Long-term performance of new concrete compositions
- Norwegian experience

ACES workshop

Corfu, October 2010
Service life design

According to most national and regional building legislation, the construction team are obliged to verify a certain service life of the new structure.

As engineers we must predict the performance of our structures after 50, 100 or more years.
In some rare cases we can relay on long-term experience

Bridge at castle of Chazelet, French Alps
Joseph Monier - 1875
Present approach in Europe is the deemed-to-satisfy (descriptive) method given in the standards.

Mix compositions given in Table F of EN 206-1 combined with minimum cover given in EN 1992-1-1

Since durability is under the authority of the member state, these requirements are given in a national annex to the standards.
Range of XC3 provisions for CEM I in Europe
UK → w/c < 0.55 and 25 mm minimum cover
DE → w/c < 0.65 and 20 mm minimum cover

Range of XC4 provisions for CEM I in Europe
NL → w/c < 0.50 and 25 mm minimum cover
DE → w/c < 0.60 and 25 mm minimum cover

Range of XS2 provisions for CEM I in Europe
UK → w/c < 0.50 and 35 mm minimum cover
NO → w/c < 0.40 and 40 mm minimum cover
In most (actually all) cases we are lacking long-term experience with the construction techniques and materials used today.

We then have to extrapolate accelerated laboratory test results or short or medium term experience.

We then need the help of a reasoning, model or a crystal bowl.
“Lab. performance test”

A reasoning or mathematical model enabling the transformation of laboratory experience to a prediction of the in-field behaviour for a given structure

Long-term in-field performance of the structure in its given environment
CEN TC-104/SC-1 has since 2007 tried to come up with an “Equivalent Durability Concept” enabling the industry to qualify new material compositions concerning durability based on performance tests on young concrete specimens.

The experts in Europe have not been able to do so.
short- or medium-term field experience

A reasoning or mathematical model enabling the transformation of short-term experience to a prediction of the long-term in-field behaviour for a given structure

Long-term in-field performance of the structure in its given environment
...... no prediction of future developments can be made without some form of model, no matter how crude.....

fib Bulletin no 53, fib Text book; 5.8.1
The significance of the assessment will increase with time and the quality of the analytical model.
Influence of data uncertainties on chloride prediction of ingress – extrapolation from $\frac{1}{2}$ year
Influence of data uncertainties on chloride prediction of ingress – extrapolation from 10 years
Influence of age of structure when assessing remaining service life
Model code for service life design
In Norway we have applied the principles given in fib MC SLD and ISO/WD 16204 to verify our deemed-to-satisfy requirements, both for traditional CEM I and for concrete with silica fume.
Design Service Life (fib MC SLD & ISO/WD 16204)

The design service life is the assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance but without major repair being necessary. Choices made by the Norwegian standardisation body

The design service life is defined by:

- A definition of the relevant limit state
- A number of years
- A level of reliability for not passing the limit state during this period

- depassivation
- 50 and 100 years
- “Failure” probability $p_f = 10^{-1}$
Carbonation

During the summer 2000 we equipped 2 students with a car, equipment for core drilling and phenolphthalein.

They mapped the ingress of carbonation on a number of structures in exposure class XC3 and XC4 in different parts of the country.

The average age was about 10 years.

We had information on the original mix composition on all the structures.

The concretes were based on CEM I and CEM I + silica fume.

The structures were built according to our standard from 1986 with a w/b ≤ 0.60 requirement.
Normalising to $w/b = 0.60$:

$$CA_{0.6,t_1} = CA_{w/b_1,t_1} \cdot (2.5 - 2.5 \cdot w/b_1)$$

$CA_{0.6,t_1}$ = carbonation depth at $w/b = 0.60$ and exposure age $t_1$

$CA_{w/b_1,t_1}$ = measured carbonation depth in a concrete with $w/c_1$ and age $t_1$

Accurate enough for $0.50 < w/b > 0.70$
Normalising to age 50 years:

\[ CA_{0.6,50} = CA_{0.6,t_1} \left( \frac{50}{t_1} \right)^{0.5} \]

\( CA_{0.6,50} \) = carbonation depth at \( w/b = 0.60 \) and exposure age 50 years

Based on \( CA_{0.6,50} \) values, calculation of

- \( \mu_{0.6,50} = \) average carbonation depth at 50 years
- \( \sigma_{0.6,50} = \) standard deviation for carbonation at 50 years
Correlation between failure reliability $Z$, resistance $R$ and Load (action) $F$.

