Different deterioration mechanisms

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Course outline

Factors Causing Deterioration

Initiating

Deterioration Process

Chemical
Physical
Biological

Leads to

Visible Damage

Cracking
Scaling
Spalling
Pop-ups
Delamination
etc.

Assessed

Condition survey

Condition evaluation

Principles for repair and protection

Repair

Condition evaluation

Principles for repair and protection

Repair

Condition survey

Visual inspection
Non-Destructive Testing
Destructive Testing

Assessed

Visible Damage

Cracking
Scaling
Spalling
Pop-ups
Delamination
etc.

Leads to

Deterioration Process

Chemical
Physical
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Factors Causing Deterioration

Intrinsic Extrinsic
Outlines

• Commonly observed deterioration mechanisms in concrete
  – Chemically induced deterioration
  – Physically induced deterioration
  – Biodegradation of structures

Commonly observed deterioration mechanisms in concrete

• Despite the costly and tragic failures of concrete structures, there is currently a lack of guidelines and procedures for assessing, testing, classifying, and prioritizing preventive and corrective action for these structures.
• Understanding mechanisms of deterioration is important for developing effective inspection, evaluation and selecting appropriate and cost-effective repair strategies for ageing concrete structures.

• Chemically induced deterioration
  – Carbonation-initiated corrosion
  – Chloride-initiated corrosion
  – Reactions in binder paste and aggregates
    • External sulfate attack
    • Delayed ettringite formation
    • Alkali silica reaction
    • Acid attack

• Physically induced deterioration
  – Freeze/thaw action
  – Thermal cracking due to temperature gradients
  – Mechanical abrasion, erosion, and cavitation
Chemically induced deterioration

Carbonation induced corrosion

- Carbonation occurs in concrete because the calcium hydroxide \((\text{Ca(OH)}_2)\), is attacked by carbon dioxide \((\text{CO}_2)\) of the air and converted to calcium carbonate.

\[
\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O}
\]

- Cement paste contains 25-50 wt% \((\text{Ca(OH)}_2)\), which mean that the pH of the fresh cement paste is at least 13.

- The carbonation process requires the presence of water because \(\text{CO}_2\) dissolves in water forming \(\text{H}_2\text{CO}_3\).

- If the concrete is too dry (RH <40%) \(\text{CO}_2\) cannot dissolve and no carbonation occurs.

- If on the other hand it is too wet (RH >90%) \(\text{CO}_2\) cannot enter the concrete and the concrete will not carbonate.

- Optimal conditions for carbonation occur at a RH of 50% (range 40-90%)

\[
\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3 \text{ carbonic acid}
\]

\[
\text{H}_2\text{CO}_3 + \text{Ca(OH)}_2 \rightleftharpoons \text{CaCO}_3 + 2\text{H}_2\text{O}
\]

\[
\text{H}_2\text{CO}_3 + \text{CaO} \rightleftharpoons \text{CaCO}_3 + 2\text{H}_2\text{O}
\]

- The pH of a fully carbonated paste is about 7.

Carbonation induced corrosion

\[ p\{\text{failure}\} = p_f = p \{d_c - x_c(t) < 0\} \]

- \( p_f \): failure probability [%]
- \( d_c \): concrete cover [mm]
- \( x_c(t) \): carbonation depth at the time \( t \) [mm]
- \( t \): age of the structure [a]

\[ X_c(t) = K_{ca} \sqrt{t} \]

- \( K_{ca} \) is the coefficient of carbonation [mm/a^{0.5}], \( K_{ca} \) based on concrete quality, aggregate types, exposure conditions, and moisture content.
- \( t \): is age of the structure [a]
**Carbonation induced corrosion**

\[ X_{ca} = k_{con} \cdot k_{cur} \cdot k_{T} \cdot k_{RH} \cdot k_{CO_2} \cdot \sqrt{t} \]

where
- \(k_{con}\) is the quality of concrete related coefficient,
- \(k_{cur}\) is the concrete curing factor,
- \(k_{RH}\) is the relative humidity related coefficient,
- \(k_{T}\) is the temperature related coefficient, and
- \(k_{CO_2}\) is the square root of the carbon dioxide content in air.

\[ k_{con} = 350 \cdot \frac{\rho_c}{\rho_w} \cdot \left( \frac{w}{c} - 0.3 \right) \cdot \sqrt{1 + \frac{\rho_c}{\rho_w} \cdot \frac{w}{c} + \frac{\rho_c}{\rho_a} \cdot \frac{a}{c}} \]

where
- \(\rho_c\) is the mass density of the cement [kg/m³],
- \(\rho_w\) is the density of the water [kg/m³],
- \(\rho_a\) is the mass density of the aggregates [kg/m³],
- \(w/c\) is the water-to-cement ratio [-], and
- \(a/c\) is the aggregate-to-cement ratio [-].

