Limestone Calcined Clay Cement LC3

www.LC3.ch

Durability of cementitious materials

Meenakshi Sharma
Laboratoire de Matériaux de Construction, LMC
Meenakshi.sharma@epfl.ch

EPFL

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Durability

» The ability to withstand wear, pressure, or damage
» The ability to last a long time without significant deterioration

First RC bridge in America (1889)

Expressway built in 1960s

Thomas, Folliard and Scrivener (2008)

2

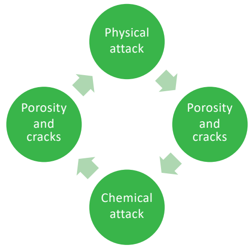
Objective

» Understanding of various deterioration processes
» Mechanism
» Identification
» Mitigation/prevention

3

Deterioration processes

» Physical attack
  » Abrasion
  » Erosion
  » Cavitation
  » Physical salt attack
  » Freeze-thaw
  » Fire damage
» Chemical attack
  » Corrosion
  » Alkali aggregate reaction
  » Sulphate attack
  » Acid attack
  » Biogenic attack



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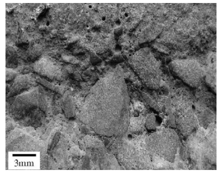
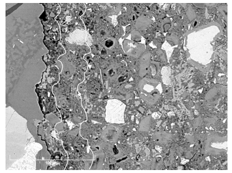
Physical attack

Abrasion

- Physical wear due to hard particles
- Abrasion resistance
  - Ability of a surface to resist being worn away by rubbing or friction
  - Paste hardness, aggregate hardness and aggregate/paste bond
- Vehicular traffic – bends and corners
- Surface properties are important
  - Porosity of top layer
  - Surface finishing
- Low paste content
- Hard and strong aggregates





Scrivener et al. (2004), Safiuddin (2015)

Erosion

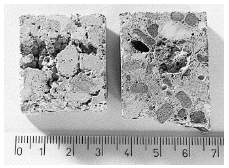
- Action of flowing water or wind
- Rain and flowing water in hydraulic structures
- Abrasion due to solid particles influences erosion - usually a part
- Surface properties are important
  - Porosity of top layer
  - Surface finishing
- Precautions
  - Reduce velocity of water flow
  - Slope should be low

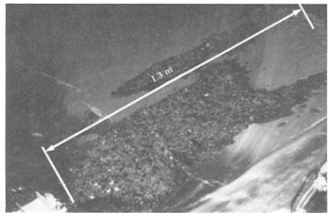
University of Sciences and of Technology Houari Boumedien, Algeria

Hadja and Kharchi (2017)

Cavitation

- Low pressure region – water vapour
- High pressure region – vapour collapse causing extreme pressures
- Collapse of vapour bubbles impacts surface
- Elimination of location of cavitation
- Concrete
  - Low w/c ratio
  - High strength



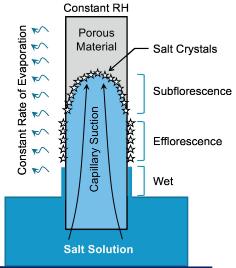


Glen Canyon Dam, Colorado River, Arizona, US

Momber (2000)

Physical salt attack

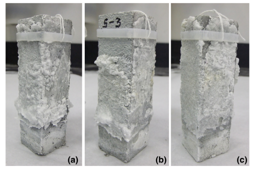
- One side in contact with salt solution
- Evaporation on another side
- Rate of evaporation > rate of supply for salt solution
  - Crystallization of salts in pore – stresses
- Rate of evaporation > rate of supply for salt solution
  - Efflorescence on the surface

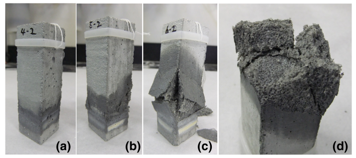


Lee and Kurtis (2017)

Physical salt attack

- Type of salt
- Prevention
  - Reduce connected porosity
  - Allow flow of water
  - Use of SCMs
  - Surface treatments





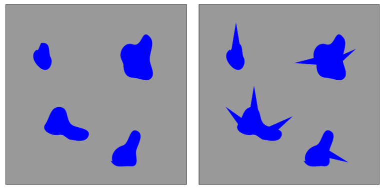
Lee and Kurtis (2017)

