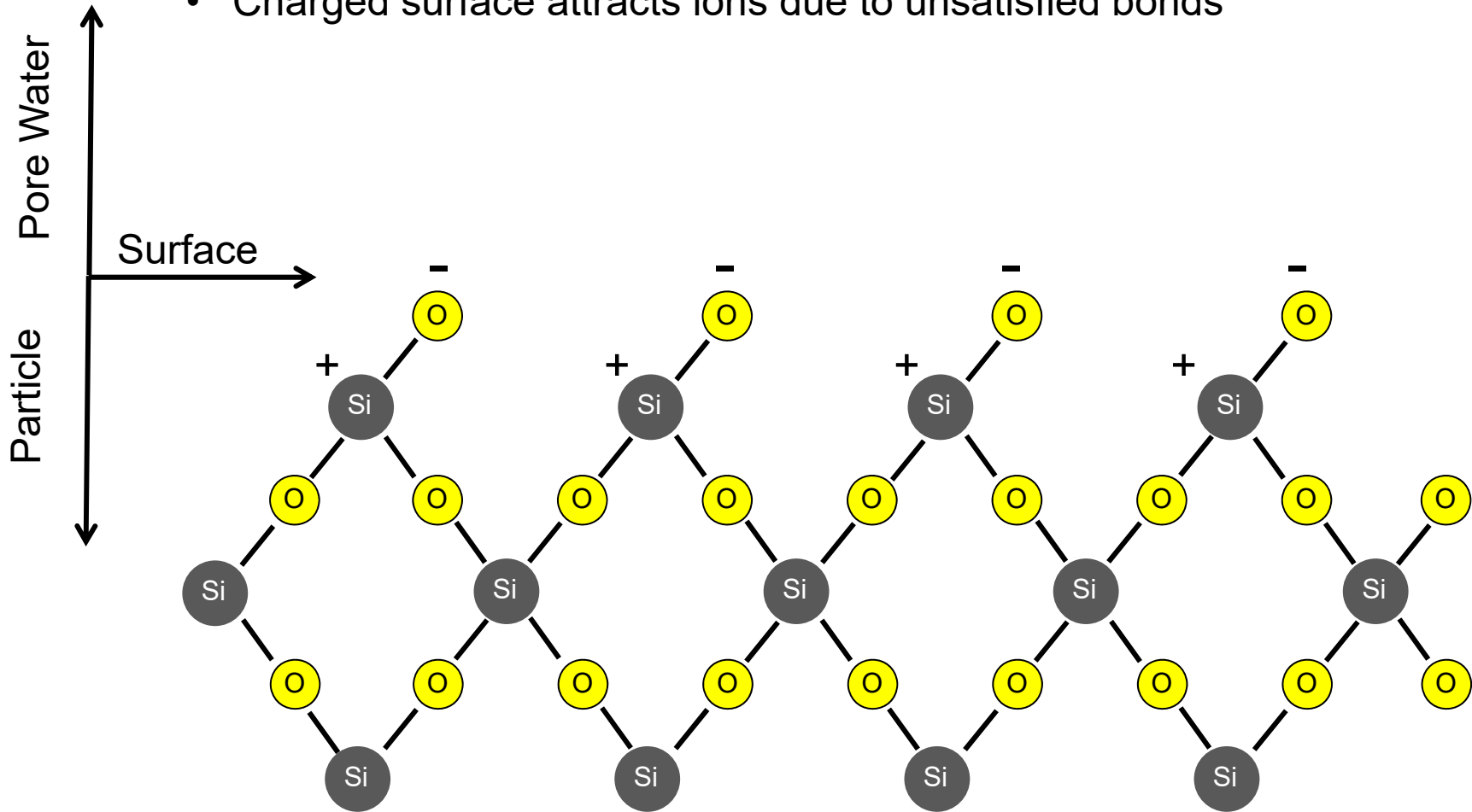
- Silicon and oxygen prefer to combine in “tetrahedral coordination”
- Four (4) oxygens surround each silicon – open surface structure



