2.9 DURABILITY THEORY

• 2.9.1 Introduction
• 2.9.2 Types of failure
• 2.9.3 Transport processes in concrete
• 2.9.4 Corrosion of reinforcement
• 2.9.5 Sulphate attack
• 2.9.6 Alkali-silica reaction
• 2.9.7 Frost attack
• 2.9.8 Salt crystallisation
• 2.9.9 Delayed Ettringite Formation
• Why Reinforced Concrete Structures Don’t Fall Down
Sources of Durability Problems

Sources of durability problems

- Design: 50%
- Construction and maintenance: 40%
- Materials: 10%
Types of Durability Problems

- Chloride attack: 19%
- Geotechnical: 23%
- Other: 19%
- AAR: 6%
- Construction defects leading to corrosion: 33%
Concrete in a Structure

As cast Surface

- Much Poorer Quality Concrete
- Poorer Quality Concrete
- Best Quality Concrete
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*Why Reinforced Concrete Structures Don’t Fall Down*
Factors Affecting Durability

<table>
<thead>
<tr>
<th>External factors</th>
<th>Internal causes</th>
<th>Structural Causes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weathering</td>
<td>Mechanical action</td>
<td>Salts</td>
</tr>
<tr>
<td></td>
<td>Chemical Action</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
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</tr>
<tr>
<td>Freeze Thaw</td>
<td>Temperature and moisture variations</td>
<td>Inorganic Salts</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spalling and loss of strength</td>
<td>Cracking leading to loss of durability</td>
<td>May cause rebar corrosion</td>
</tr>
</tbody>
</table>

Fig 2.9.4
2.9 DURABILITY THEORY

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- *Why Reinforced Concrete Structures Don’t Fall Down*
What is being transported?

- Ions (e.g. Na$^+$ and Cl$^-$) may move through the water

OR

- Water itself may move with the ions in it
The Transport Processes

- Pressure driven flow
- Diffusion,
- Electromigration
- Thermal migration

Processes which Promote or Inhibit Transport

- Adsorption (inhibits)
- Capillary suction (promotes)
- Osmosis (promotes)
Electromigration - Where Does the Voltage Come from?

- An external source such as leakage from a direct current power supply
- Electrical potential of pitting corrosion on reinforcing steel.
# Factors Affecting Durability

<table>
<thead>
<tr>
<th>Factors which can be controlled</th>
<th>Properties of the matrix</th>
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<th>Deterioration Processes</th>
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<tbody>
<tr>
<td></td>
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<td>Water to cement ratio</td>
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<td>(formation factor)</td>
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<tr>
<td>Curing conditions</td>
<td>Porosity (total pore</td>
<td>Electromigration</td>
<td>Alkali-silica reaction</td>
</tr>
<tr>
<td></td>
<td>volume)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Degree of compaction</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Cement Type</td>
<td>Matrix chemistry</td>
<td>Capillary suction</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adsorption</td>
<td></td>
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## Reduce the porosity with w/c ratio

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PFA will reduce Electromigration

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</tr>
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<td></td>
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<td></td>
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Using SRPC will reduce Adsorption

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<tr>
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<td></td>
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</table>
Curing has two distinct functions

1. To stop the concrete from drying out during hydration. If this occurs a significant loss of durability will occur.

2. To retain heat at the surface. This may be done for the following reasons
   i. To prevent frost damage (below 5°C)
   ii. To increase early strength
   iii. To reduce temperature gradients
Types of Pores

- **Gel pores**
- **Capillary pores**
- **Entrained air bubbles**
  - Entrapped air voids larger than \(10^3 \text{ } \mu\text{m}\)
**Pore Sizes**

<table>
<thead>
<tr>
<th>Size range m</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-10} - 10^{-9}$</td>
<td>Ions, $S^{2-}$, $Cl^{-}$, $O^{2-}$</td>
</tr>
<tr>
<td>$10^{-9} - 10^{-8}$</td>
<td>Gel pores: These are part of the hydrated cement structure, they are not interconnected and do not affect durability.</td>
</tr>
<tr>
<td>$10^{-8} - 10^{-6}$</td>
<td>Capillary pores: These are connected and considerably affect durability. Their volume may be calculated (see section 2.4). They are formed by excess water which does not react with the cement, either due to a high w/c ratio or insufficient hydration due to poor curing.</td>
</tr>
<tr>
<td>$10^{-4} - 10^{-3}$</td>
<td>Entrained air bubbles: Not interconnected.</td>
</tr>
</tbody>
</table>
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- Why Reinforced Concrete Structures Don’t Fall Down
The Corrosion Process

\[ \text{Fe}^{++} + 2\text{(OH)}^- + \text{H}_2\text{O} + \text{O}_2 \rightarrow \text{Fe}_2\text{O}_3 + n\text{H}_2\text{O} \]
Moscow
Corrosion
Electrochemical reactions producing rust