Concrete cover
NS 3473
$c_{\text{min}} = 25$ mm
$\Delta_{\text{minus}} = 10$ mm
## Data from existing structures

Input parameters and calculated results (50 years)

<table>
<thead>
<tr>
<th>Concrete family</th>
<th>$X_i$</th>
<th>Description</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>XC3 Concrete without silica fume</td>
<td>$CC$</td>
<td>Concrete cover</td>
<td>35.0</td>
<td>6.1</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>$CA$</td>
<td>Carbonation depth</td>
<td>13.8</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>w/b</td>
<td>w/b-ratio (k=1.0)</td>
<td>0.60</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>XC4 Concrete without silica fume</td>
<td>$CC$</td>
<td>Concrete cover</td>
<td>35.0</td>
<td>6.1</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>$CA$</td>
<td>Carbonation depth</td>
<td>11.0</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>w/b</td>
<td>w/b-ratio (k=1.0)</td>
<td>0.60</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>XC4 Concrete with silica fume</td>
<td>$CC$</td>
<td>Concrete cover</td>
<td>35.0</td>
<td>6.1</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>$CA$</td>
<td>Carbonation depth</td>
<td>14.5</td>
<td>6.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>w/b</td>
<td>w/b-ratio (k=1.0)</td>
<td>0.60</td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

Reliability index $\beta$ are better than 1.3 ($pf = 10^{-1}$)
NS-3473 / NS-EN 1992-1-1+NA
NS-EN 206-1+NA
NS 3465 / NS-EN 13670+NA

Give safe provisions for XC3 and XC4

- $w/b \leq 0.60$
- $C_{\text{min}} = 25 \text{ mm (50 years)}$
- $C_{\text{min}} = 35 \text{ mm (100 years)}$
- $\Delta_{(\text{minus})} = 10 \text{ mm}$
Marine Structures

Verification of the durability provisions given in the Norwegian standards
The purpose of the study:

To evaluate the requirements for durability in NS 3473: 2003 and NS-EN 206-1: 2003 for marine concrete structures (XS3) during the revision of our national annex to NS-EN 1992:

- \( w/c \leq 0.40 + \) addition of silica fume, FA or GGBS
- minimum cover = 50 mm (50 years)
- minimum cover = 60 mm (100 years)
Since 1973 34 structures representing some 2.6 mill m$^3$ HSC/HPC have been installed in the North Sea.

North Sea:
- Water: 5 – 17 °C
- Salinity: 35 g/l
- Design wind: 45 m/s
- Design wave height: 30 m

Heidrun-LWAC Floater
A rough marine environment!
We had access to 180 chloride profiles from 10 structures measured after up to 20 years exposure. These profiles have been analyzed with regard to remaining service life (depassivation of reinforcement).
<table>
<thead>
<tr>
<th>Structure</th>
<th>aggregate</th>
<th>Cement</th>
<th>Silica fume</th>
<th>w/(c+s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ekofisk</td>
<td>NDA</td>
<td>CEM I</td>
<td>-</td>
<td>0.45</td>
</tr>
<tr>
<td>Brent B</td>
<td>NDA</td>
<td>CEM I</td>
<td>-</td>
<td>0.38</td>
</tr>
<tr>
<td>Statfjord A</td>
<td>NDA</td>
<td>CEM I</td>
<td>-</td>
<td>0.38</td>
</tr>
<tr>
<td>Shore Approach</td>
<td>NDA</td>
<td>CEM I</td>
<td>8 %</td>
<td>0.36</td>
</tr>
<tr>
<td>Gullfaks A</td>
<td>NDA</td>
<td>CEM I</td>
<td>-</td>
<td>0.38</td>
</tr>
<tr>
<td>Oseberg A</td>
<td>NDA</td>
<td>CEM I</td>
<td>-</td>
<td>0.37</td>
</tr>
<tr>
<td>Gullfaks C</td>
<td>NDA</td>
<td>CEM I</td>
<td>2 %</td>
<td>0.38</td>
</tr>
<tr>
<td>Draugen</td>
<td>NDA</td>
<td>CEM I</td>
<td>2 %</td>
<td>0.40</td>
</tr>
<tr>
<td>Heidrun</td>
<td>NDA &amp; LWA</td>
<td>CEM I</td>
<td>5 %</td>
<td>0.39</td>
</tr>
<tr>
<td>Troll B</td>
<td>NDA &amp; LWA</td>
<td>CEM I</td>
<td>7 %</td>
<td>0.35</td>
</tr>
</tbody>
</table>
These structures have been subject to routine inspections by the operators, including:

- Drilling of cores
- Mapping of chloride profiles
Each profile (core) has been analyzed based on Fick's 2. law with a time-dependent diffusion coefficient.

Surface chloride concentration

$C_s$

$D_{app}(t) = D_{app}(t_0) \left( \frac{t_0}{t} \right)^\alpha$
Example:

Mapped chloride profile from “Draugen” after 14 years
Best curve-fit to the model gave:

\[ C_s = 0.68 \% \text{Cl}^- \text{ of concrete weight} \]

\[ D_{14\text{ år}} = 0.42 \times 10^{-12} \text{ m}^2/\text{sek} \]
If we assume:

- 0.07 % Cl\(^-\) of concrete weight represents the threshold value for depassivation (*with minimal risk*)
Further we assume that:

- 0.07 % Cl- of concrete weight represents the threshold value for depassivation (with minimal risk)
- 50 mm minimum cover to the reinforcement
Further we assume that:

- 0.07% Cl- of concrete weight represents the threshold value for depassivation (with minimal risk)
- 50 mm minimum cover to the reinforcement
Extrapolation of remaining time till the chloride concentration reach

- $C_{cr} = 0.07 \% \text{ Cl}^- \text{ (minimal risk)}$ at
- 50 mm depth

![Graph showing chloride concentration over depth and time.