[†] http://www.quartzpage.de/gen_struct.html

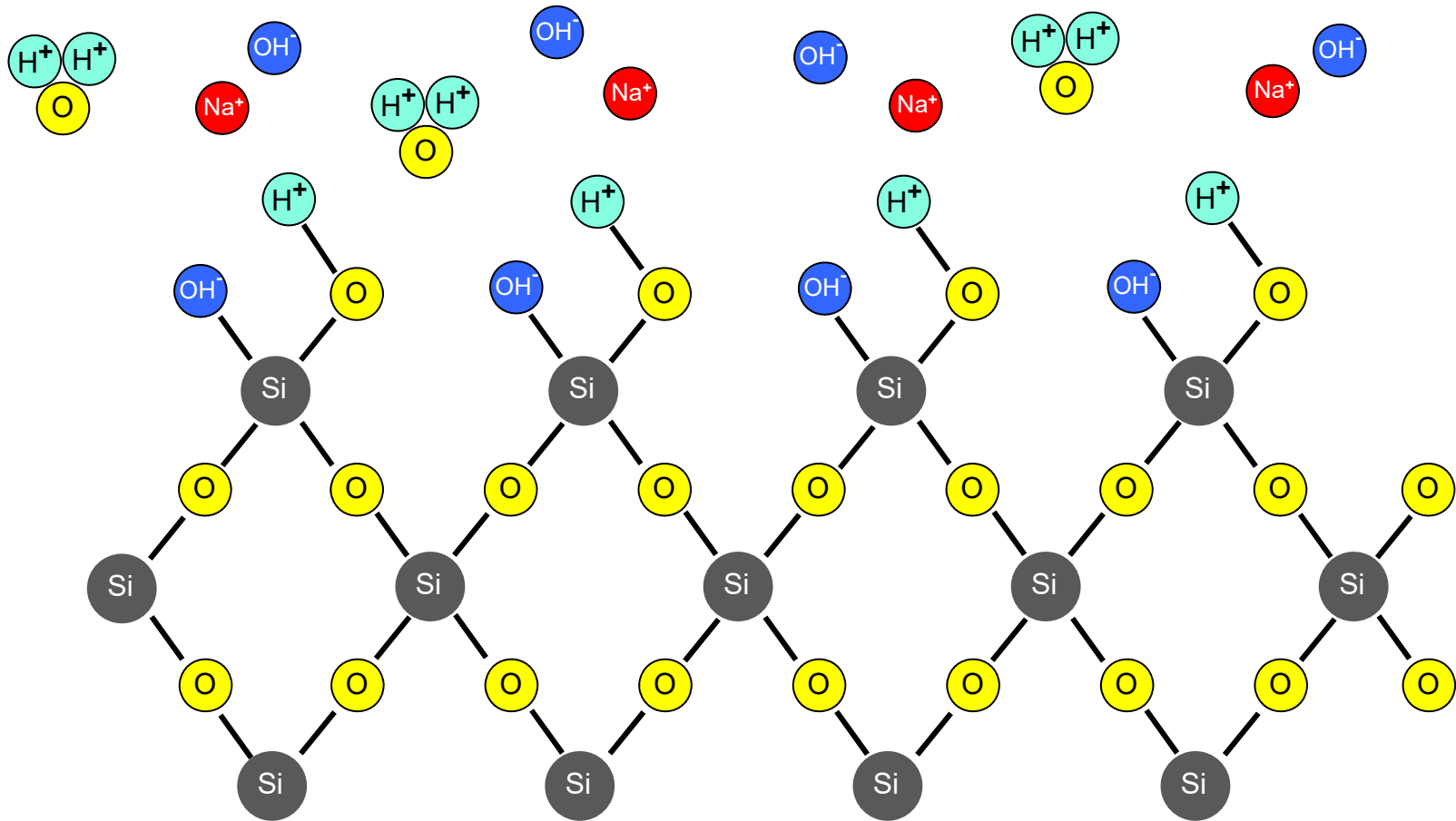
Alkali-Silica Reactivity

- Charged surface attracts ions due to unsatisfied bonds



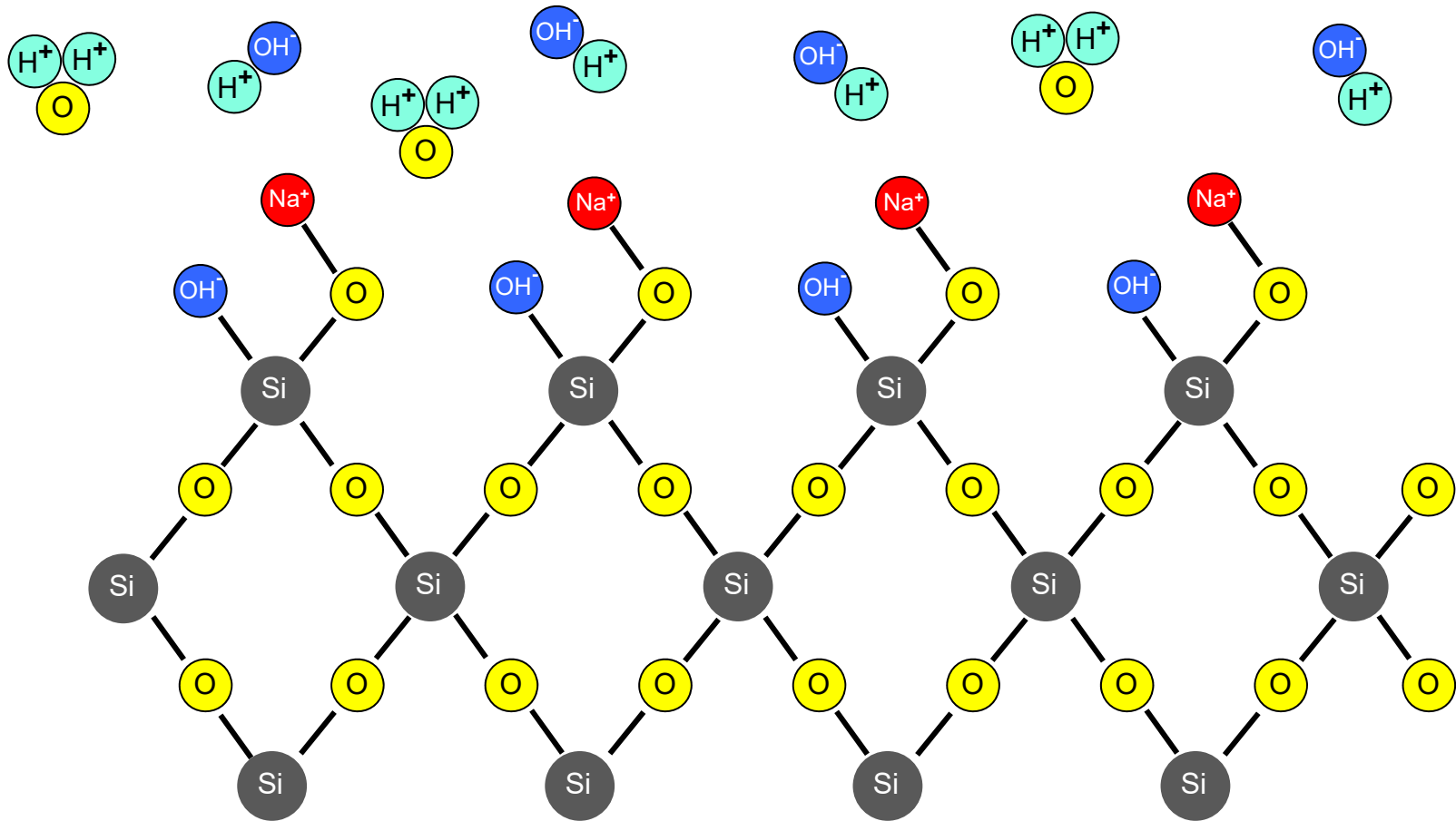
Alkali-Silica Reactivity

- Charged surface attracts H^+ and OH^- ions from alkali pore water