Freeze-thaw deterioration

- Concrete is susceptible to cracking and even crumbling when subjected to cyclic freezing and thawing
- Necessary conditions:
  - Saturated or nearly-saturated concrete
  - Freezing and thawing cycles

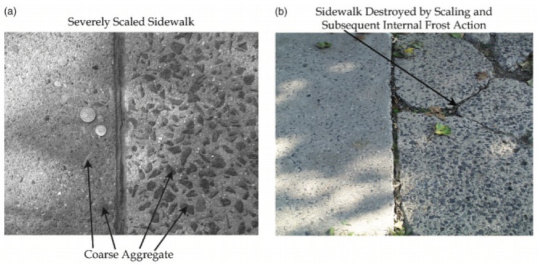
Mechanism of freeze thaw

- Ice occupy approximately 8% higher volume
- Freezing – ice forms – higher volume – movement of water
  - No cracks – if increase in volume accommodated
  - Cracks – insufficient pore volume
- Thawing – ice melts and reduces volume – empty pore or crack
  - External water enters concrete
- Repetition of cycle



Identification of freeze thaw

- D-line cracking or disintegration
- Scaling – de-icing salts and zonal freezing
- Popouts



Valenza and Scherer 2006

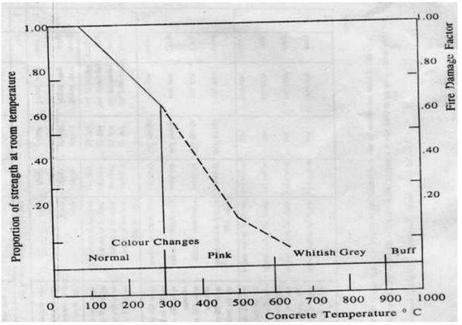
Factors affecting deterioration

- Degree of saturation
- Available water volume
- Pore structure
- Concrete age
- Climatic conditions
- Aggregate characteristics
- De-icing salts
- Air entrainment

Fire damage

- At high temperature concrete tends to lose strength
- Above 200°C strength loss can start to be significant
- Colour changes from grey to pink to buff
- Aggregates may start to decompose
- Higher strength concretes spall more
- Concrete generally good insulator
- Steel loses strength at high temperature
- Characterisation can be used to determine temperature reached

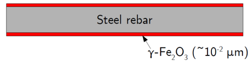
Fire damage



Chemical attack

Corrosion of reinforcement in concrete

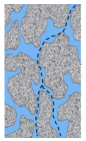
- Reinforcement – tensile strength
- Steel – produced from iron ore
- Corrosion of steel reinforcement
- How reinforcement in concrete can be stable?
  - Passivating layer
  - Concrete cover depth



Thomas, Folliard and Scrivener, 2008

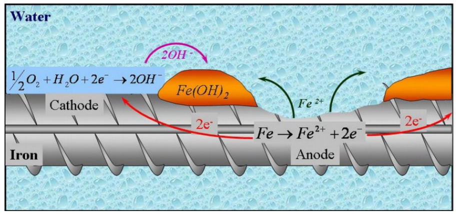
Mechanism of corrosion

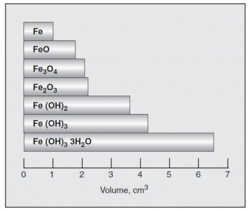
- Electrochemical process – anode and cathode & electrolytic solution
- Concrete
  - Breakdown of passive layer or presence of two different type of metals
  - Solution available in the pores of concrete



Mechanism of corrosion

- Corrosion reaction



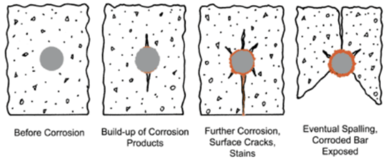


Thomas, Folliard and Scrivener (2008)
Mehta and Monteiro, 2006

Influence of corrosion

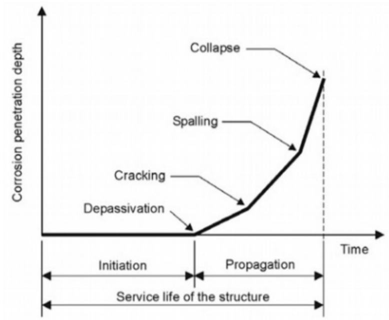
- Influence on steel
  - Reduction in the cross-sectional area
  - Reduction in tensile strength of reinforcement

