Corrosion Mechanisms, Monitoring, and Service Life Enhancement of Reinforced Concrete Structures

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Outline

• Significance of corrosion

• Corrosion mechanisms in concrete structures

• Corrosion monitoring in the field

• Ways to enhance and estimate service life
The Golden Gate Bridge, San Francisco, USA is facing a lot of corrosion issues.
After just 13 years of service, tendons in the Sunshine Skyway bridge, Florida failed.
Wire mesh to protect the spalled concrete from falling onto the vehicles underneath the Mercier Bridge, Montreal, Canada
The cost of corrosion is significant

- In 2012, the direct cost of corrosion in India was Rs. 2 lakhs crores/year!

A corrosion protection strategy to minimise the repair and maintenance costs is a MUST

Corrosion cost split-up in the USA (FHWA 1998)

- TRANSPORTATION: $29.7 Billion (21.5%)
- UTILITIES: $47.9 Billion (34.7%)
- INFRASTRUCTURE: $22.6 Billion (16.4%)
- GOVERNMENT: $20.1 Billion (14.6%)
- PROD. & MFTRG.: $17.6 Billion (12.8%)

FHWA 1998, George Hays 2004
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Why does iron corrode?

3. \[ 4\text{Fe(OH)}_3 \rightarrow 2\text{Fe}_2\text{O}_3 + 6\text{H}_2\text{O} \]
2. \[ 4\text{Fe(OH)}_2 + \text{O}_2 + 2\text{H}_2\text{O} \rightarrow 4\text{Fe(OH)}_3 \]
1. \[ 2\text{O}_2 + 4\text{H}_2\text{O} + 4\text{Fe} \rightarrow 4\text{Fe(OH)}_2 \]
Concrete – An Introduction

- Concrete microstructure and pore solution
  - C-S-H
  - Ca(OH)$_2$; NaOH; KOH
  - Many other complex chemical compounds

\[ \text{pH} = -\log_{10}[\text{H}^+] \]

pH scale

Neutral: 7

Acidic: 0 - 5

Alkaline: 8 - 14

pH of concrete pore solution

Steel – An Introduction

• Ferrous alloys with various elements such as C, Mn, P, S, Si, Ni, Mo, Cr, V etc.
Why steel embedded in uncontaminated concrete does not corrode?

• Steel does not corrode due to high pH of concrete pore solution

• A protective layer ("Passive film") is formed
  – A thin, invisible, and stable layer of initial corrosion products (i.e., iron oxides and hydroxides).

• However, corrosion can occur when exposed to aggressive conditions

Hoar (1967)
What are the essential parts of a corrosion cell?

Note: “Current” flows in the opposite direction as the “electrons” move.

http://www.corrosion-club.com/images/corrosioncell.gif
What are typical electrochemical half-cell reactions associated with the corrosion of steel in concrete?

- Anodic (oxidation) reaction
  \[ \text{Fe} \rightarrow \text{Fe}^{2+} + 2e^- \]

- Cathodic (reduction) reaction
  \[ \frac{1}{2} \text{O}_2 + \text{H}_2\text{O} + 2e^- \rightarrow 2(\text{OH})^- \]

At the splash zone, corrosion can occur at a higher rate.

Corrosion of Steel in Water with Oxygen

Anode & cathode coexist on the same piece of metal!
Two major types of corrosion in concrete structures

- Carbonation-induced corrosion
  - General or uniform section loss

- Chloride-induced corrosion
  - Localized, pitting or non-uniform section loss
Carbonation-induced corrosion

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

Flaws in passive layer and high chloride content

Pits growing at various locations
Chloride-induced corrosion

The process is regenerating and instead of spreading along the bar, corrosion continues at local anodes and deep pits are formed.

\[
\frac{1}{2} O_2 + H_2O + 2e^- \rightarrow 2OH^-
\]

\[
Fe^{2+} + 2Cl^- \rightarrow FeCl_2
\]

\[
2H^+ + 2Cl^- \rightarrow \frac{1}{2} Cl_2 + H_2O + 2e^- \]

\[
FeCl_2 + 2H_2O \rightarrow 2HCl + Fe(OH)_2
\]
Pitting corrosion on strands and deformed bars due to chloride attack

- 7-wire strand
- Deformed bar
Typical locations for chloride induced corrosion and solutions?

http://is2c.nl/project-10979/moisture-and-salt-transport/
Typical locations for chloride induced corrosion and solutions?
A huge concern about the epoxy-coated steel

It is more dangerous to use scratched/damaged epoxy-coated steel than conventional uncoated steel

Courtesy: M. Thomas
Volume of rust is \(~6\) times more than that of steel
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How to detect corrosion in concrete structures?