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**Initiation: Carbonation induced corrosion**

\[ k_{RH} = \left( \frac{1 - RH}{100} \right)^n \text{ for } RH \geq 65\% \]

Where:
- \(RH\) is the relative humidity in the concrete cover [%],
- \(n\) is an exponent of range \((1 - 2.5)\).

The carbon dioxide content of the atmosphere by volume is considered to be 0.035% (350 ppm) and the value of \(k_{CO_2}\) is considered to be 0.0187.

According to Duracrete (2000), the values of the concrete curing coefficient \((k_{cur})\) for the carbonation resistance are 1.0 for 7 days’ curing and 0.76 for 28 days’ curing of the concrete.

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Al-Neshawy, F. (2013), Computerised prediction of the deterioration of concrete building facades caused by moisture and changes in temperature.
Carbonation induced corrosion

- Factors affecting carbonation
  - CO$_2$ volume in the ambient air
  - Permeability of the cover concrete over reinforcement
  - Pore filling degree (moisture content) of the cover concrete, (RH 40% - 90%)
  - The thickness of the cover concrete.
- Normal carbonation results in a decrease of the porosity making the carbonated paste stronger.
- Carbonation is therefore an advantage in non-reinforced concrete.
- However, it is a disadvantage in reinforced concrete, as pH of carbonated concrete drops to about 7; a value below the passivation threshold of steel.

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Figure 2.12: Corrosion of steel in concrete as a function of the alkalinity of the concrete.

Fahim Al-Neshawy, Ph.D. thesis
Chloride induced corrosion

Source of chloride
- if concrete is in contact with environments with a high chloride content, such as seawater or de-icing salts,
- or if concrete is prepared using salt contaminated raw materials.

Spraying roads with corrosive de-icing solutions:
- Sodium Chloride (NaCl the most common de-icing chemical)
- Magnesium Chloride (MgCl₂)
- Calcium Chloride (CaCl₂)
- Potassium Chloride (KCl)

Chloride transport in concrete
- The main mechanisms for chloride transport in concrete are:
  - capillary suction,
  - diffusion and
  - migration.
- Capillary suction
  - occurs for dried or partially dried concrete, when it comes in contact with water (and dissolved ions), due to the surface tension in the capillaries.
  - an important mechanism for marine concrete in the tidal and splash zone as well as in the case of concrete in road applications where de-icing salts are used.
- Diffusion
  - When concrete is saturated such as in submerged conditions, diffusion is the relevant mechanism for chloride transport.
  - Diffusion occurs due to concentration gradients.
- Migration
  - Chloride transport is driven by a difference in electrical potential
  - Chloride moves into zones with less electrical potential
  - The negative chloride ions migrate towards the (positive) and zone of the reinforcement

Chloride induced corrosion

- Fick’s second law of diffusion
  \[
  \frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2}
  \]

- Assuming constant D, the mass balance is usually solved by applying the error function solution
  \[
  c(x, t) = c_i + (c_s - c_i) \left[ 1 - \text{erf} \left( \frac{x}{2\sqrt{D \cdot t}} \right) \right]
  \]
  \[
  \text{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} \, dt
  \]

  - \( c \) is the chloride concentration (\%/m^3)
  - \( t \) is the time of exposure (s)
  - \( D \) is the diffusion coefficient (m^2/s)
  - \( x \) is the depth (m)

  - \( C(x, t) \) is the chloride concentration at depth \( x \) after time \( t \) (\%/m^3)
  - \( c_i \) is the initial chloride content in concrete (\%/m^3)
  - \( c_s \) is the surface chloride concentration (\%/m^3)
  - \( \text{Erf}() \) is the error function


Chloride induced corrosion

Decomposition of passivity layer

\[
\begin{align*}
\text{Fe}^{2+} + 2\text{Cl}^- & \rightarrow \text{FeCl}_2 \\
& \text{soluble in pore solution}
\end{align*}
\]