- Influence on concrete



Bertolini et al. 2013

Stages during reinforcement corrosion



Bertolini et al. 2013

The result

concrete.org.uk

Major reason of corrosion

- Carbonation
  - CO_2 in environment
  - Disruption of passivating film due to lowering of pH
- Chloride attack
  - Deicing salts, sea water, sand etc.
  - Disruption of passivating film at high pH
- Hydrogen embrittlement
- Stray currents

Carbonation

- Carbon-dioxide reacts with alkalis to carbonate them, this reduces the pH of the solution

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$
$$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$$
$$2KOH + CO_2 \rightarrow K_2CO_3 + H_2O$$
$$(CaO)_x.(SiO_2)_y.(H_2O)_z + xCO_2 \rightarrow xCaCO_3 + ySiO_2.(H_2O)_t + (z\text{-}yt)\ H_2O$$

- Carbonation of CH increases solid volume
- Carbonation of C-S-H reduces solid volume

Testing carbonation

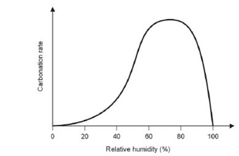
- Phenolphthalein test
- Phenolphthalein solution is pink at pH > 9.2 and colourless below 9.2
- pH
- Reserve alkalinity

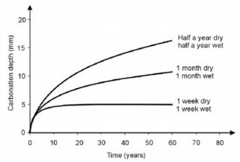


Thomas, Folliard and Scrivener, 2008

Carbonation

- Rate of carbonation depends on diffusivity/permeability
- Reserve alkalinity
- Environmental CO_2 concentration
- Temperature
- Relative humidity
- Exposure condition





Pedeferri et al. 2013

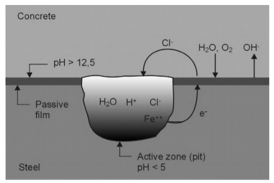
Chloride

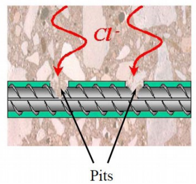
- Ferrous ions combine with the chloride ions to form ferrous chloride

$$2Fe^{2+} + 4Cl^- \rightarrow 2FeCl_2$$

- Self-propagating due to acidic conditions created

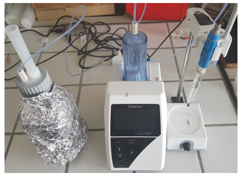
$$2FeCl_2 + 4H_2O \rightarrow 2Fe(OH)_2 + 4H^+ + 4Cl^-$$
$$2FeOCl^- + 2H_2O \rightarrow 2Fe(OH)_2 + 2Cl^-$$





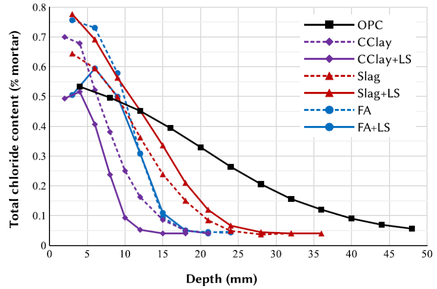
Thomas, Folliard and Scrivener, 2008
Bertolini et al. 2013

Chloride detection – bulk diffusion



From: Georget 2020

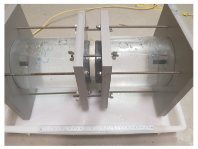
Chloride detection

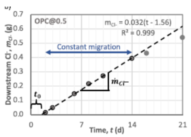


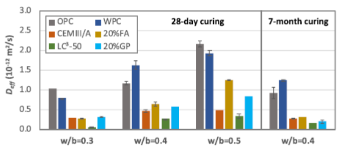
Shiyu et al. 2019

Mini- migration test

- Upstream: 0.5 M NaCl, 0.3 M NaOH
- Downstream: 0.3 M NaOH
- Voltage is applied







Wilson et al. 2021

Alkali aggregate reaction

- Aggregates can react under certain conditions
  - Aggregates can imbibe water
  - Swelling and cracking occurs
- Usually a slow process
- Less often cause of failure than other mechanisms

