DURABILITY OF CONCRETE

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Relationship between durability and performance
Durability of concrete

- Durability of concrete may be defined as the ability of concrete to resist:
  - weathering action,
  - chemical attack, and
  - abrasion while maintaining its desired engineering properties.

- Different concretes require different degrees of durability depending on the exposure environment and properties desired.
  - For example, concrete exposed to tidal seawater will have different requirements than an indoor concrete floor.

Factors Affecting Durability

- The Concrete System
  - Materials
    - Binder type
    - Binder content
    - Aggregates
    - Admixture
    - Mix design
  - Process
    - Mixing
    - Transporting
    - Compaction
    - Curing
    - Temperature
    - Workmanship

- Aggressiveness of the Environment
  - Physical
    - Abrasion
    - Erosion
    - Cavitation
    - Freeze-thaw
  - Chemical
    - Dissolution
    - Leaching
    - Expansion
    - Alteration
Why durability problems?

- Concrete
  - Hydrated Cement Phase (HCP)
  - Aggregate phase
  - Interstitial Transition Zone (ITZ)
- Gel pores, Capillary pores, Air voids
- Permeability and porosity
- Aggressive species
  - Moisture, Sulphates, Chlorides, Carbon dioxide, Oxygen, Alkalies etc.
TRANSPORT MECHANISMS IN CONCRETE

Permeation and transportation mechanisms

- In all chemical and physical processes influencing durability of concrete structures, two factors are dominant:
  1. Transportation within the pore structures or cracks
  2. Movement of water (often containing dissolved salts or gasses)
- Permeation of water and gasses can be divided into three distinct phenomena:
  1. Permeability
  2. Absorption
  3. Diffusion
- Many factors influence these phenomena both internally and externally
Permeability

The flow property of concrete which quantitatively characterises the ease by which a fluid will pass through it, under a pressure differential.

Typically affects: dams, tunnel linings, liquid retaining structures, submerged offshore structures.

Permeability - influencing factors

Permeability = f {pressure gradient, capillary pore size, pore interconnection}

- Environmental Conditions
  - Pressure gradient
- Capillary size and interconnectivity
  - Aggregate type
  - Hydrate structure
    - Water/cement ratio
    - Cement type

Primary parameter
Secondary parameter
**Permeability**

- For steady-state flow, the coefficient of permeability, $K$, is determined from Darcy's expression:

$$\frac{dq}{dt} = \frac{K \cdot (\Delta H \cdot A)}{(L \cdot \mu)}$$

Where:

- $\frac{dq}{dt} = \text{rate of fluid flow}$,
- $\mu = \text{viscosity of the fluid}$,
- $\Delta H = \text{pressure gradient}$,
- $A = \text{surface area}$, and
- $L = \text{thickness of the solid}$.

**Permeability of Cement Paste**

<table>
<thead>
<tr>
<th>Age (days)</th>
<th>Permeability (cm/s $10^{-11}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh</td>
<td>20,000,000</td>
</tr>
<tr>
<td>5</td>
<td>4,000</td>
</tr>
<tr>
<td>6</td>
<td>1,000</td>
</tr>
<tr>
<td>8</td>
<td>400</td>
</tr>
<tr>
<td>13</td>
<td>50</td>
</tr>
<tr>
<td>24</td>
<td>10</td>
</tr>
<tr>
<td>ultimate</td>
<td>6</td>
</tr>
</tbody>
</table>
Permeability of Cement Paste

- When porosity decreases from 40 to 30%, the permeability drops from 110 to $20 \times 10^{-12}$ cm/sec

- However, a decrease in porosity from 30% to 20% results in a small drop in permeability

- Reasons:
  - Large pores are reduced in size and number.
  - There is creation of tortuosity.