- ASTM C876 Standard Test Method for Half-Cell Potentials of Uncoated Reinforcement in Concrete
  - If $E < -0.35$ V, 90% chance of corrosion
  - If $E > -0.25$ V, 90% chance no corrosion
  - If $-0.35$ V < $E$ < $-0.25$ V, then?

When using Cu/CuSO$_4$ reference electrode

Mehta and Monteiro
Some commercially available equipment to detect corrosion using potential mapping

- Canin+
Some commercially available equipment to measure corrosion rate

- GECOR6

Photo courtesy: James Instruments
Linear polarization resistance and guard ring techniques to measure corrosion rate
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The cost of corrosion is significant

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A corrosion protection strategy to minimise the repair and maintenance costs is a MUST

Corrosion cost split-up in the USA (FHWA 1998)

FHWA 1998, George Hays 2004
Service life = the time during which the structure is able to safely meet the user requirements

- The corrosion initiation phase is typically the longest phase in the service life of a structure.
- Determining the duration of this phase is very important in determining a structure’s service life.
Core-crete $\rightarrow$ Strength
Cover-crete $\rightarrow$ Durability

Cover-crete with low permeability is essential to achieve durability
Critical durability parameters

1. Rate of penetration (diffusion) of chlorides through covercrete (not corecrete)
   a) w/c
   b) SCMs
   c) SPs
2. Cover depth (covercrete)
3. Chloride threshold of steel
4. Chlorides at the surface of concrete
Adding excess water will reduce the strength and durability of concrete

\[ D_{28} = 1 \times 10^{(-12.06 + 2.40W/CM)} \text{ m}^2/\text{s} \]

Thomas and Bentz 2001, Life 365
Adding SCMs will improve the strength and durability of concrete

$$
\begin{align*}
C_2S + C_3S + H &\rightarrow CH + C-S-H \\
\text{Cement} + \text{Water} &\rightarrow \text{Calcium hydroxide} + \text{SCMs} \\
&\rightarrow more\ C-S-H
\end{align*}
$$

Concrete becomes stronger and less permeable when silica fume, fly ash and/or slag are added.
Adding silica fume will improve the strength and durability of concrete.

\[ D_{SF} = D_{PC} \times e^{-0.165 \cdot SF} \]

Pozzolanic reactions produce more C-S-H.

Thomas and Bentz 2001, Life 365
Adding fly ash and/or slag will improve the strength and durability of concrete.

\[ D(t) = D_{ref} \cdot \left( \frac{t_{ref}}{t} \right)^m \]

\[ m = 0.2 + 0.4(\%FA/50 + \%SG/70) \]

Pozzolanic reactions produce more C-S-H.
Critical chloride threshold levels of various steels

Pillai and Trejo, 2005
Tools are available to estimate the service life of concretes with various SCMs

http://www.life-365.org
Effects of w/c and SCMs on service life

<table>
<thead>
<tr>
<th>Case No.</th>
<th>w/c</th>
<th>Fly ash (%)</th>
<th>Silica fume (%)</th>
<th>Time to corrosion initiation (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4</td>
<td>0</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
<td>15</td>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>0.4</td>
<td>0</td>
<td>15</td>
<td>180</td>
</tr>
</tbody>
</table>

Silica fume concrete was used in Bandra-Worli Sealink
Life-365 software

Life-365™
Life-365 Service Life Prediction Model™
for Reinforced Concrete Exposed to Chlorides

Version 2.0.1

Life-365 Service Life Prediction Model and
Life-365 are trademarks of the Silica Fume
Association. Used with permission
Life-365 software

![Life-365 Software Interface](image-url)

### Project Details
- **Title:** Project-1
- **Analyst:** Jayachandran
- **Date:** 03/13/2012

### Structure Type and Dimensions
- **Type of structure:** Slabs and walls (1-D)
- **Thickness (mm):** 200.0
- **Reinf. depth (mm):** 60.0
- **Area (square m):** 10000