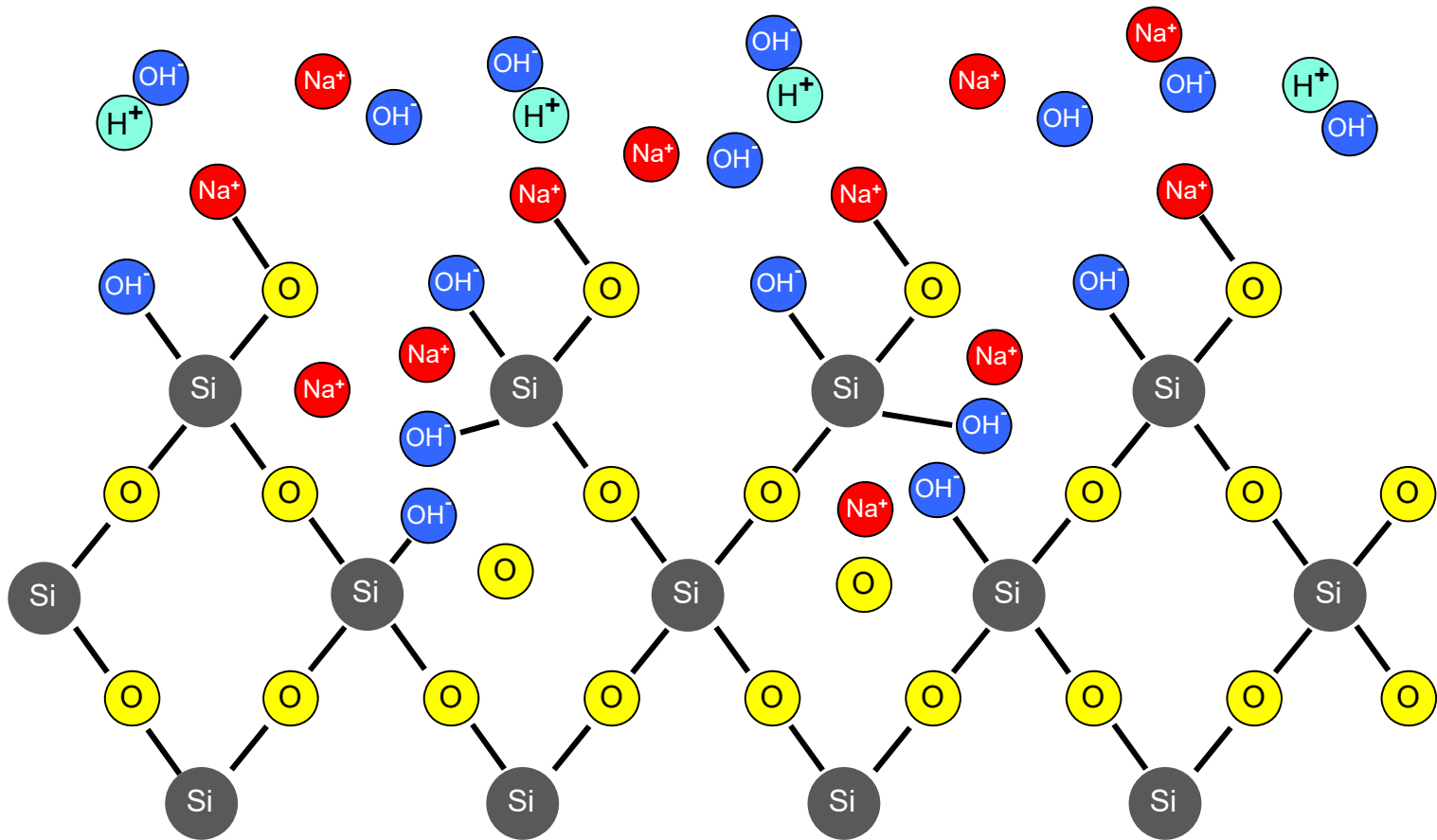
Alkali-Silica Reactivity

- With alkalis in pore water, Na^+ substitutes for H^+



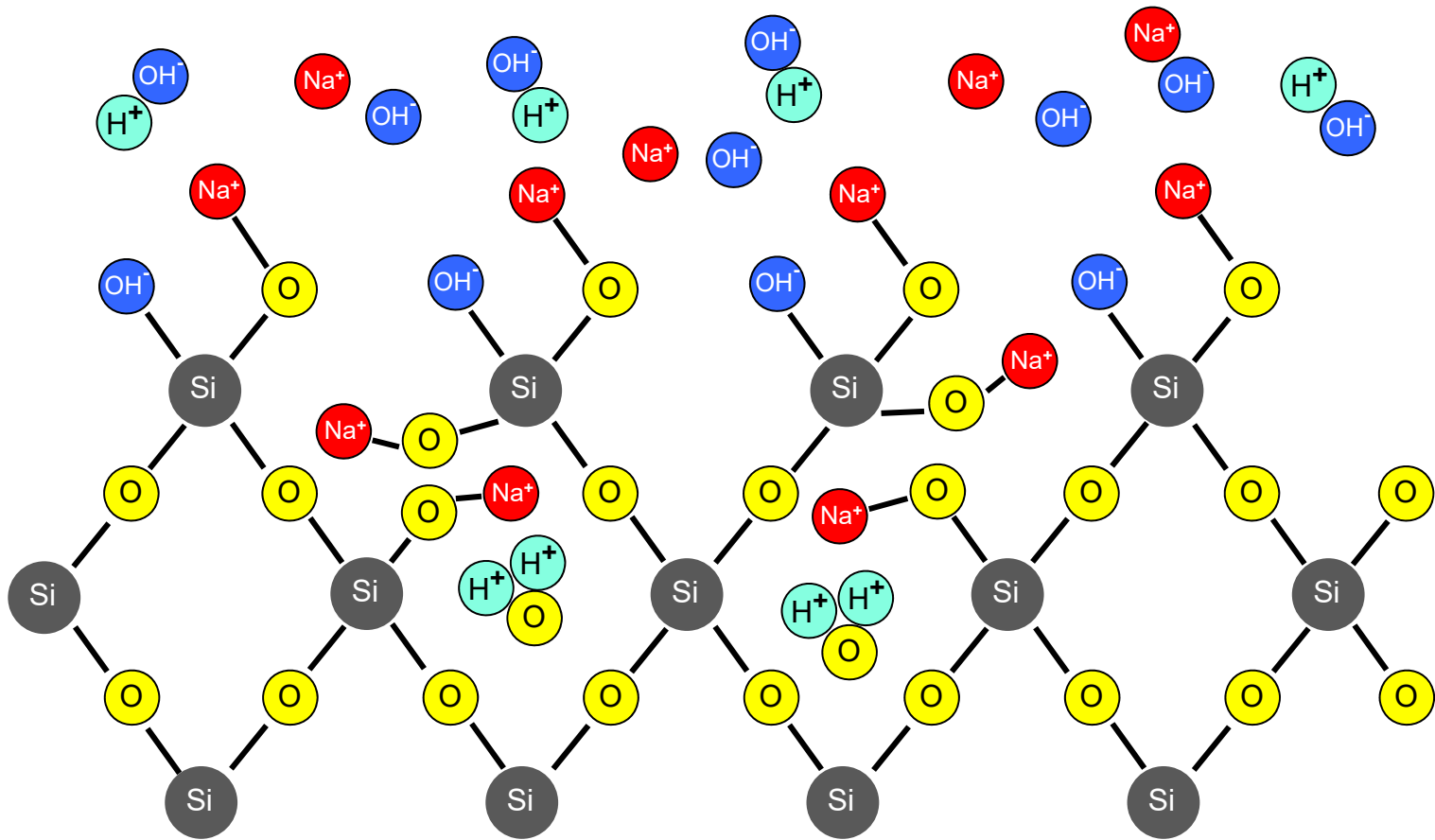
Alkali-Silica Reactivity

- If any excess alkalis still exist, the associated hydroxyl (OH^-) breaks the Si-O-Si bond and free an oxygen