Permeability of Aggregates

<table>
<thead>
<tr>
<th>Type of Rock</th>
<th>Permeability (cm/s $10^{-11}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dense trap</td>
<td>$2.47 \times 10^{-12}$</td>
</tr>
<tr>
<td>quartz diorite</td>
<td>$8.24 \times 10^{-12}$</td>
</tr>
<tr>
<td>marble</td>
<td>$2.39 \times 10^{-10}$</td>
</tr>
<tr>
<td>granite</td>
<td>$5.35 \times 10^{-9}$</td>
</tr>
<tr>
<td>sandstone</td>
<td>$1.23 \times 10^{-8}$</td>
</tr>
</tbody>
</table>
Absorption

The process by which concrete takes in liquid, normally water or aqueous solution by capillary action. Sorptivity is the rate at which water enters the concrete.

Absorption = $f$ {moisture gradient, capillary pore size, pore interconnection}

Typically affects: Structures subjected to cyclic wetting and drying, e.g., marine structures in the tidal zone.

Absorption - Influencing Factors

- Environmental Conditions
  - Moisture gradient

- Capillary size and interconnectivity
  - Aggregate type
  - Water/cement ratio
  - Cement type

- Hydrate structure
  - Pore fluid content
  - Degree of saturation

Absorption = $\varpropto$ {moisture gradient, capillary pore size, pore interconnection}
**Diffusion**

The process by which a vapour, gas or ion can pass through concrete under the action of a concentration gradient.

\[
\text{Diffusion} = f\{\text{concentration gradient, capillary pore size, pore interconnection, degree of reactivity of substrate}\}
\]

Typically affects: Foundation elements, Highway structures.

**Diffusion – Influencing Factors**

- Environmental Conditions
- Ionic concentration gradient
- Capillary size and interconnectivity
  - Aggregate type
  - Water/cement ratio
  - Cement type
- Hydrate chemistry
  - Curing conditions
- Pore fluid chemistry

\[
\text{Diffusion} = f\{\text{concentration gradient, capillary pore size, pore interconnection, degree of reactivity of substrate}\}
\]
## Environment / exposure conditions

<table>
<thead>
<tr>
<th>Climate</th>
<th>Horizontal extension</th>
<th>Vertical extension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regional climate</td>
<td>1-200 km</td>
<td>1 m -100 km</td>
</tr>
<tr>
<td>Local climate</td>
<td>100 m - 10 km</td>
<td>0.1 m - 1 km</td>
</tr>
<tr>
<td>Near surface and surface climate</td>
<td>0.01 - 100 m</td>
<td>0.01 - 10 m</td>
</tr>
</tbody>
</table>

DURACRETE: The European Union – Brite EuRam III
*Models for Environmental Actions on Concrete Structures*
### Exposure classes / Properties of concrete

**Table 2 - Exposure class XC: Corrosion of the reinforcements induced by carbonation**

<table>
<thead>
<tr>
<th>Class designation:</th>
<th>Environment description:</th>
<th>Examples where exposure classes may occur:</th>
<th>Max. W/C</th>
<th>Minimum strength class**</th>
<th>Min. cement content (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XC1</td>
<td>Dry or permanently wet</td>
<td>• Inside building with low air humidity</td>
<td>0.65</td>
<td>20/25</td>
<td>260</td>
</tr>
<tr>
<td>XC2</td>
<td>Wet, rarely dry</td>
<td>• Water retaining structures</td>
<td>0.60</td>
<td>25/30</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Foundations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XC3</td>
<td>Moderate humidity</td>
<td>• Inside building with moderate/high air humidity</td>
<td>0.55</td>
<td>30/37</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• External structures sheltered from rain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XC4</td>
<td>Cyclic wet and dry</td>
<td>• External structures exposed to rain water</td>
<td>0.50</td>
<td>30/37</td>
<td>300</td>
</tr>
</tbody>
</table>

*This may not be the case if there is barrier between the concrete and its environment.