Corrosion of steel

\[
\begin{align*}
\frac{1}{2}\text{O}_2 + \text{H}_2\text{O} + 2\text{e}^- & \rightarrow 2\text{OH}^- \\
& \text{reduction}
\end{align*}
\]

\[
\begin{align*}
\text{Fe}^{2+} + 2\text{OH}^- & \rightarrow \text{Fe(OH)}_2 \\
2\text{Fe(OH)}_2 + \frac{1}{2}\text{O}_2 + \text{H}_2\text{O} & \rightarrow 2\text{Fe(OH)}_3
\end{align*}
\]

Formation of rust

\[
\begin{align*}
2\text{Fe(OH)}_3 + \frac{1}{2}\text{O}_2 + 3\text{H}_2\text{O} & \rightarrow \text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O} \\
& \text{Rust}
\end{align*}
\]

https://engineering.purdue.edu/~concrete/students/fars had/MS-Chapter%202.pdf
Carbonation induced corrosion

- For corrosion process to continue the presence of **oxygen and moisture are necessary**.
- Limited corrosion in dry concrete (RH < 60%) or in fully immersed in water (due to the lack of oxygen).
- The RH that is most susceptible for corrosion is between 70 and 80 percent.
- A minimum concentration of chlorides (0.4 % threshold) is required to disrupt the passive oxide film on the embedded reinforcement.

Chloride induced corrosion

1. Chlorides penetrate into concrete with the help of surface moisture.
2. Moisture and oxygen
3. Further penetration of chlorides results in further corrosion, delamination and spalling.
4. When chlorides penetrate to reinforcing steel corrosion begins.

**Corrosion initiation of concrete reinforcement caused by chloride when concrete is wet**


Hans Beushausen & Mark Alexander (Concrete deterioration causes, mechanisms, prevention)
Sulphate Attack – Mechanism

- Common sulphate environments are soils, groundwater, and seawater
- Magnesium sulphate is the most severe because of the presence of magnesium ions
- When sulphates get into concrete, it combines with the C-S-H, or concrete paste, and begins destroying the paste that holds the concrete together
- As sulphate dries, new compounds are formed, called Delayed Ettringite (DEF)
- DEF crystals occupy empty space, and as they continue to form, they cause the paste to crack, further damaging the concrete.
- Sulphate attack decline the compressive strength.

External sulphate attack

DEF RELATED EXTERNAL SULPHATE ATTACK (ESA)

- capillary pores (high w/c and poor curing)
- macrovoids (low w/c and improper compaction of fresh concrete related to its inadequate workability)
- microcracks (loadings in service and cyclic heating/cooling or wetting/drying)

Conditions necessary for DEF to occur are:
- High temperature (above 65-70°C)
- Moisture: permanent saturation
- Commonly associated with ASR

http://www.understanding-cement.com/sulfate.html
Delayed ettringite formation

- Delayed Ettringite Formation (DEF) is a form of internal sulfate attack.
- Concrete composition, curing conditions and exposure conditions influence the potential for DEF.
- DEF is a result of heat curing of the concrete where the normal ettringite formation is suppressed.
- The sulfate concentration in the pore liquid is high for an unusually long period of time in the hardened concrete.
- The sulfate reacts with calcium- and aluminium-containing phases of the cement paste and the cement paste expands.
- Due to this expansion empty cracks are formed around aggregates.
- The cracks may remain empty or later be partly or even completely filled with ettringite.

M. Collepardi “State-of-the-Art Review on Delayed Ettringite Attack on Concrete”
Alkali silica reaction

**ASR Definition:**
- A Process in which silica (found in aggregate) in the presence of moisture, is broken down by alkalis (found in cement) produces an expansive gel.
- The expanding gel creates tensile forces, causing the concrete to crack.
- The cracking then allows more water to infiltrate into the concrete creating more gel, more expansion etc.
- Ultimately the concrete fails or disintegrates.