### Economic Parameters
- **Base Year:** 2012
- **Analysis Period (yr):** 75
- **Inflation rate (%):** 1.80%
- **Real discount rate (%):** 3.00%

### Define Alternatives (up to 6)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control concrete</td>
<td>A project that uses the normal mix of concrete</td>
</tr>
<tr>
<td>50% FA</td>
<td>A project that uses the new mix of concrete</td>
</tr>
<tr>
<td>50% Slag</td>
<td>A project that uses the new mix of concrete</td>
</tr>
<tr>
<td>25% FA + 25% Slag</td>
<td>A new description</td>
</tr>
<tr>
<td>25% Slag + 10% SF</td>
<td>A new description</td>
</tr>
</tbody>
</table>
**Life-365 software – probabilistic version**

![Software Interface](image)

### Define Concrete Mixtures

<table>
<thead>
<tr>
<th>Mix</th>
<th>User Defined</th>
<th>D25 (m/m³/sec)</th>
<th>m</th>
<th>C5 (% wt. conc.)</th>
<th>Int. (Yrs)</th>
<th>Prop. (Yrs)</th>
<th>Service Life (Yrs) = Int + Prop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control concrete</td>
<td>no</td>
<td>6.871E-12</td>
<td>0.30</td>
<td>0.050</td>
<td>4.8</td>
<td>6.0</td>
<td>10.8</td>
</tr>
<tr>
<td>50% FA</td>
<td>no</td>
<td>6.871E-12</td>
<td>0.00</td>
<td>0.050</td>
<td>199</td>
<td>6.0</td>
<td>25.9</td>
</tr>
<tr>
<td>50% Slag</td>
<td>no</td>
<td>6.871E-12</td>
<td>0.49</td>
<td>0.050</td>
<td>11.4</td>
<td>6.0</td>
<td>17.4</td>
</tr>
<tr>
<td>25% FA + 25% Slag</td>
<td>no</td>
<td>6.871E-12</td>
<td>0.54</td>
<td>0.050</td>
<td>14.7</td>
<td>6.0</td>
<td>20.7</td>
</tr>
<tr>
<td>25% Slag + 10% SF</td>
<td>no</td>
<td>1.7038E-12</td>
<td>0.54</td>
<td>0.050</td>
<td>32.2</td>
<td>6.0</td>
<td>38.2</td>
</tr>
</tbody>
</table>

**Selected mixture:** 25% Slag + 10% SF (a new description)

### Service Life Graphs

- **Service Life**
- **Cross-section**
- **Initiation**
- **Concrete Characteristics**
- **Inst.**
- **Int. Variation**

Select: **25% Slag + 10% SF**

- Concentration (% wt. conc.): 0.80
- Depth (m): 0.343
- Hydration (yrs): 25.0
- C5 (% wt. conc.): 0.05
- Prop (yrs): 6.0
- Service Life (yrs) = Int + Prop: 33.2

Select nearest year [0 to int]:

- Year: 33.2

**Note:** The service life graph shows the concentration and depth of the mixture over time. The service life is calculated as the sum of the initiation and propagation times.
Life-365 software

![Life-365 software interface](image)

The image shows a software interface for Life-365 v2.0.1, including tabs for Project, Exposure, Concrete Mixtures, Individual Costs, Life-Cycle Cost, SL Report, LCC Report. The interface is focused on defining concrete mixtures and includes a section for calculating service life, computing uncertainty, and setting options. There are graphs showing the concentration versus depth and concentration versus time at a depth of 60 mm, with various mixtures represented by different colors.
Life-365 software

Diffusivity Versus Time

- Control concrete
- 50% FA
- 50% Slag
- 25% FA + 25% Slag
- 25% Slag + 10% SF

Surface Concentration Versus Time

- Control concrete
- 50% FA
- 50% Slag
- 25% FA + 25% Slag
- 25% Slag + 10% SF

In the Concrete Characteristic panel, the left graph shows how the diffusivity of the concrete varies over time. The diffusivity of most concrete mixtures will show two basic characteristics: a decline in diffusivity over time, as the concrete hardens, and an annual oscillation caused by the effects of annual changes in temperature. Specifically, the larger the annual variation in temperature of a particular region, the larger the annual variation in diffusivity. The right panel shows the change in chloride concentration on the surface of the concrete structure over time.
Life-365 software
Life-365 software