### Exposure classes / Properties of concrete

**Table 3 - Exposure class XD: Corrosion of the reinforcements induced by chlorides other than from sea water**

<table>
<thead>
<tr>
<th>Class designation:</th>
<th>Environment description:</th>
<th>Examples where exposure classes may occur:</th>
<th>Max. W/C</th>
<th>Minimum strength class*</th>
<th>Min. cement content (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XD1</td>
<td>Moderate humidity</td>
<td>• Structures exposed to direct spray containing chlorides</td>
<td>0.55</td>
<td>30/37</td>
<td>300</td>
</tr>
<tr>
<td>XD2</td>
<td>Wet, rarely dry</td>
<td>• Swimming pools</td>
<td>0.55</td>
<td>30/37</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Structures exposed to industrial waters with Cl⁻</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XD3</td>
<td>Cyclic wet and dry</td>
<td>• Parts of bridges</td>
<td>0.45</td>
<td>35/45</td>
<td>320</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Pavements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Car park slabs</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Cylinder/cube concrete strength class (N/mm²) based on cement of strength class 32.5

### Exposure classes / Properties of concrete

#### Table 4 - Exposure class XS: Corrosion of the reinforcements induced by chlorides from sea water

<table>
<thead>
<tr>
<th>Class designation</th>
<th>Environment description:</th>
<th>Examples where exposure classes may occur:</th>
<th>Max. W/C</th>
<th>Minimum strength class*</th>
<th>Min. cement content (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XS1</td>
<td>Exposed to airborne salt but not in direct contact with sea water</td>
<td>Structures near to or on the cost</td>
<td>0.50</td>
<td>30/37</td>
<td>300</td>
</tr>
<tr>
<td>XS2</td>
<td>Submerged</td>
<td>Parts of marine structures</td>
<td>0.45</td>
<td>35/45</td>
<td>320</td>
</tr>
<tr>
<td>XS3</td>
<td>Total, splash, and spray zones</td>
<td>Parts of marine structures</td>
<td>0.45</td>
<td>35/45</td>
<td>340</td>
</tr>
</tbody>
</table>

*cyliner/cube concrete strength class (N/mm²) based on cement of strength class 32.5

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#### Table 5 - Exposure class XF: Freeze-thaw attack

<table>
<thead>
<tr>
<th>Class designation</th>
<th>Environment description:</th>
<th>Examples where exposure classes may occur:</th>
<th>Max. W/C</th>
<th>Minimum strength class*</th>
<th>Min. cement content (kg/m³)</th>
<th>Min. air volume (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XF1</td>
<td>Moderate water saturation, without deicing salts</td>
<td>• Vertical surfaces exposed to rain and freezing</td>
<td>0.55</td>
<td>30/37</td>
<td>300</td>
<td>-</td>
</tr>
<tr>
<td>XF2</td>
<td>Moderate water saturation, with deicing salts</td>
<td>• Vertical surfaces of road structure exposed to freezing and airborne deicing salts</td>
<td>0.55</td>
<td>25/30</td>
<td>300</td>
<td>4</td>
</tr>
<tr>
<td>XF3</td>
<td>High water saturation, without deicing salts</td>
<td>• Horizontal surfaces exposed to rain and freezing</td>
<td>0.50</td>
<td>30/37</td>
<td>320</td>
<td>4</td>
</tr>
<tr>
<td>XF4</td>
<td>High water saturation, with deicing salts</td>
<td>• Horizontal surfaces of road structures and vertical surfaces exposed to direct spray of deicing salts</td>
<td>0.45</td>
<td>30/37</td>
<td>340</td>
<td>4</td>
</tr>
</tbody>
</table>

*cyliner/cube concrete strength class (N/mm²) based on cement of strength class 32.5
### Exposure classes / Properties of concrete