![Conditions leading to ASR](http://www.transportation.nebraska.gov/info/docs/ASR-Poster.pdf)

Quebec, Canada

ASR will often form individual three-armed star shapes that join up to produce a pattern of cracks.
Acid attack

- Concrete is susceptible to acid attack because of its alkaline nature.
- The components of the cement paste break down during contact with acids.
- Most pronounced is the dissolution of calcium hydroxide which occurs according to the following reaction:
  \[ 2 \text{HX} + \text{Ca(OH)}_2 \rightarrow \text{CaX}_2 + 2 \text{H}_2\text{O} \]
  (X is the negative ion of the acid)
- The decomposition of the concrete depends on the porosity of the cement paste, on the concentration of the acid, the solubility of the acid calcium salts (CaX₂) and on the fluid transport through the concrete.
- Insoluble calcium salts may precipitate in the voids and can slow down the attack.
- Acids such as nitric acid, hydrochloric acid and acetic acid are very aggressive as their calcium salts are readily soluble and removed from the attack front.
- Other acids such as phosphoric acid and humic acid are less harmful as their calcium salt, due to their low solubility, inhibit the attack by blocking the pathways within the concrete such as interconnected cracks, voids and porosity.
- Sulphuric acid is very damaging to concrete as it combines an acid attack and a sulfate attack.

Physically induced deterioration
Freeze-Thaw Damage Mechanisms

Critical Saturation
- When water freezes, it expands about 9%.
- As the water in moist concrete freezes, it produces pressure in the capillaries and pores of the concrete.
- If the pressure exceeds the tensile strength of the concrete, the cavity will dilate and rupture.
- The accumulative effect of successive freeze-thaw cycles and disruption of paste and aggregate can eventually cause significant expansion and cracking, scaling, and crumbling of the concrete.

Hydraulic Pressure
- Damage from freezing is caused by a buildup of hydraulic pressure from the resistance to flow of unfrozen water in cement paste capillaries.
- As water freezes, if the cement paste does not expand to accommodate it, unfrozen water will be pushed through the capillary pores, away from the sites of freezing, like water through a pipe.

The ice lens growth theory
- Micro-ice lens formation in bigger pores as a result of the migration of water from fine to coarse pores.
- Ice in the capillary and the air pore attracts un-frozen water.
- The movement of the un-frozen water dries out the gel and the small capillary pores, creating shrinkage.

Osmotic pressure theory
- Water in the capillary pores is not pure; it contains various soluble substances.
- Such solutions freeze at lower temperature than pure water.
- When solutions of different concentrations are separated by a permeable barrier, the solvent particles move towards the solution of greater concentration.

http://courses.washington.edu/cm425/durability.pdf

Freeze-Thaw Damage Mechanisms

De-icer Scaling
- De-icing chemicals used for snow and ice removal, such as sodium chloride, cause freeze-thaw deterioration.
- The additional problem caused by de-icers is believed to be a build-up of osmotic and hydraulic pressures in excess of the normal hydraulic pressures produced when water in concrete freezes.
- In addition, because salt absorbs moisture, it keeps the concrete more saturated, increasing the potential for freeze-thaw deterioration.

Air entraining agents
- Air voids allow hydraulic pressure to dissipate, avoiding damaging high pressures.
- A number of air voids decreases the average distance water must travel for pressure relief, but too many air voids decrease the overall strength of concrete. In general, each 1% air addition decreases concrete strength by 5%.

Thermal cracking
- Thermal cracking occurs due to excessive temperature differences within a concrete structure or its surroundings.
- The temperature difference causes the cooler portion to contract more than the warmer portion, which restrains the contraction.
- Thermal cracks appear when the restraint results in tensile stresses that exceed the in-place concrete tensile strength.
- Cracking due to temperature can occur in concrete members that are not considered mass concrete.
Mechanical abrasion, erosion, and cavitation

- **Abrasion:**
  - Dry attrition (wear on pavements and industrial floors by traffic)
  - the deterioration starts at the surface

- **Erosion:**
  - Wear produced by abrasive action of fluids containing solid particles in suspension (canal lining, spillways and pipes).

- **Cavitation:**
  - Loss of mass by formation of vapor bubbles and their subsequent collapse.