- Alkali silica reaction (ASR)
- Alkali silicate reaction
- Alkali carbonate reaction (ACR)

Mechanism of ASR

- Reactive silica from aggregates + alkalis from cement – gel
- Gel – imbibe water – volume increase – expansion
- Restraint – stresses due to ASR expansion

$$4SiO_2 + 2NaOH \rightarrow Na_2Si_4O_9 + H_2O$$

- SiO^- ions formed in the aggregates diffuse out slowly
- Na^+, K^+, Ca^+, OH^- ions from solution attracted into the aggregates
- Pressure builds in the aggregate
- Surface reaction slow in quartz
- Penetration of ions if poorly crystalline

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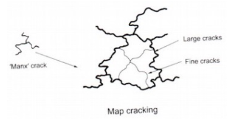
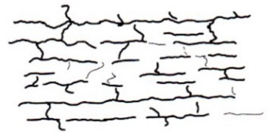
Alkali silica reaction

- Crack depth – 25 to 50mm
- Unreinforced concrete
  - Manx cracks
  - Crack join
- Reinforced concrete
  - Manx cracks
  - Regular cracks





Richardson 2002

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Alkali silica reaction

- Identification
  - Presence of gel in cracks
  - Presence of potentially reactive aggregates
  - Crack pattern
- Crack pattern
  - Similar to drying shrinkage and freeze-thaw deterioration
- Gel
  - Transparent or brownish
  - Carbonates and turns white on exposure to the atmosphere
  - Similar to leaching of calcium hydroxide or efflorescence

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Prevention of ASR

- Reduction in alkalinity can reduce expansion:
  - Supplementary cementitious materials
- Chemical effects on gel
  - Lithium salts: replacement of Na & K in gel
- Air entrainment

- Low alkali content: less gel
- High alkali content: vigorous reaction before hardening?
- Pessimum effect of aggregates

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Sulphate attack

- Excess sulphates in concrete can lead to excessive expansion
- Internal attack (>5% SO_3 by wt)
  - Over-sulphated cement
  - Sulphate contamination of aggregates
  - High temperature curing
- External attack
  - Ingress of sulphates from external sources like ground water, soil, industrial waste, sewage, etc.

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Mechanism of sulphate attack

- Chemical reactions leading to formation of:
- Ettringite, e.g.
  - Monosolphate + Sulphate + Water → Ettringite
- Gypsum, e.g.
  - Portlandite + Sodium Sulphate → Gypsum + Sodium Hydroxide + Water
  - Portlandite + Magnesium Sulphate → Gypsum + Magnesium Hydroxide + Water
- Thaumasite ($CaSiO_3.CaCO_3.CaSO_4.15H_2O$)
  - Sulphates + Calcium Silicates + Calcium Carbonate → Thaumasite

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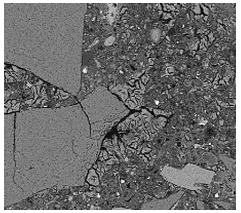
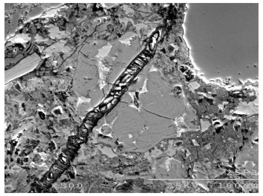
The result





Mistaken identity

Thomas, Folliard and Scrivener, 2008
Sibbick, 2007

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Protection against sulphate attack

- Improve quality of concrete
- Use of surface protection
- Sacrificial layer of concrete
- Sulphate resistant cements (e.g. Types II and V)
- Supplementary cementitious materials
- Air entrainment
- Air temperature during hydration
- Size and geometry of pour
- Cement content
- Cement fineness

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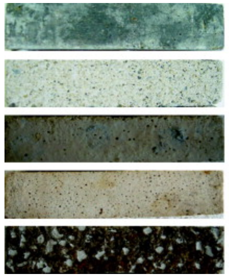
Acid attack

» Acids attack CH and C-S-H
» Source of acids:
  » Acid-rain
» Industrial sources, etc.
» Etching to complete breakdown of concrete
» Rate of attack depends on H^+ concentration
» Prevention
  » Reduce direct exposure to acid
  » Surface protection
  » Low permeability concrete
  » Aggregate type