#### Table 6 - Exposure class XA: chemical attack in natural soils, ground water, and sea water

<table>
<thead>
<tr>
<th>Class designation</th>
<th>SOIL:</th>
<th>WATER:</th>
<th>Max. W/C</th>
<th>Minimum Strength Class</th>
<th>Min. Cement content kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acidity (Baumann Gully)**</td>
<td>SO₄²⁻ (mg/l)</td>
<td>SO₄²⁻ (mg/l)</td>
<td>PH</td>
<td>CO₂ (mg/l)</td>
</tr>
<tr>
<td>XA1</td>
<td>&gt;200</td>
<td>≥2000</td>
<td>≤2000</td>
<td>≥6.5</td>
<td>≥15</td>
</tr>
<tr>
<td></td>
<td>≤3000</td>
<td>≤6000</td>
<td>≤5.5</td>
<td>≤40</td>
<td>≤300</td>
</tr>
<tr>
<td>XA2</td>
<td>—</td>
<td>&gt;3000</td>
<td>≤600</td>
<td>&gt;5.0</td>
<td>&gt;10</td>
</tr>
<tr>
<td></td>
<td>≤12000</td>
<td>≤3000</td>
<td>≤5.5</td>
<td>≤4.5</td>
<td>≤60</td>
</tr>
<tr>
<td>XA3</td>
<td>—</td>
<td>&gt;12000</td>
<td>≤6000</td>
<td>≥4.5</td>
<td>≥100</td>
</tr>
<tr>
<td></td>
<td>≤24000</td>
<td>≤6000</td>
<td>≥4.0</td>
<td>≥100</td>
<td>≤100</td>
</tr>
</tbody>
</table>

* When two or more aggressive characteristics lead to the same class, the environment shall be classified into the next higher class.

** To be checked according to the German DIN 4030-2 test

*** Clay soils with a permeability below 10⁻⁵ m/s may be moved into a lower class

**** Cylinder/Cube concrete strength class (N/mm²) based on cement strength class 32.5


**DETERIORATION OF CONCRETE**
Deteriorating Agencies

- **External agencies**
  - Chemical –
    - Sulphates, Chlorides, CO2,
    - Natural waters,
  - Mechanical –
    - Abrasion, Erosion, Cavitation,
    - Impact,
    - Temperature
- **Internal agencies**
  - Alkali aggregate reactions
  - Volume change due to non compatible thermal and mechanical properties of aggregates and cement paste
  - Presence of sulfates and chloride from the ingredients of concrete

Common durability problems in concrete

- Corrosion of steel in reinforced concrete
  - Carbonation induced corrosion
  - Chloride induced corrosion
- Sulphate and other chemical attack
- Alkali-aggregate reaction
- Freezing and thawing
Corrosion of steel in reinforced concrete

**CORROSION INITIATORS**
- Carbonation
- Chlorides
- Stray Currents

**At Construction**
- Calcium Chloride
- Saline Batchwater
- Sea Sand
  (Acid Etching)

**From Environment**
- Marine Saline Groundwater
- Airborne Salt
- Magnesite

Aggression by CO₂: Carbonation induced corrosion
Aggression by CO$_2$: Carbonation induced corrosion

- Cement paste contains 25-50 wt% (Ca(OH)$_2$), → pH ≈ 13
- The carbonation process requires the presence of water because CO$_2$ dissolves in water forming H$_2$CO$_3$.
  - If the concrete is too dry (RH <40%) CO$_2$ cannot dissolve and no carbonation occurs.
  - If on the other hand it is too wet (RH >90%) 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%)

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

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

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

- The pH of a fully carbonated paste is < 9.

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.

- **Corrosive de-icing solutions:**
  - Sodium Chloride (NaCl the most common de-icing chemical)
  - Magnesium Chloride (MgCl$_2$)
  - Calcium Chloride (CaCl$_2$)
  - Potassium Chloride (KCl)

Aggression by chlorides: Chloride induced corrosion

Corrosion initiation of concrete reinforcement caused by chloride when concrete is wet
Aggression by chlorides: Chloride induced corrosion

Chloride induced corrosion

When reinforcing steel corrodes, electrons flow through the bar and ions flow through the concrete.
Chloride induced corrosion

Decomposition of passivity layer
\[ Fe^{2+} + 2Cl^- \rightarrow FeCl_2 \] (soluble in pore solution)

Corrosion of steel
\[ Fe \rightarrow Fe^{2+} + 2e^- \] (oxidation)
\[ \frac{1}{2} O_2 + H_2O + 2e^- \rightarrow 2OH^- \] (reduction)