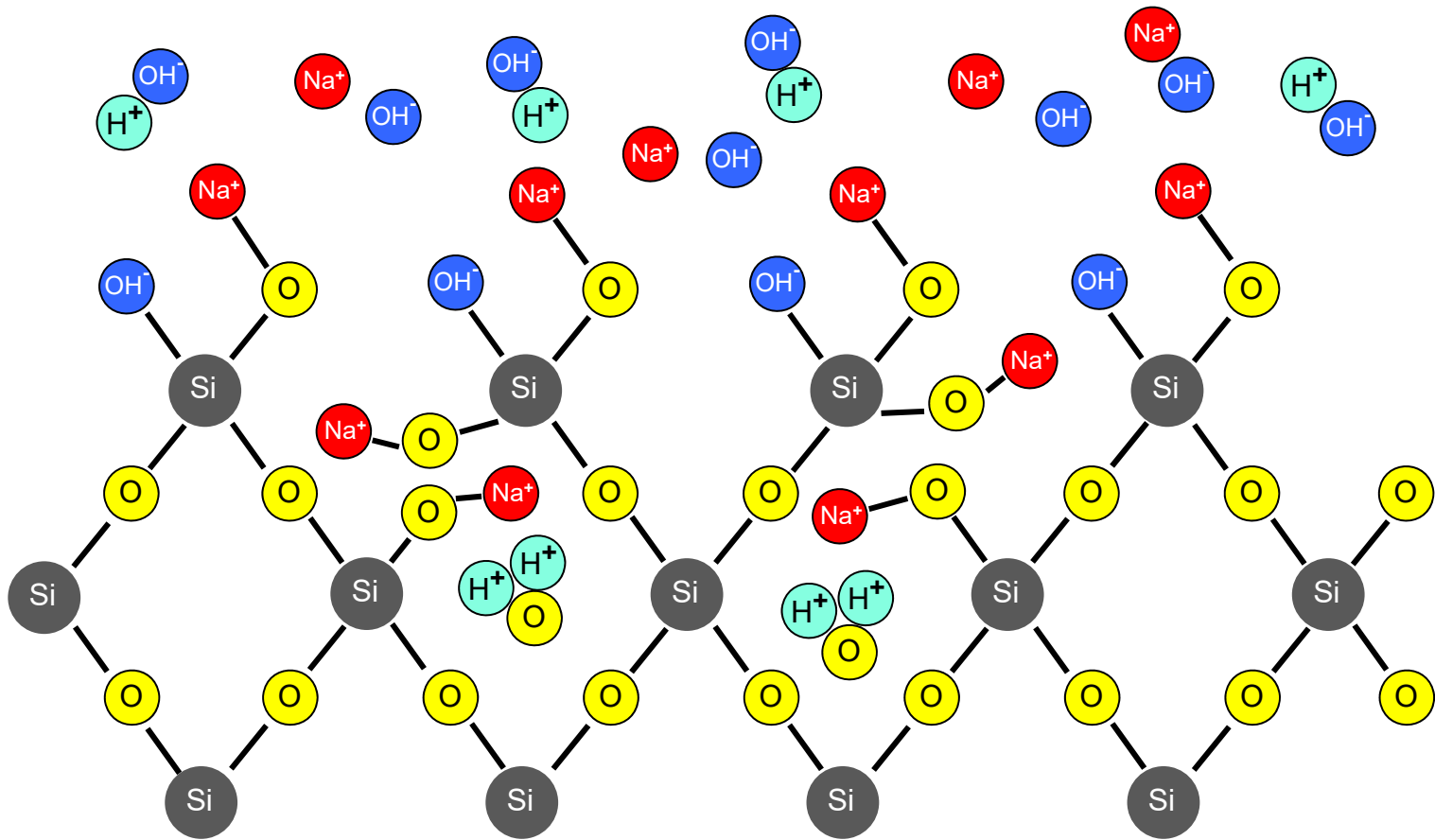
Alkali-Silica Reactivity

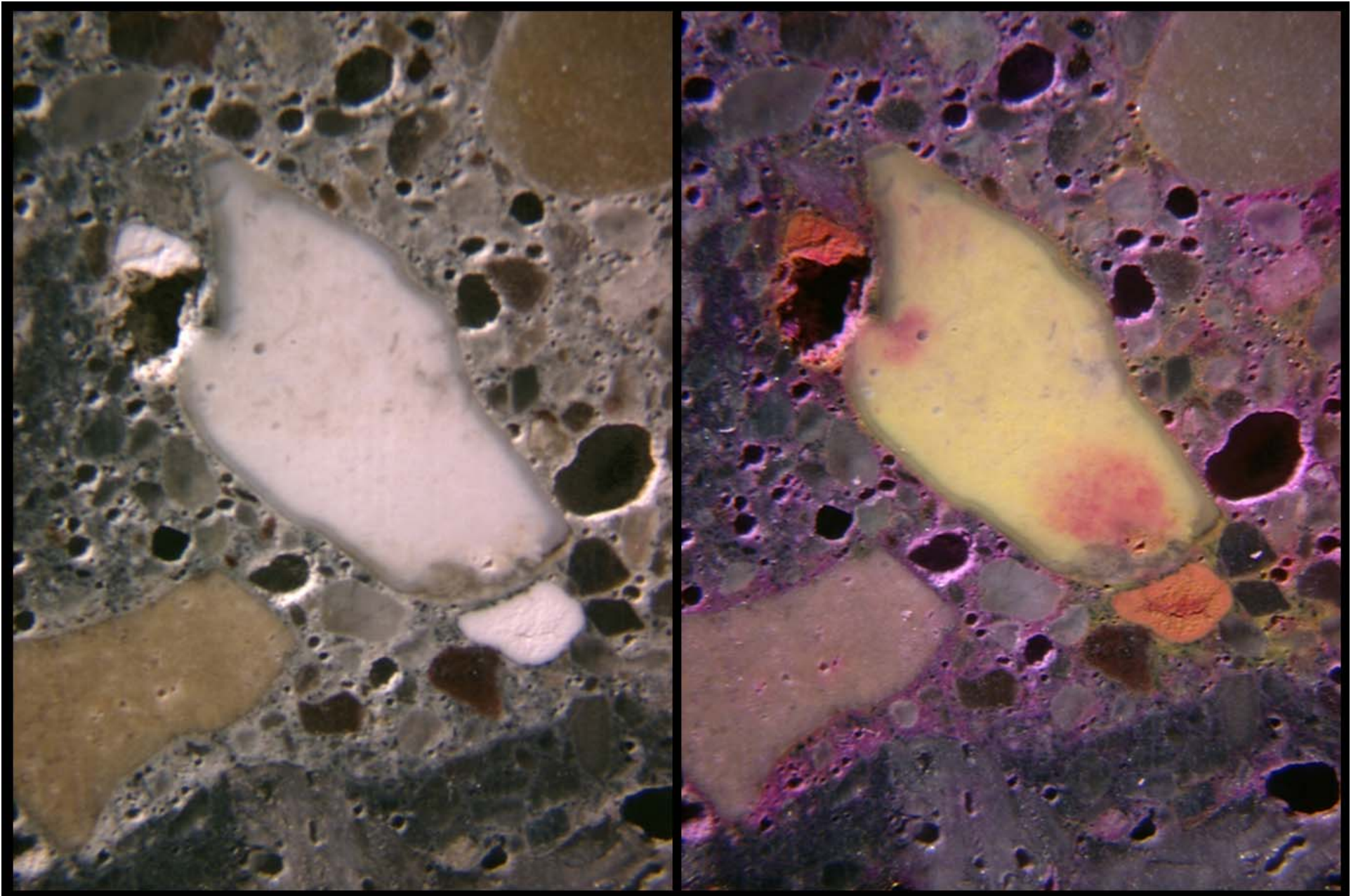
- Hydrogen dissociates from OH^- , combines with O^{2-} to form water. Na^+ substitutes for H^+ and the attack has progressed



Alkali-Silica Reactivity

- $\text{Si-O-Si} + 2\text{OH}^- + 2\text{Na}^+ \rightarrow 2(\text{Si-O-Na}) + \text{H}_2\text{O}$





7.2 x 5.4 mm

Photo credit K. Peterson, University of Toronto

Alkali-Silica Reactivity

- Prevention
 - Avoid use of reactive aggregates
 - Limit alkalis in the concrete mixture
- Mitigation
 - Use of SCMs
 - Fly Ash
 - Slag Cement
 - Use of Lithium

Alkali-Silica Reactivity

- Guidance

- *ASTM C1778 - Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete*
- *AASHTO PP-65 - Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction*
 - Performance Approach
 - Demonstrate performance (ASTM C1260 and ASTM C1293)
 - Prescriptive Approach
 - Limit the alkali content of the concrete mixture
 - Mitigate with SCMs

Alkali-Silica Reactivity

- Testing

- Various Screening Methods

- ASTM C295 - *Standard Guide for Petrographic Examination of Aggregates for Concrete*
 - ASTM C1260 - *Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)*
 - ASTM C1567 - *Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)*
 - ASTM C1293 - *Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction*

Alkali-Silica Reactivity

- Testing

- ASTM C295

- Outlines procedures for the petrographic examination of materials proposed for use as aggregates in cementitious mixtures or as raw materials for use in production of aggregates
 - Can identify, and approximate the quantity of, potentially ASR reactive aggregates
 - Useful way to screen potential sources
 - If an aggregate is identified as potentially reactive by petrography, expansion testing is still required to identify if the aggregate exhibits deleterious ASR or to identify mitigation strategies

Alkali-Silica Reactivity

- Testing

- ASTM C1260

- Used to detect the potential for deleterious alkali-silica reaction of aggregate in mortar bars
 - Samples are exposed to NaOH solution for 14 days (cement alkali content not a factor) and expansion measured
 - Accepted expansion limit (0.1 at 14 days) chosen empirically to correlate with an ASTM C1293 expansion of 0.04
 - Performing the test with modifications (e.g., exposure time other than 14 days, expansion limit other than 0.1 - or any other changes – undermines the validity of the test

Alkali-Silica Reactivity

- Testing

- ASTM C1567

- Used to detect the potential for deleterious alkali-silica reaction of combinations of cementitious materials and aggregate in mortar bars
 - Samples are exposed to NaOH solution for 14 days and expansion measured
 - Accepted expansion limit (0.1 at 14 days) chosen empirically to correlate with an ASTM C1293 expansion of 0.04
 - Mitigation of expansion can be evaluated by the test, but the actual SCM replacement level required must be confirmed by ASTM C1293 or field experience

