Durability of Concrete and Service Life of Reinforced Concrete Structures under Combined Mechanical and Environmental Actions

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2. Combined actions, three selected examples:
   (1) Sustained load and carbonation
   (2) Durability under cyclic load
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3. Conclusions
Introduction

Basic elements of probabilistic service life design:

\[ Z = R - S \]

- (Environ.) Load
- Resistance
- Reliability

\[ p_f = \Phi \left( -\frac{\mu_Z}{\sigma_Z} \right) = \Phi (-\beta), \text{ with } \mu_Z = \mu_R - \mu_S, \sigma_Z = \sqrt{\sigma_R^2 + \sigma_S^2} \]

- Reliability Index
- \( \Phi (\cdot) \) Normal Distribution
- Failure Probability
Introduction

**Service life design** according to DuraCrete (Brite-Euram) probabilistic concept, an example:

(A) Major deterioration mechanism: *Chloride induced corrosion*

\[
x(t) = 2 \cdot C_{(\text{Crit})} \cdot \sqrt{k_t \cdot D_{\text{RCM,0}} \cdot k_e \cdot k_c \cdot \left(\frac{t_0}{t}\right)^n \cdot t}
\]

\(x(t)\) = chloride penetration depth as function of time
\(D_0\) = Chloride diffusion coefficient, determined at time \(t_0\)
\(D_{\text{RCN,0}}\) = chloride migration coefficient
\(k_e\) and \(k_c\) are constants
\(C_{\text{crit}}\) = critical chloride content, \(C_{SN}\) = surface chloride content
Introduction

Service life design according to DuraCrete (Brite-Euram) probabilistic concept, an example:

(B) Major Deterioration Mechanism: Carbonation

\[ X_c(t) = \sqrt{2 \cdot k_e \cdot k_c \cdot (k_t \cdot R_{\text{ACC},0}^{-1} + \epsilon_t) \cdot \Delta C_s \cdot \sqrt{t} \cdot \left( \frac{t_0}{t} \right)^w} \]

\( X_c(t) \) = depth of carbonation as function of time,

\( k_e, k_c, k_t \) = parameters

\( R_{\text{ACC},0} \) = carbonation resistance of dry concrete determined with the accelerated carbonation test

\( \Delta C_s \) = \( \text{CO}_2 \) concentration of the ambient air

\( \epsilon_t \) = error term to translate laboratory results into natural conditions
Introduction

Calculated probability of failure $p_f$ and reliability index $\beta$ as function of time

\[ \begin{align*}
\beta &= 3.4, \\
p_f &= 0.03\% \\
\beta &= 2.6, \\
p_f &= 0.49\% \\
\beta &= 2.3, \\
p_f &= 1.02\% \\
\beta &= 2.0, \\
p_f &= 2.08\%
\end{align*} \]
Introduction

- Apparently very precise data for service life are obtained with service life design.
- But are results of the probabilistic design realistic?
- Are material parameters obtained in a laboratory by means of accelerated tests reliable?
- What is the influence of imposed load or strain and damage due to frost action?
- Is there a need to take combined actions into consideration?
Introduction

Different actions and processes, which may act alone or in combination to reduce service life of reinforced concrete structures

<table>
<thead>
<tr>
<th>Mechanical</th>
<th>Migration</th>
<th>Chemical</th>
<th>Thermal</th>
<th>Hygral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression</td>
<td>Drying</td>
<td>Carbonation</td>
<td>Heat of hydration</td>
<td>Shrinkage stress</td>
</tr>
<tr>
<td>Tension</td>
<td>Capillary absorption</td>
<td>Chloride</td>
<td>Thermal gradients</td>
<td>Hygral gradient</td>
</tr>
<tr>
<td>Shear</td>
<td>Ion migration</td>
<td>Sulphate</td>
<td>Thermal eigenstresses</td>
<td>Swelling</td>
</tr>
<tr>
<td>Torsion</td>
<td>Electrophoresis</td>
<td>Ammonium</td>
<td>Thermal decomposition</td>
<td>Convection</td>
</tr>
<tr>
<td>Sustained</td>
<td>Electrophoresis</td>
<td>Hydrolysis</td>
<td>Frost action</td>
<td></td>
</tr>
<tr>
<td>Cyclic</td>
<td>Leaching</td>
<td>Alkali-aggregate reaction</td>
<td>Freeze-thaw cycles</td>
<td></td>
</tr>
</tbody>
</table>
Combination of Mechanical Load and Carbonation

Experimental set-up: Concrete beams under four point bending; Accelerated carbonation under load
Combination of Mechanical Load and Carbonation

A-0: Unloaded specimens
A-30-Y: Compressive zone in beams loaded with 30% of the ultimate load
A-30-L: Tensile zone in beams loaded with 30% of the ultimate load

Experimental results: calcium carbonate profiles as measured on unloaded beams and beams under four point bending
Combination of Mechanical Load and Carbonation