0 d
30 d
90 d
150 d
210 d

Chen, Wang and Xie 2013

Biogenic attack

Biogenic attack

» Sulphate attack
  » Anaerobic conditions
  » Conversion of sulphate to H_2S (Desulfovibrio)
  » Conversion of H_2S to H_2SO_4 by aerobic bacteria on surface
  » Thiobacillus thiooxidans (concretivorus), produces upto 10% sulfuric acid (pH < 1)
  » Acid attack
» Ammonium attack
  » NH_4^+ reacts with OH^- producing NH_3
  » Green Fungus (Fusarium) produces acids
  » pH reduction and acid attack
  » Corrosion of reinforcement

Biogenic sulfuric acid attack

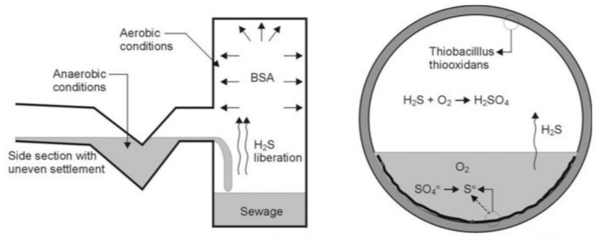
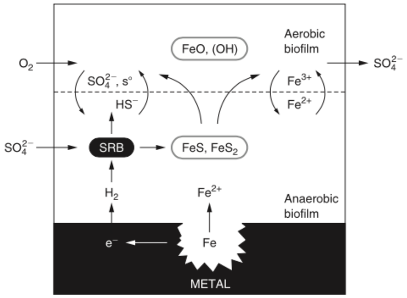


Figure 3.3 Biogenic sulfuric acid attack: *a)* conditions in sewer system that promote BSA; *b)* main reactions involved

Bertolini et al. 2013

Corrosion of reinforcement by bacteria

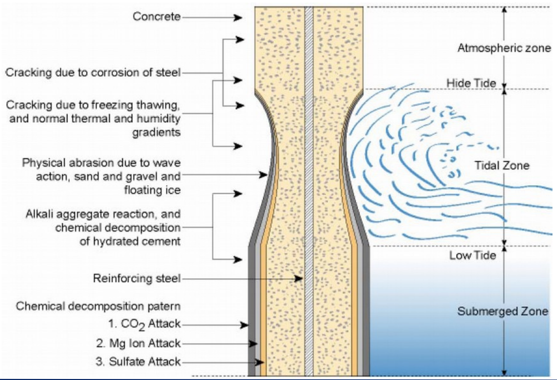


Beech and Sunner 2007

Factors affecting biogenic attack

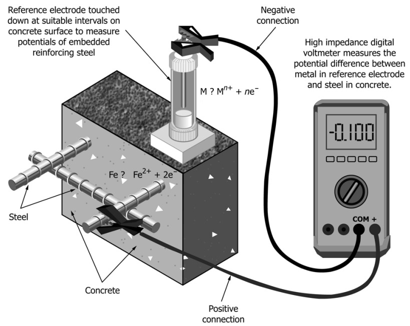
- Cement composition
- Permeability of concrete
- Temperature
- Sewage characteristics
- Prevention
  - Surface protection – low w/c concrete

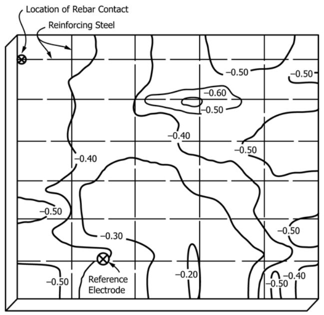
Concrete in sea



Thank You!

Half cell potential





ASTM C876 – 15

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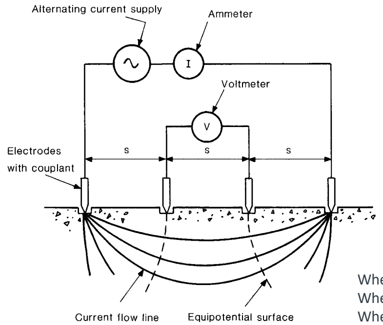
Electrical resistivity



When $\rho \geq 120\ \Omega$-m corrosion is unlikely
When $\rho = 80$ to $120\ \Omega$-m corrosion is possible
When $\rho \leq 80\ \Omega$-m corrosion is fairly certain

Bungey et al. 2006

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