Fe → 2e⁻ + Fe^{++}  \[\text{Anode}\]

\[
\frac{1}{2}O_2 + H_2O + 2e^- \leftrightarrow 2(OH^-) \quad \text{Cathode}
\]

\[
4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3
\]
(red rust - carbonation)

3Fe + 8OH⁻ → Fe₃O₄ + 8e⁻ + 4H₂O
(black rust - chlorides)
The most significant deleterious agencies affecting passivity and thereby protection to reinforcement are:

- Carbonation (neutralisation of the alkaline pore fluid)
- Chloride ions
Carbonation depths

<table>
<thead>
<tr>
<th>Carbonation depth mm</th>
<th>Age Years</th>
<th>20 MPa concrete</th>
<th>40 MPa concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>4</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>7</td>
<td>64</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.9.1 Age of concrete for different depths of carbonation
Carbonation
The most significant deleterious agencies affecting passivity and thereby protection to reinforcement are:

- Carbonation (neutralisation of the alkaline pore fluid)
- Chloride ions
Schematic of chloride ingress

CHLORIDE CONTAINING ENVIRONMENT
eg seawater, de-icing salts

Cl⁻ Ingress

DIFFUSION / ABSORPTION
Schematic of binding with PFA
Cracks from Corrosion
Pitting

Migration of Cl⁻  Flow of corrosion current

O₂  Cl⁻  Cl⁻  O₂

Anode pit w. acid solution of FeCl₂

Passive steel acting as cathode
The consequences of the electrical nature of corrosion:

• Reducing the area of the anode (eg by coating part of the corroding steel) may increase corrosion elsewhere.
• Corroding areas may be located by measuring an increased anodic potential.
• Application of a positive potential to the surface of the concrete will stop the corrosion process (cathodic protection).
• Stray currents from welding, conductor rails, contact between different metals etc may produce rapid corrosion by creating an anodic region.
• Using a cementitious material with a high resistivity, such as a pozzolanic mix, will decrease corrosion.
Anode and Cathode on Structure

Fig. 9 – Current flow and potential distribution, (a) concrete in air, (b) concrete in sea water. Solid line, equipotential lines; dashed line, current flow.
Egypt
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*Why Reinforced Concrete Structures Don’t Fall Down*
Sulphate Attack
Common sources of sulphate

- Groundwater
- Sulphate rich soils
- Sea water
- Demolition hardcore
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Why Reinforced Concrete Structures Don’t Fall Down
Frost Attack on Kerb
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Salt Crystallisation

In these two examples there is no damage to the structure (yet). On the left the water has come from the cooling units above. On the right it has probably come down the steps from outside. The source of the salt is not clear. These 2 locations are well away from the car park entrance.
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Why Reinforced Concrete Structures Don’t Fall Down
Why should they fall down?

- The corrosion process is a chemical reaction between oxygen (from the air) and the metal (steel).
- The air and water can move easily through the concrete to the steel.
The main reason why concrete structures don’t fall down.

The main products of the reaction between cement and water are:

- Calcium silicate hydrate (CSH gel) - this is the main structural part.
- Lime (calcium hydroxide) – this provides alkalinity that promotes the formation of the passive film that protects the steel.
Chlorides – break down the passive film. Where do they come from?

- External sources: road salt, sea water
- Internal sources: contaminated materials
Transport processes:

- Transport of fluids in solids: permeation (pressure driven flow), capillary suction, thermal gradient, osmosis, and electro-osmosis.
- Transport of ions in fluids: diffusion, electromigration.
How to reduce transport rates in your structures

Increase the depth of cover

or

Reduce the porosity (i.e. the volume of voids) by:

• Reducing the water/cementitious ratio
• Using pulverised fuel ash or Blastfurnace slag (refines the porosity)
• Locally reducing the w/c ratio with controlled permeability formwork
• Good compaction
• Good curing
How to measure the transport properties in your structure:

- Initial surface absorption test,
- Figg gas permeability test,
- Electrical resistivity tests
How the concrete stops the chlorides

- The four cement compounds that make up the CSH gel are:
- Dicalcium silicate, Tricalcium silicate, Tetracalcium alumino-ferrite, Tricalcium aluminate
- The aluminate reacts with chlorides to form immobile chloro-aluminates.
How to protect your structure by promoting the adsorption of chlorides

- Do not: Use sulphate resisting Portland cement – it has a lower aluminate content.
- Do: Use pulverised fuel ash or blastfurnace slag. They have additional adsorption sites.
How the chlorides get moving again…. Carbonation

- The reaction between lime and carbon dioxide to produce carbonates
- Causes corrosion directly by removing alkalinity
- Makes chloro-aluminates unstable
How to reduce carbonation

• Reduce the transport of carbon dioxide by:
• Using a carbonation resisting coating or using concrete with lower transport rates (as for chlorides)
Corrosion is an electrical process; this may affect your structure in the following ways

- Application of a negative potential to the steel will stop corrosion (cathodic protection)
- Application of a positive potential to the steel (e.g. from welding) will cause corrosion.
- Using a concrete with a high electrical resistivity (e.g. with pfa) will reduce corrosion
Thank you

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