Alkali-Silica Reactivity


- Testing

- ASTM C1293

- Estimates the susceptibility of an aggregate, or combination of an aggregate with pozzolan or slag, for participation in expansive ASR by measurement of length change of concrete prisms
 - Samples are spiked with alkali to create any possible ASR and expansion is monitored for 1 – 2 years, depending on the test intent - accepted expansion limit (0.04 at 1 year)
 - Pozzolan replacement levels established by ASTM C1293 should be treated as the minimum required
 - The “gold standard” of ASR testing – not without incorrect results but the best test available
 - Concerns with the test include alkali leaching from the specimens over time

Alkali-Carbonate Reactivity

- Overview

- Caused by a reaction between alkalis in the paste pore solution and **specific** carbonate/dolomitic aggregates that under go dedolomitization and brucite formation
 - Manifests as map cracking over entire slab area with accompanying expansion related distress
 - Commonly manifests in 5 to 15 years
 - Only sure prevention is to avoid susceptible aggregates, although blending and sizing aggregates and/or significantly reducing total alkalinity may be effective
 - Mitigation is not possible
- 

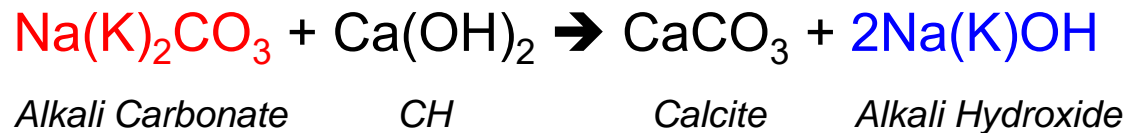
Alkali-Carbonate Reactivity

- Mechanism

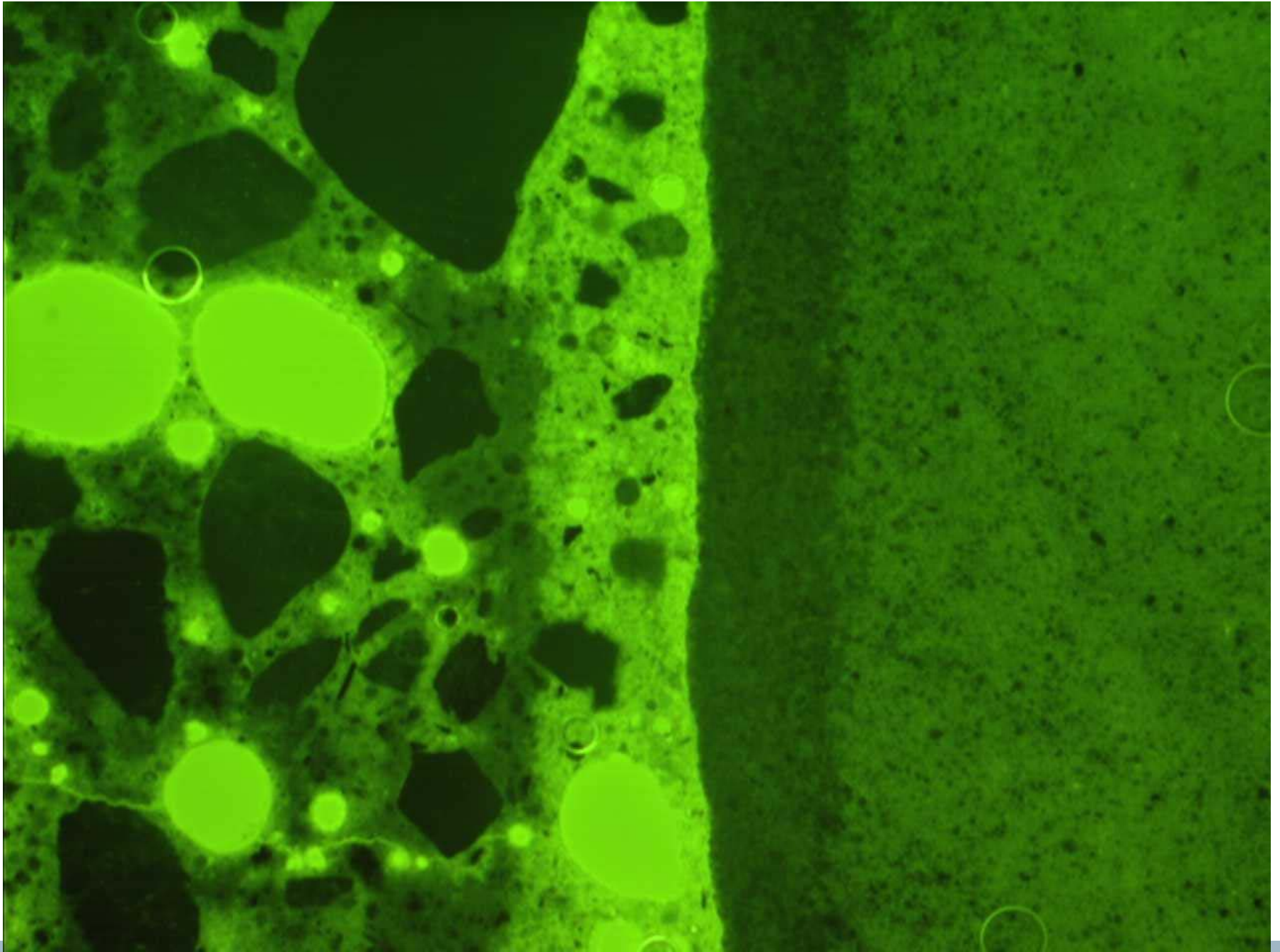
Dedolomitization



Recycle Alkalis – leads to carbonate halos



Recycling of alkalis makes mitigation ineffective



1.24 x 0.93 mm

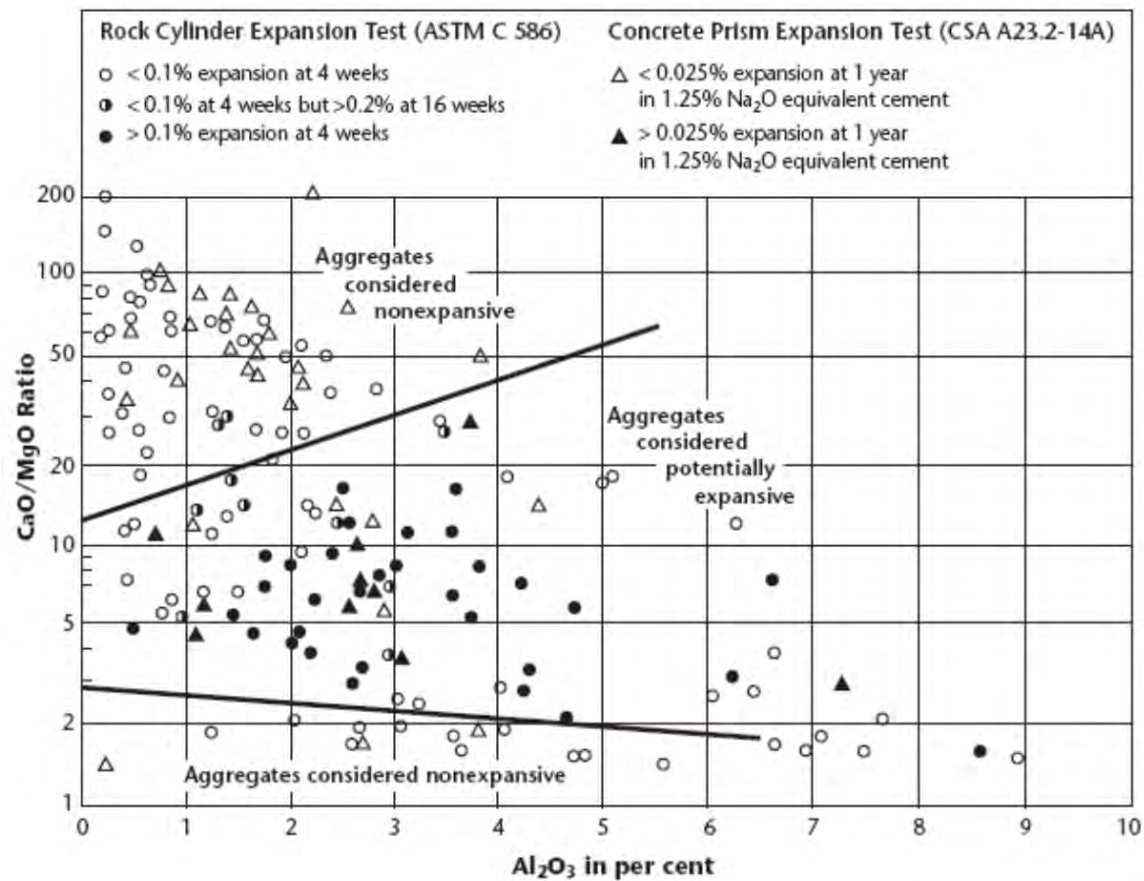
Photo credit K. Peterson, University of Toronto