Classes for mechanical erosion

- **Moderate wear stress**
  - ship-induced rubbing (e.g. inside of lock chambers, above the tail water – 1,0 m)
  - River structures; ice rubbing

- **Strong wear stress**
  - weirs and stilling basins stressed by moderate sediment transport and high flow velocities

- **Very strong wear stress**
  - torrent structures
  - diversion tunnels

Fire damage

Damage to concrete attributable to fire has 3 principal types

i. Cracking and micro-cracking in the surface zone
   - This is usually sub-parallel to the external surface and leads to flaking and breaking away of surface layers.
   - Cracks also commonly develop along aggregate surfaces – presumably reflecting the differences in coefficient of linear expansion between cement paste and aggregate.
   - Larger cracks can occur, particularly where reinforcement is affected by the increase in temperature.

ii. Alteration of the phases in aggregate and paste
   - The main changes occurring in aggregate and paste relate to oxidation and dehydration.
   - Loss of moisture can be rapid and probably influences cracking.
   - The paste generally changes colour and various colour zones can develop. A change from buff or cream to pink tends to occur at about 300°C and from pink to whiteish grey at about 600°C.
   - The change from a normal to light paste colour to pink is most marked. It occurs in some limestones and some siliceous rocks

http://www.buildsmartercolorado.org/documents/Evaluating%20Fire%20Damage%20to%20Concrete%20Structures_tcm45-343618.pdf
Fire damage

Damage to concrete attributable to fire has 3 principal types

iii. Dehydration of the cement hydrates
   - This can take place within the concrete at temperatures a little above 100°C.
   - It is often possible to detect a broad zone of slightly porous light buff paste which represents the dehydrated zone between 100 and 300°C.

Biodegradation of structures

- [http://www.arcchip.cz/w08/w08_vilten.pdf](http://www.arcchip.cz/w08/w08_vilten.pdf)
Natural aging of the buildings and moisture, mould and decay problems in buildings

- During the service life of buildings, natural aging of materials due to biological processes can take place.
- Biodeterioration is important critical factor for durability of wood and wood based products.
- The service life of timber in a structure depends primarily upon the humidity and moisture conditions during the use of wood materials.
- The humidity and temperature conditions regulate the presence of wood attacking organisms.

- Mould and decay problems in buildings are caused by moisture damage: water leakage, convection of damp air and moisture condensation, rising damp from the ground and moisture accumulation in the structure.
- Moisture, mould and decay problems, however, can be very complicated in buildings.
- In buildings, mould fungi cause problems in different structures and materials: roofs, attics, basements, floors and walls.
- Apart from wooden material, surfaces of many other materials support growth of microbes and mould problems are more common than decay damage.

Moisture damages are causes to mould problems and decay damage

Water can invade different ways in building and cause different problems, defects and damages

- Detection the damages and simulation the causes of problems

- MOISTURE DAMAGE tolerances are overloaded

- MOULD
  - RH: > 75 - 95 %
  - Temp: 0 - 55 C
  - Time: d, w, m

- DECAY
  - RH: > 90 - 95 %
  - Temp: 5 - 50 C
  - Time: w, m, y

http://www.arcchip.cz/w08/w08_viitanen.pdf
## Biological damage

The typical organisms found in old buildings in Finland are:
- fungi: mold, bluestain and rot fungi
- bacteria: actinobacteria and streptomycetes
- insects: beetles and ants

### Mould fungi
- The growth of mould fungi is often an early indication of increased humidity or moisture levels
- the problems caused by fungi in buildings vary depending on the type of fungal attack.
- Problems caused by mould fungi are mainly discolouration, odour and health disadvantages.

### Decay fungi
- Different classifications are used for the decay fungi in practice
  - brown rot,
  - soft rot
  - white rot

### Insects
- Wood destroying insects usually utilize wood as a foodstuff, either directly or indirectly.
- Many insects are dependant on partially decayed wood, live in symbiosis with wood destroying fungi.
- Some insects are only boring wood to make nests without feeding on it, e.g. carpenter ants.

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Brown rot can appear everywhere in a house

White rot indicates the water leakage spots in the house

Soft rot requires permanent contact with water

Moulds are microorganisms that produce thousands of tiny particles called spores

Insect damage of wood

[http://www.arcchip.cz/w08/w08_viitanen.pdf](http://www.arcchip.cz/w08/w08_viitanen.pdf)
Summary

Lecture summary
- Deterioration mechanisms
- Chemical degradation
- Corrosion (chloride & carbonation)
- Alkali silica reaction
- Sulfate attack
- Physical degradation
- Freeze-thaw attack
- Biodegradation of structures and materials
- Moisture problems

Next lecture
- Concrete Defects and Damage
- Concrete Damage due to Reinforcement Corrosion
- Typical times of appearance of defects
- Recognizing defects and probable causes
  - Defects due to construction
  - Load-induced Defects
  - Defects related environmental factors and material properties
  - Other defects