Formation of rust
\[ Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2 \]
\[ 2Fe(OH)_2 + \frac{1}{2} O_2 + H_2O \rightarrow 2Fe(OH)_3 \rightarrow Fe_2O_3 \cdot 3H_2O \]

Rust

Chloride induced corrosion

Ingress of corrosive species (into porous concrete)
Cracking and spalling of the concrete cover
Build up of voluminous corrosion products
Corroding reinforcing steel

Porous concrete
Corrosive species may already be present in concrete from "contaminated" mix ingredients

<table>
<thead>
<tr>
<th></th>
<th>Fe</th>
<th>Fe O</th>
<th>Fe_3O_4</th>
<th>Fe_2O_3</th>
<th>Fe (OH)_2</th>
<th>Fe (OH)_3</th>
<th>Fe (OH)_3 3H_2O</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

Volume, cm³
Aggression by sulphates: mechanism

Sulfate attack is characterised by the chemical reaction between sulfate ions with the aluminate component, calcium and hydroxyl of hardened Portland cement.

The reaction leads to the formation of expansive ettringite and to a lesser extent, gypsum.

The reaction, providing there is enough water present, will cause expansion leading to cracking. This in turn will allow further ingress of sulfates and accelerate the degradation process.

\[ \text{Ca(OH)}_2 + \text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O} \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O} + 2\text{NaOH} + 8\text{H}_2\text{O} \]

gypsum

Aggression by sulphates

- **Delayed Ettringite Formation (DEF):**
  - is a form of internal sulfate attack.
- Conditions necessary for DEF to occur are:
  - High temperature (above 65-70°C)
  - Moisture: permanent saturation
  - Commonly associated with ASR

- **Solution**
  - Cement with low C3A (less than 8%)
  - Low w/c (less than 0.45)
  - Pozzolan
To avoid damage by sulfate attack specify:

- appropriate cement type
- appropriate w/c
- supplementary cementitious materials
- good construction practices and curing

Alkali Aggregate Reaction: AAR

**AAR Definition:**

- AAR is a chemical reaction between certain types of aggregates and hydroxyl ions (OH-) associated with alkalis in the cement
- Under some conditions, the reaction may result in damaging expansion and cracking of the concrete
- Concrete deterioration caused by alkali-aggregate reaction is generally slow, but progressive.

**two types of AAR:**

1. Alkali-Silica Reaction
2. Alkali-Carbonate Reaction
Alkali Aggregate Reaction: Alkali silica reaction

Alkalis (from cement or de-icing salts) + Reactive Silica (in some aggregate) + Moisture

\[ \text{ASR Gel which expands} \]

Concrete expansion and cracking

Alkali content in cement expressed as \( \text{Na}_2\text{O}_{\text{eq}} = \text{Na}_2\text{O} + 0.658 \text{K}_2\text{O} \)
Low alkali cement has \( \text{Na}_2\text{O}_{\text{eq}} < 0.60 \)

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Alkali Aggregate Reaction: Alkali silica reaction

[Image of cracked concrete column]
Alkali-carbonate reactions (ACR)

- Dedolomitization, the breaking down of dolomite, is normally associated with expansion.
- This reaction and subsequent crystallization of brucite may cause considerable expansion.
- The deterioration caused by ACR is similar to that caused by ASR; however, ACR is relatively rare because aggregates susceptible to this phenomenon are less common and are usually unsuitable for use in concrete for other reasons.

How to prevent damage by ASR

- **Avoid high alkali content:**
  - use low alkali portland cement: $\text{Na}_2\text{O}_{eq} < 0.60\%$
  - reduce alkali content in concrete $< 3 \text{ kg/m}^3$
  - partial replacement of cement with low alkali mineral admixtures (FA)
- **Avoid reactive aggregate (amorphous silica)**
- **Control access to water:**
  - low w/c,
  - proper placement and curing,
  - use mineral admixtures to decrease permeability
- **Use lithium containing chemical admixtures prior to placement of concrete or as a treatment in existing concrete**
Damage by Freeze-Thaw

- The most potentially destructive weathering factor is freezing and thawing while the concrete is wet, particularly in the presence of deicing chemicals.