Alkali-Carbonate Reactivity

- Mechanism – Possible Reasons For Expansion
 - Swelling of clay minerals in dolomite
 - Dedolomitization increases permeability, more water ingress, possible swelling
 - Crystal growth in dolomite matrix
 - Brucite formation
 - Increased alkalis leading to ASR
 - Microcrystalline silica is present in many aggregates reported to be ACR susceptible
 - **IMPORTANT:** Requires a specific dolomite rock type – Only a very slight fraction of dolomite rocks are ACR reactive – specific geologic deposits/locations (i.e., argillaceous dolomitic limestone, fine grained matrix with dolomite crystals embedded)
- Prevention – Avoid ACR susceptible aggregates

Alkali-Carbonate Reactivity

- Testing – Reject aggregates based on chemistry



Alkali-Carbonate Reactivity

- Testing

- *ASTM C586 Standard Test Method for Potential Alkali Reactivity of Carbonate Rocks as Concrete Aggregates (Rock-Cylinder Method)*

- Used to screen rock materials for potential ACR reactivity

- *ASTM C1105 Standard Test Method for Length Change of Concrete Due to Alkali-Carbonate Rock Reaction*

- Determines the susceptibility of cement-aggregate combinations to expansive alkali-carbonate reaction for certain calcitic dolomites and dolomitic limestones

- Aggregates passing ASTM C1105 should be evaluated for ASR potential using ASTM C1260 or C1293, as appropriate

External Sulfate Attack

- Overview

- Expansive formation of sulfate minerals resulting from an external source of sulfate ions
- Fine cracking and deterioration near joints and slab edges and on underside of slab
- Usually manifests within 1 to 5 years
- Mitigated through the use of low w/c , minimizing aluminate phases in cementitious materials, or using pozzolans or ground slag

External Sulfate Attack

- Mechanism

- Sulfate-laden solution enters concrete
- Sulfate reacts with alumina and calcia to form ettringite
 - Monosulfate – normally present in HCP is converted to ettringite
 - Ettringite can form in HCP or at the HCP-aggregate interface
- Conversion to ettringite results in volume increase – expansion – and cracking
- Ettringite that forms in air voids does not exert expansive pressures but may compromise the air-void system

External Sulfate Attack

- Mechanism – Example Reactions

Symbols Used

S = sulfate ion (SO_4^{2-})

CH = calcium hydroxide ($\text{Ca}(\text{OH})_2$)

AFm = monosulfate ($3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_4 \cdot 12\text{H}_2\text{O}$)

AFt = ettringite ($3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 32\text{H}_2\text{O}$)

Ettringite Formation with Calcium Hydroxide Dissolution



External Sulfate Attack

- Mechanism – Example Reactions

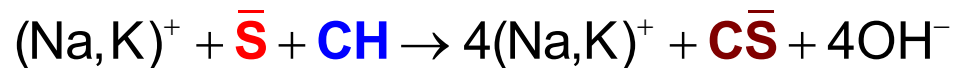
Symbols Used

S = sulfate ion (SO_4^{2-})

CH = calcium hydroxide ($\text{Ca}(\text{OH})_2$)

CS = calcium sulfate, gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$)

Gypsum Formation with Calcium Hydroxide Dissolution



External Sulfate Attack

- Mechanism – Example Reactions

Symbols Used

$\bar{\text{S}}$ = sulfate ion (SO_4^{2-})

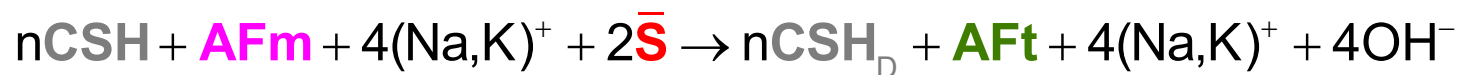
CSH = calcium silicate hydrate ($1.7\text{Ca} \square \text{SiO}_2 \square 4\text{H}_2\text{O}$)

CSH_D = decalcified calcium silicate hydrate ($< 1.7\text{Ca} \square \text{SiO}_2 \square 4\text{H}_2\text{O}$)

AFm = monosulfate ($3\text{CaO} \square \text{Al}_2\text{O}_3 \square \text{CaSO}_4 \square 12\text{H}_2\text{O}$)

AFt = ettringite ($3\text{CaO} \square \text{Al}_2\text{O}_3 \square 3\text{CaSO}_4 \square 32\text{H}_2\text{O}$)

Decalcification of CSH Due To Ettringite Formation



External Sulfate Attack

- Mechanism – Example Reactions

Symbols Used

$\bar{\text{S}}$ = sulfate ion (SO_4^{2-})