![Graph showing probability distribution over years for different concrete compositions.](image)

<table>
<thead>
<tr>
<th>Alt name</th>
<th>D28</th>
<th>m</th>
<th>Ct</th>
<th>Init.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control concrete</td>
<td>8.87E-12 m* m/sec</td>
<td>0.2</td>
<td>0.05 % wt. conc.</td>
<td>4.8 yrs</td>
</tr>
<tr>
<td>50% FA</td>
<td>8.87E-12 m* m/sec</td>
<td>0.6</td>
<td>0.05 % wt. conc.</td>
<td>19.9 yrs</td>
</tr>
<tr>
<td>50% Slag</td>
<td>8.87E-12 m* m/sec</td>
<td>0.49</td>
<td>0.05 % wt. conc.</td>
<td>11.4 yrs</td>
</tr>
<tr>
<td>25% FA + 25% Slag</td>
<td>8.87E-12 m* m/sec</td>
<td>0.54</td>
<td>0.05 % wt. conc.</td>
<td>14.7 yrs</td>
</tr>
<tr>
<td>25% Slag + 10% SF</td>
<td>1.70E-12 m* m/sec</td>
<td>0.34</td>
<td>0.05 % wt. conc.</td>
<td>33.1 yrs</td>
</tr>
</tbody>
</table>
# Life-365 software – Results in tabular format

## Concrete Mixes

<table>
<thead>
<tr>
<th>Alt name</th>
<th>User?</th>
<th>w/cm</th>
<th>SCMs</th>
<th>Inhib.</th>
<th>Barrier</th>
<th>Reinf.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control concrete</td>
<td>0.42</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Black Steel</td>
</tr>
<tr>
<td>50% FA</td>
<td>0.42</td>
<td></td>
<td>Class F Fly Ash (50%)</td>
<td></td>
<td></td>
<td>Black Steel</td>
</tr>
<tr>
<td>50% Slag</td>
<td>0.42</td>
<td></td>
<td>Slag (50%)</td>
<td></td>
<td></td>
<td>Black Steel</td>
</tr>
<tr>
<td>25% FA + 25% Slag</td>
<td>0.42</td>
<td></td>
<td>Slag (25%); Class F Fly Ash (25%);</td>
<td></td>
<td></td>
<td>Black Steel</td>
</tr>
<tr>
<td>25% Slag + 10% SF</td>
<td>0.42</td>
<td></td>
<td>Slag (29%); Silica Fume (10%);</td>
<td></td>
<td></td>
<td>Black Steel</td>
</tr>
</tbody>
</table>

*Notes:* *n/a* indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

## Diffusion Properties and Service Lives

<table>
<thead>
<tr>
<th>Alt name</th>
<th>D28</th>
<th>m</th>
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<th>Init.</th>
<th>Prop.</th>
<th>Service life</th>
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</tr>
<tr>
<td>50% FA</td>
<td>8.87E-12 m m/sec</td>
<td>0.6</td>
<td>0.05 % wt. conc.</td>
<td>19.9 yrs</td>
<td>6 yrs</td>
<td>25.9 yrs</td>
</tr>
<tr>
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<td>0.34</td>
<td>0.05 % wt. conc.</td>
<td>33.1 yrs</td>
<td>6 yrs</td>
<td>39.1 yrs</td>
</tr>
</tbody>
</table>

*Notes:* “*” indicates that the user has directly specified this value; “*->*” indicates the service life exceeds the study period.
Sensitivity of corrosion initiation time on input parameters

- Slope ≈ 54°
- Slope ≈ 30°
- Slope ≈ -35°

Pillai and Annapareddy 2013
Nomograph for estimating corrosion initiation time (based on Life-365 software)

Pillai and Annapareddy 2013
Summary

• Significance of corrosion
• Carbonation-induced corrosion
• Chloride-induced corrosion
• Corrosion monitoring in the field
• Ways to enhance and estimate service life
Where there is a will, there is a way!

Thank You

(pillai@iitm.ac.in)

Courtesy: Prof. Devanshu Pandit
A great text book with an emphasis on the durability of concrete.