- Deterioration is caused by the freezing of water and subsequent expansion in the paste, the aggregate particles, or both.

Freeze-Thaw Damage Mechanisms

**Critical Saturation**
- when approximately 91% of its pores are filled with water → critical saturation
- When water freezes to ice it occupies 9% more volume than that of water.
- If there is no space for this volume expansion in a porous, water containing material like concrete, freezing may cause distress in the concrete.
Freeze-Thaw Damage Mechanisms

**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 pressure generated increases as fluid viscosity, flow rate, or length increase, and as permeability or area decrease.
- Spacing between bubbles $\approx 0.20$ mm

$$\Delta h = \frac{\eta}{k} \frac{Q}{A}$$

$\Delta h$ is the pressure gradient, $\eta$ is the fluid viscosity, $k$ is the permeability, $Q$ is the flow rate, $l$ is the length of the flow path, and $A$ is the flow area.

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**Freeze-Thaw Damage Mechanisms**

**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.
Freezing and thawing - damage

- ASR often go hand in hand with F/T.
- Often is may be difficult to evaluate which mechanism caused the initial damage, however, if all other mechanisms can be excluded the typical signs of F/T are:
  - Spalling and scaling of the surface
  - Large chunks (cm size) are coming o’ (pop outs)
  - Exposing of aggregate
  - Usually exposed aggregate are un-cracked
  - Surface parallel cracking
  - Gaps around aggregate - in the ideal case

Damage by Freeze-Thaw - solution

- With the addition of an air entrainment admixture, concrete is highly resistant to freezing and thawing.

- During freezing, the water displaced by ice formation in the paste is accommodated so that it is not disruptive; the microscopic air bubbles in the paste provide chambers for the water to enter and thus relieve the hydraullic pressure generated.
Concrete with a low water-cementitious ratio (0.40 or lower) is more durable than concrete with a high water-cementitious ratio (0.50 or higher).

- Air-entrained concrete with a low water-cementitious ratio and an air content of 5 to 8% will withstand a great number of cycles of freezing and thawing without distress.
- The air-bubbles should be well distributed and have a distance between each other of less than 0.25 mm in the cement paste.

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Damage by Freeze-Thaw - solution

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Aggression by mechanical elements

**Abrasion** (hiertyminen)
- If a material is repeatedly struck by particles from a harder body, abrasion takes place due to the friction

**Erosion** (kuluminen)
- Same but by wet processes (wear due to wind, water or ice)
Aggression by mechanical elements

**Abrasion** (hiertyminen):
- progressive loss of mass from concrete surface by dry attrition (e.g., pavement wear)
- **Impact:**
  - Damage due to impact is not necessarily immediately visible, and in certain cases many impact cycles are required

**Cavitation**
- Cavitation is a problem where flowing water (> 12 m/s) is present.
- The high speed of the water provoke turbulence and areas of low pressure, and vortexes will form which erode the substrate
To avoid abrasion/erosion damage

- densely graded, strong and hard aggregate
  - enough fines to densify the surface
- >30 MPa concrete (ACI 201)
- low w/c
- max slump 750 mm
- sodium nitrate seal

High temperatures

Damage to concrete attributable to fire has 3 principal types:

i. Cracking and micro-cracking in the surface zone
ii. Dehydration of the cement hydrates
iii. Change of the phases in aggregate and paste

ASTM E 119 Time temperature curve
Fire Resistance

Variation of relative compressive strength of normal strength concrete as a function of temperature.

Phases of deterioration due to fire

The concrete withstands temperatures of up to 650°C

The first part to break off is the concrete around the reinforcement, which is fundamental in protecting the rods

Once the reinforcement rods are exposed, heat propagates more quickly

If the structure is exposed to fire for a considerable time, the steel also loses its performance characteristics, causing the structure to collapse
References


Next lecture: Fri. 04.12.2015

Estimation of service life-span of concrete structures

- Factor method for predicting design service life

Exercise 11 – Service life calculation