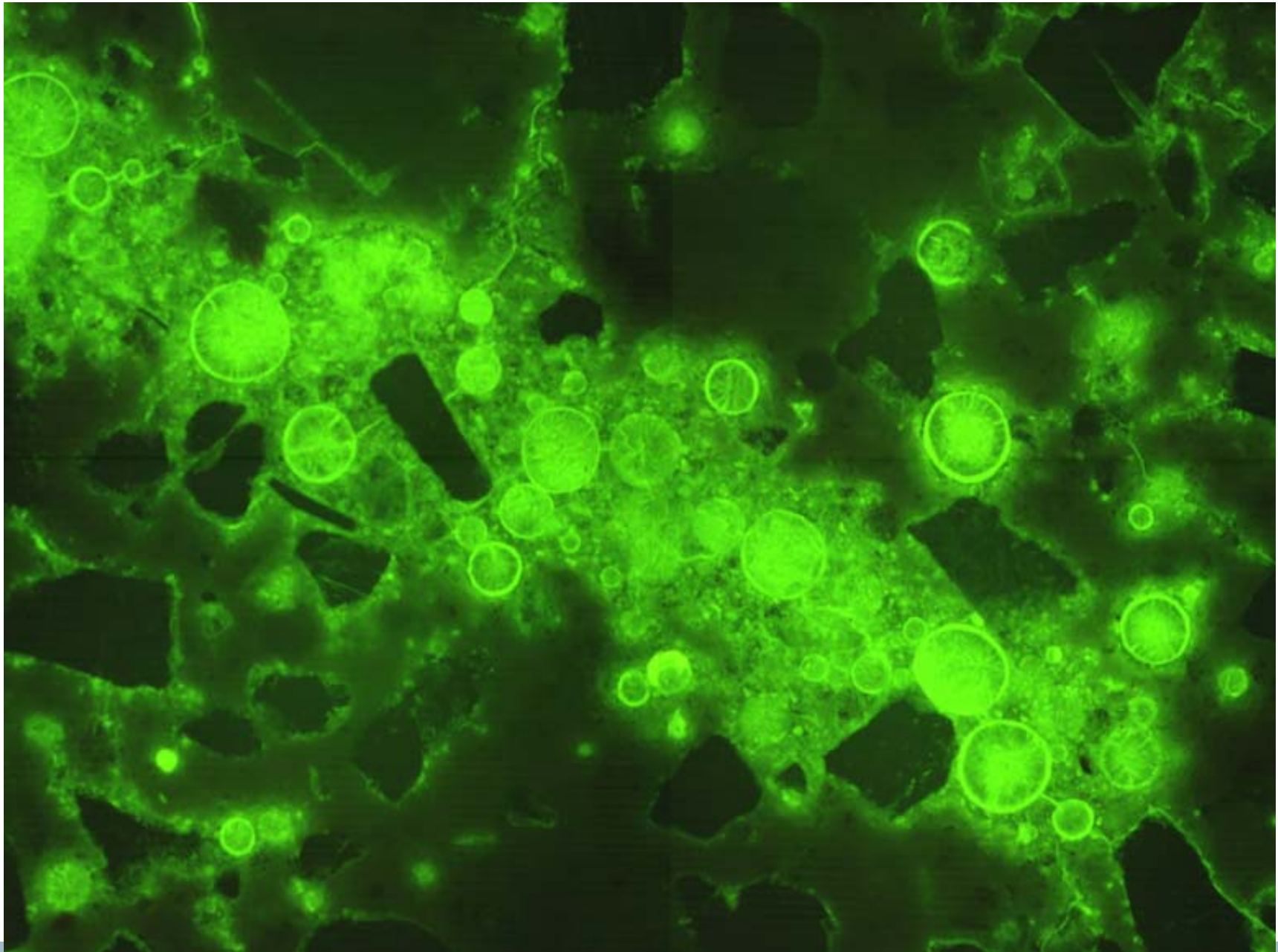
CSH = calcium silicate hydrate ($1.7\text{Ca} \cdot \text{SiO}_2 \cdot 4\text{H}_2\text{O}$)

CSH_D = decalcified calcium silicate hydrate ($< 1.7\text{Ca} \cdot \text{SiO}_2 \cdot 4\text{H}_2\text{O}$)

CS = calcium sulfate, gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$)

Decalcification of CSH Due To Gypsum Formation





2.54 x 1.90 mm

Photo credit K. Peterson, University of Toronto

External Sulfate Attack

- Prevention

- Reduce concrete permeability

- Lower w/c – see ACI 201.2R-08 *Guide to Durable Concrete* for guidance on w/c determination based on sulfate exposure

- Use pozzolans or slag to densify the CSH and reduce the available CH for reaction – see ACI 201.2R-08 *Guide to Durable Concrete* for guidance on replacement level

- Reduce aluminate phases in cementitious materials that can react

- Use ASTM C150 Type II or Type V cement and limit aluminate phases in SCMs – see ACI 201.2R-08 *Guide to Durable Concrete* for guidance on cement selection based on exposure class and SCM composition

Internal Sulfate Attack

- Overview

- Expansive formation of ettringite in paste due to an internal source of sulfates
 - Most commonly associated with high curing temperatures (delayed ettringite formation)
 - Can also be associated with an internal source of sulfates (e.g. aggregate, fly ash, etc.)
- Fine cracking concentrated at joints but may effect entire slab area
- Usually manifests in 1 to 5 years
- Prevented by controlling internal sources of sulfate and avoiding high curing temperatures

Internal Sulfate Attack

- Mechanism

- Internal attack is most commonly associated with steam cured concrete
 - If concrete is cured at temperatures above 70-80 °C (158-176 °F) the formation of ettringite during the initial set is “delayed” and monosulfate is formed
 - The monosulfate later converts to ettringite after the concrete hardens resulting in expansion and cracking
- Other forms of internal sulfate attack involve sources of sulfate from the constituent materials leading to the same reactions observed with external sources of sulfate

Internal Sulfate Attack

- Prevention

- Fortunately not a distress associated with cast in place concrete
- For steam cured concrete observe proper curing temperatures
- For all concrete limit sulfate contents in constituent materials
 - Portland cement is typically sulfate balanced and not an issue
 - SCMs and aggregates can be likely sources of sulfate
 - Problems with sulfide-bearing aggregates have been reported
 - Pyrrhotite [$\text{Fe}_{(1-x)}\text{S}$ ($x = 0$ to 0.2)] weathering/oxidizing to provide sulfate internally


Sulfate Attack

- Testing

- Internal sulfate attack can be addressed by monitoring the chemical composition of the concrete materials
- *ASTM C1012 Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution*
 - Used to evaluate combinations of materials for susceptibility from external sulfate attack by monitoring the length change of mortar bars immersed in a sulfate solution
 - Test duration a minimum of twelve (12) months, or eighteen (18) months in the case of ACI 201 defined Class 3 exposure
 - Test exhibits considerable variation

Corrosion of Embedded Steel

- Overview

- Associated most often with chloride ingress, which destroys passivity film protecting steel
 - Appears as cracking and spalling above and around embedded steel
 - Rust staining
 - Commonly manifests in 3 to 10 years
 - Prevented by providing adequate concrete cover, reducing concrete permeability, protecting steel, or using corrosion inhibitors
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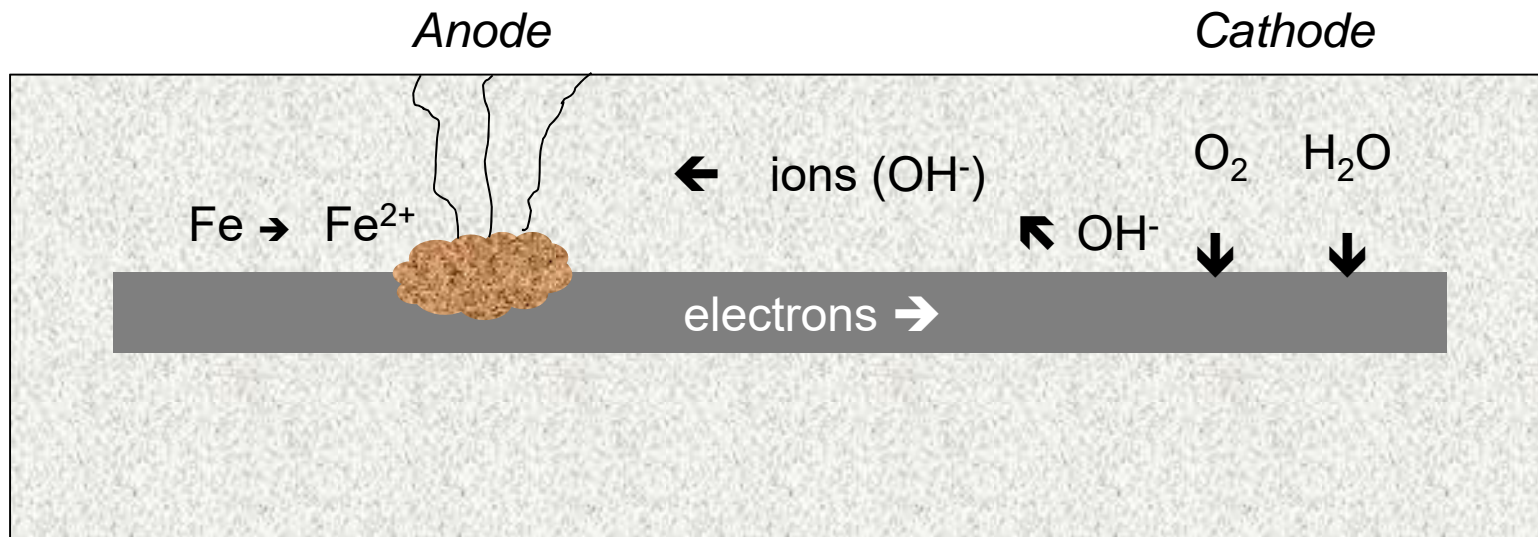
Corrosion of Embedded Steel