- 14 år
- 120 år

Klorider; % of betongvekt

Dybde; mm

RaKon as SKANSKA
Results from core taken from Ekofisk extrapolated till 0.07 % Cl⁻ reach 50 mm depth

<table>
<thead>
<tr>
<th>Core No.</th>
<th>Age at inspection</th>
<th>Cs</th>
<th>D</th>
<th>Years till 0.07% Cl⁻ reach 50 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17</td>
<td>0.447</td>
<td>1.03</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>17</td>
<td>0.405</td>
<td>1.19</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>17</td>
<td>0.580</td>
<td>1.10</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>17</td>
<td>0.513</td>
<td>0.94</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>17</td>
<td>0.677</td>
<td>0.70</td>
<td>27</td>
</tr>
<tr>
<td>6</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>7</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>
Cores taken from Ekofisk

Sorted according to remaining period till depassivation

<table>
<thead>
<tr>
<th>Core No.</th>
<th>Age at inspection</th>
<th>Cs</th>
<th>D</th>
<th>Years till 0.07% Cl- reach 50 mm</th>
<th>Accumulated (%) compared to all cores</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>17</td>
<td>0.580</td>
<td>1.10</td>
<td>11</td>
<td>10 %</td>
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<td>50 %</td>
</tr>
<tr>
<td>6</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>7</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>
“Ekofisk” installed in 1973 with “tradtional” concrete based on CEM I cement and w/c = 0.45

10 cores drilled after 17 years
What does 0.07 % Cl\(^-\) (of concrete weight) mean?

Threshold values for initiation of corrosion

<table>
<thead>
<tr>
<th>Cl(^-) in % av cement</th>
<th>Cl(^-) in % av concrete (assumed 440 kg cement/m(^3))</th>
<th>Probability for corrosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 2.0</td>
<td>&gt; 0.36</td>
<td>certain</td>
</tr>
<tr>
<td>1.0 - 2.0</td>
<td>0.18 - 0.36</td>
<td>probable</td>
</tr>
<tr>
<td>0.4 - 1.0</td>
<td>0.07 - 0.18</td>
<td>possible</td>
</tr>
<tr>
<td>&lt; 0.4</td>
<td>&lt; 0.07</td>
<td>Minimal</td>
</tr>
</tbody>
</table>

Browne et al. 1980
What does 0.07 % Cl\(^-\) (of concrete) mean?

- 10 – 20 % probability for depassivation (Maria Cruz Alonso)
- 10 % probability for depassivation (Gehlen & Schiessl)
- Equals 0.4 % av cement-weight -> requirement for new structures

What does 50 mm minimum cover mean (XS3 / 50 år, NS 3473) ?

- 60 mm nominal cover according to EN 13670
- 5 – 10 % of surface reinforcement may have < 50 mm (ISO/WD 16204 and fib MC SLD)
“Brent B” installed in 1975
15 cores drilled after 19 years.
“Brent B” installed in 1975

15 cores drilled after 19 years.
“Oseberg A”

87 cores drilled between 9 and 18 years after installation in 1988
“Oseberg A”

87 cores drilled between 9 and 18 years after installation in 1988
“Shore Approach”

10 cores drilled after 12 and 26 years after installation in 1982
“Shore Approach”

10 cores drilled after 12 and 26 years after installation in 1982

0.07 % Cl⁻
0.07% Cl\textsuperscript{-} will reach 50 mm after > 120 år

Statfjord A
0.07% Cl- will reach 50 mm after > 120 år

Statfjord A
Gullfaks A
0.07% Cl⁻ will reach 50 mm after > 120 år

Statfjord A
Gullfaks A
Gullfaks C
0.07% Cl- will reach 50 mm after > 120 år

Statfjord A
Gullfaks A
Gullfaks C
Heidrun
0.07% Cl- will reach 50 mm after > 120 år

Statfjord A
Gullfaks A
Gullfaks C
Heidrun
Troll B
0.07% Cl- will reach 50 mm after > 120 år

Statfjord A
Gullfaks A
Gullfaks C
Heidrun
Troll B
Draugen

RaKon as SKANSKA
Conclusion 1/2:

- The great majority of cores verify that the structures will achieve a service life exceeding, with ample margin, the assumption in Norwegian standards.

- From a few structures, a few cores demonstrated very low resistance to chloride ingress.

- These cores reflected problems during the construction (for instance inadequate compaction, lifting cracks)
Conclusion 2/2:

- The present Norwegian standards are OK concerning specified w/c, cement type and cover.
- To avoid local defects, focus should be on constructability and the execution.
- This is more important than to specify:
  - Even lower w/c,
  - More exotic cement-types,
  - Stressed concrete composition resulting in problematic workability
  - Further increased cover.
Katie Melua

Concert 2006 in the "basement" of "Troll A"

- 302 meters below sea surface
End Corfu