Concrete under tensile load:
\[ k_t(\sigma/\sigma_u) = 1 + 1.41(\sigma/\sigma_u) + 0.82(\sigma/\sigma_u) \]

Concrete under compressive load:
\[ k_c(\sigma/\sigma_u) = 1 - 2.27(\sigma/\sigma_u) + 4.86(\sigma/\sigma_u) \]

Experimental data (compressive): 
- curve of \( f(\sigma/\sigma_0) \) (compressive)
- experimental data (compressive)

Experimental data (tensile): 
- curve of \( f(\sigma/\sigma_0) \) (tensile)
- experimental data (tensile)

\[ x_c(t) = k_0 \ k_\sigma \ \sqrt{t} \]
Influence Cyclic Load on Durability

Experimental: Dumb bell specimens have been prepared to study the influence of cyclic tensile load on porosity.
The following damage index has been introduced:

\[ D(N) = \frac{P_0}{P_N} - 1 \]

Lower stress level: 10% and upper stress level 65%, 75% and 85% of ultimate load
Influence of Cyclic Load on Durability

<table>
<thead>
<tr>
<th>Stress level</th>
<th>Number of cycles N</th>
<th>Porosity, %</th>
<th>Damage Index D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>5.69</td>
<td>0</td>
</tr>
<tr>
<td>65 %</td>
<td>1</td>
<td>7.77</td>
<td>0.366</td>
</tr>
<tr>
<td></td>
<td>20000</td>
<td>7.84</td>
<td>0.378</td>
</tr>
<tr>
<td></td>
<td>50000</td>
<td>8.14</td>
<td>0.431</td>
</tr>
<tr>
<td></td>
<td>100000</td>
<td>8.34</td>
<td>0.466</td>
</tr>
<tr>
<td>75 %</td>
<td>1</td>
<td>8.29</td>
<td>0.457</td>
</tr>
<tr>
<td></td>
<td>20000</td>
<td>8.17</td>
<td>0.436</td>
</tr>
<tr>
<td></td>
<td>50000</td>
<td>8.68</td>
<td>0.526</td>
</tr>
<tr>
<td></td>
<td>100000</td>
<td>9.45</td>
<td>0.661</td>
</tr>
<tr>
<td>85 %</td>
<td>1</td>
<td>8.82</td>
<td>0.550</td>
</tr>
<tr>
<td></td>
<td>20000</td>
<td>8.17</td>
<td>0.471</td>
</tr>
</tbody>
</table>

**Results:** Porosity increases with increasing number of load cycles; Porosity also increases with increasing upper stress level. Increased porosity means accelerated capillary absorption.
Increasing porosity as function of the applied number of cycles and of the upper level of the applied load.
### Frost Action and Carbonation

<table>
<thead>
<tr>
<th>Type</th>
<th>W/B</th>
<th>Cement</th>
<th>Sand</th>
<th>Gravel</th>
<th>Water</th>
<th>Fly ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.4</td>
<td>380</td>
<td>579</td>
<td>1269</td>
<td>152</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>0.5</td>
<td>320</td>
<td>653</td>
<td>1267</td>
<td>160</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>0.6</td>
<td>300</td>
<td>710</td>
<td>1210</td>
<td>180</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>0.5</td>
<td>256</td>
<td>653</td>
<td>1267</td>
<td>160</td>
<td>64</td>
</tr>
</tbody>
</table>

**Experimental:** Four types of concrete have been tested. After 150 freeze-thaw cycles specimens were exposed to high CO2 concentration for one week for accelerated carbonation. Then calcium carbonate profiles have been determined.
Frost Action and Carbonation

Results:

Calcium carbonate profiles after one week of accelerated carbonation.

Calcium carbonate profiles after 100 freeze-thaw cycles applied prior to one week of accelerated carbonation.
Frost Action and Chloride Penetration

**Experimental:** Chloride penetration by capillary absorption has been determined on the same four types of concrete with and without 150 prior freeze-thaw cycles. One surface of the specimens was put in contact with an aqueous 3 % NaCl solution for 24 hours.
Frost Action and Chloride Penetration

**Results:**

Chloride profiles after 24 hours of contact with 3 % NaCl solution.

Chloride profiles after 150 freeze-thaw cycles followed by 24 hours of contact with 3 % NaCl solution.
Conclusions I

• There exists a huge number of possible load combinations, which all may reduce service life of reinforced concrete structures as predicted on the basis of one dominant deteriorating mechanism.

• So far we do not know the most serious load combinations.
Conclusions II

• Applied tensile and compressive load and freeze-thaw cycles induce damage into the composite structure of concrete. Capillary absorption and gas permeability are both increased. These processes are at the origin of accelerated carbonation and chloride penetration.

• The predicted service life can be significantly reduced by combined actions. It has to be taken into consideration.