Corrosion of Embedded Steel

- Mechanism

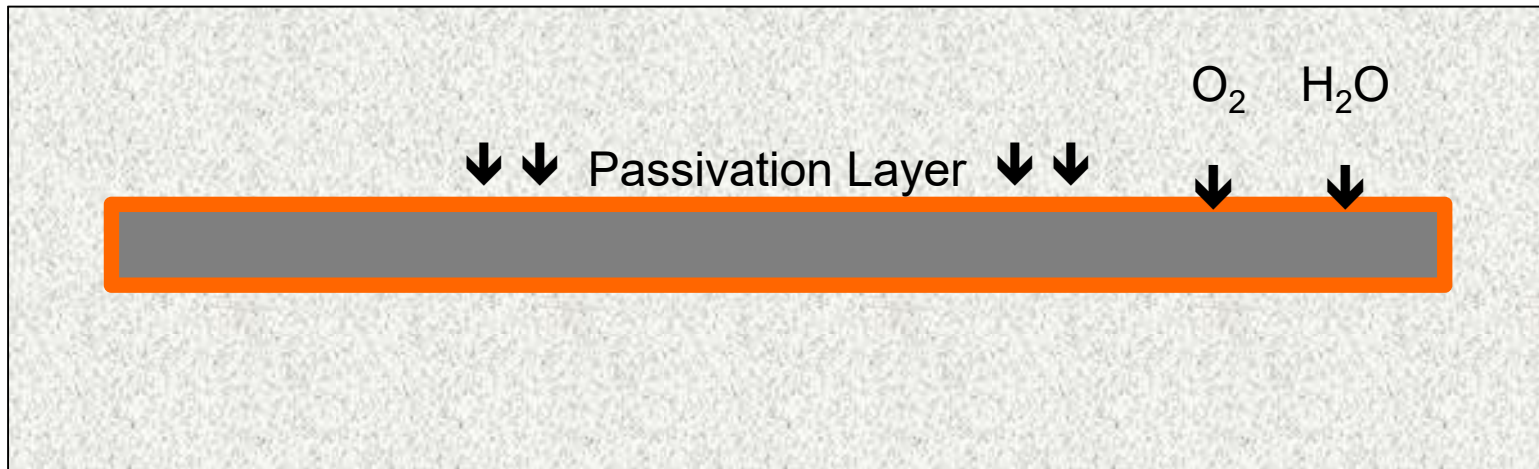
- At the anode iron is oxidized and combines with OH^- to form corrosion product
- At the cathode electrons, oxygen, and water combine to form OH^-
- Both reactions must occur simultaneously



Corrosion of Embedded Steel

- Mechanism

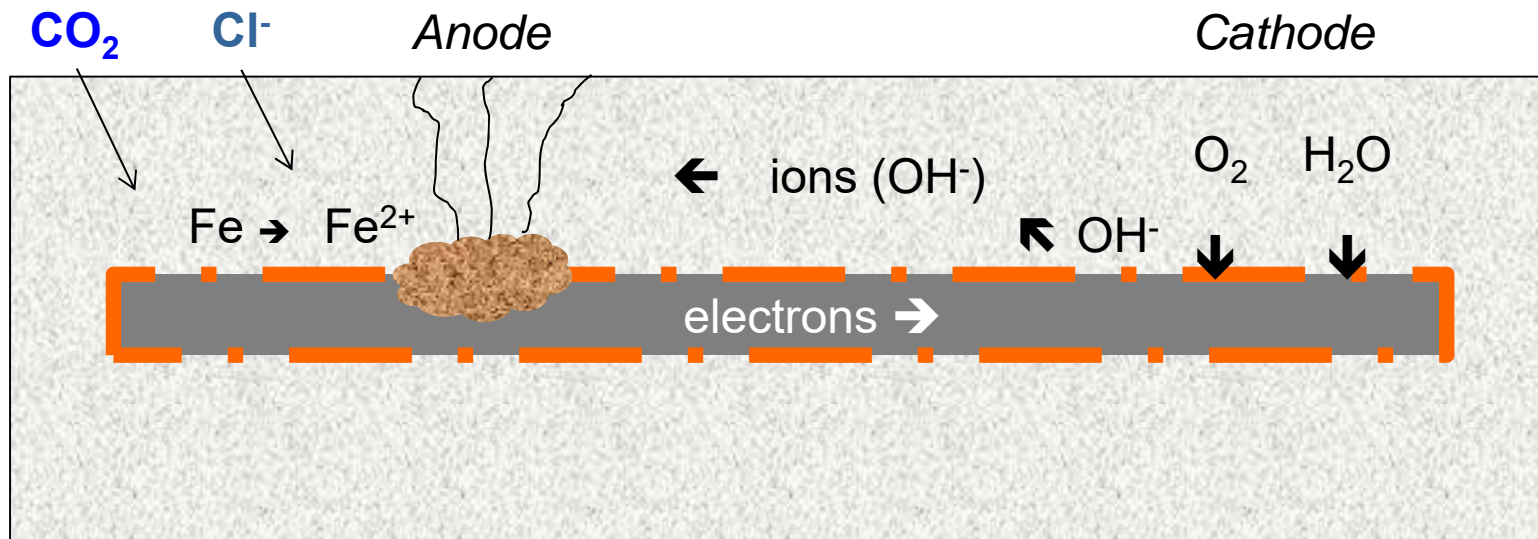
- Under normal conditions the high pH of the concrete creates a corrosion layer on the steel that protects it from corrosion – passivation layer
- Passivation layer blocks the diffusion of water and oxygen to the steel and the cathode reaction is shut down, stopping the overall corrosion reaction



Corrosion of Embedded Steel

- Mechanism

- Carbon dioxide (CO_2) lowers the pH of the concrete and the passivation layer breaks down
- Chloride (Cl^-) attacks the passivation layer directly – *mechanism unclear*
- Limiting fluid ingress (CO_2 , O_2 , Cl^- , and H_2O) limits corrosion



Corrosion of Embedded Steel

- Prevention

- Provide adequate cover (concrete) over steel to reduce/slow the ingress of fluids
- Reduce concrete permeability (low w/c, penetrating sealers)
- Use corrosion inhibiting chemicals in the concrete to counteract the effects of chlorides or CO₂
- Minimize cracking in the concrete cover

Final Thoughts

- Many manifestations of MRD look similar, and therefore identification **can not** be made based on visual assessment alone
 - Water is necessary for deleterious expansion to occur
 - Severe environments (freezing and thawing, deicers, sulfates, etc.) exacerbate the problem
 - Durable materials are typically low shrinkage and relatively impermeable
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