CRCP - Reinforcement Corrosion Considerations

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Contents

• Introduction
• Reinforcement corrosion fundamentals
  – Common causes of reinforcement corrosion
• Different reinforcing materials
  – Impact on corrosion resistance
• Durability Considerations
  – Design recommendations for prevention
• Take aways
A50/N50: Eindhoven - Emmeloord
A50/N50: Eindhoven - Emmeloord
In Benelux

Kosten voor aanleg en onderhoud van een wegstructuur in doorgaand gewapend beton en een wegstructuur in asphalt – Autosnelweg A15 – E42 tussen Namen en Charleroi

Jaren

Kostprijs in €

Vernharding in doorgaand gewapend beton

Vernharding in asfalt

Bron: Direction Générale des Routes et Autoroutes de la Région wallonne, 2002

Austin, TX • Bradenton, FL • Chicago, IL • Horsham, PA • Naperville, IL • Washington, DC
In Benelux

<table>
<thead>
<tr>
<th>Geen zwaar verkeer (fietspaden, voetpaden)</th>
<th>Beperkt zwaar verkeer (&lt; 250 ZV / d / richting)</th>
<th>Zwaar verkeer (≥ 250 en ≤ 2000 ZV / d / richting)</th>
<th>Zwaar en druk verkeer (&gt; 2000 ZV / d / richting)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 cm</td>
<td>12 cm</td>
<td>23 cm</td>
<td>23 cm</td>
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<tr>
<td>20 cm</td>
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<td>17 cm</td>
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<td>17 cm</td>
<td>17 cm</td>
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</tbody>
</table>

Samendrukbaarheidsmodulus

MI in MPa

Ondergrond

Onderfundering

Steenslag gestabiliseerd met cement

Mager beton

Platen zonder deuvels

Platen met deuvels

Walsbeton

Doorgaand gewapend beton

Bitumineuze laag

Zware vrachtwagens per dag en per richting
CRCP

- Continuous longitudinal reinforcement
- No transverse joints
- Transverse cracks ~ 0.02 in.
- CRCP can extend, joint-free, for many miles
- Service life ~30-40 y

Wikipave.org
Corrosion of reinforcement

• NACE “Corrosion Costs and Preventive Strategies in the United States” 1993
  – Infrastructure: $22.6 billion
  – Highways are predominant

-Source NACE, Corrosion Costs and Preventive Strategies in the US
Motivation

• **NEW** construction:
  – design for long life,
  – plan maintenance,
  – monitor

• **EXISTING** pavements:
  – assess,
  – repair,
  – replace
Motivation

• Rule of 5’s: “$1 spent on durability in the design phase is equivalent to $5 in the execution phase, and to $25 in the service phase” (DeSitter, 1980s)
Every bridge in America

WASHINGTONPOST.COM/WONKBLOG
Source: Federal Highway Administration
America’s most dangerous bridges
Percent of bridges rated “structurally deficient”

Source: Federal Highway Administration

WASHINGTONPOST.COM/WONKBLOG
Degradation mechanisms

- Carbonation
- Acid attack
- Salt attack
- Bio-organic attack
- Alkali – Silica reaction
- Rebar corrosion
- Thermal radiation
Steel corrosion

• Embedded reinforcement = Corrosion

• Steel manufacturing:
  – $\text{Fe}_x\text{O}_y$ (impurities) + Energy $\rightarrow$ Fe (steel)
  – Scrap metals + Energy $\rightarrow$ Fe (steel)

• During exposure (std. temp and atmospheric conditions):
  – Fe + (aggressive substances) $\rightarrow$ $\text{Fe}_x\text{O}_y$ (oxides) + e$^-$
Concrete: electrolyte

- Pourbaix Diagrams (Michel Pourbaix, Atlas of Electrochemical Equilibria in Aqueous Solutions - NACE)
- When embedded in alkaline electrolytes, a passive film is formed on the steel surface
- Passive film: atomically thin layer composed of $\gamma$-Fe$_2$O$_3$
- Reinforcement is protected as long as the passive film is not disturbed
Metals in concrete (ACI 222)

- **Steel**
  - Protected by concrete alkalinity (pH > 13)
  - Formation of passive layer
  - Corrosion is negligible when steel is passive

- **Causes for degradation of the passive layer:**
  - Loss of concrete alkalinity (carbonation)
  - Accumulation of aggressive ions on the steel surface (Chlorides)

Corrosion (anode): \( \text{Fe} \rightarrow \text{Fe}^{2+} + 2e^- \)

Reduction (cathode): \( \text{O}_2 + 2\text{H}_2\text{O} + 4e^- \rightarrow 4\text{OH}^- \)

Andrade et al. 1993
When corrosion begins: Limit state

Based on Tuutti. 1982
Key Parameters

- Key parameters:
- Environmental:
  - CO$_2$ / Cl concentration
  - Temperature
  - RH
- Concrete quality
  - W/CM ratio
  - Concrete porosity
  - Transport properties of concrete
Carbonation

- Reaction with $\text{CO}_2$
- Usually, low concrete cover / highly permeable
- Loss of concrete alkalinity (pH<12)
- Embedded steel corrodes homogeneously
- Most common in urban / industrial environment
Carbonation

Consumption of $\text{Ca(OH)}_2$, leading to drop of pH

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

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

$($OH$)^{-}$ concentration decreases $\rightarrow$ lower pH

If $\text{pH} < 8 - 9$ $\rightarrow$ enhanced probability of corrosion

Rate of carbonation:

\[ d = a \sqrt{t} \]

\[ d = b + a \sqrt{t} \]

Highest carbonation rate at RH = 55 to 65 %

W/c = 0.45:

- 2 mm after 5 y
- 5 mm after 50 y

Austin, TX • Bradenton, FL • Chicago, IL • Horsham, PA • Naperville, IL • Washington, DC
Carbonation

![Graph showing carbonation rate vs. relative humidity and carbonation depth vs. time]

Carbonation

Cracked surface sprayed with phenolphthalein alcoholic solution. This turns the non-carbonated concrete into pink and the carbonation portion into grey to light brown.

Along cracks the carbonation front penetrates deeper into the concrete.
Chloride induced corrosion

- Chloride ingress
  - Marine: seawater
  - Urban: de-icing salts (winter)

- Chloride induced corrosion:

- Cl at steel surface $> C_{\text{crit}}$
  - Transport: diffusion, convection
Chloride induced corrosion

- Simple Cl transport:
  - Time independent
  - Cl concentration driven
  - Diffusion governed
- Transition from $t_1$ to $t_2$
  - $C_{crit}$
- Predicting $t_1$
- Concrete age at test: 28 d
- Test methods:
  - ASTM C1556 – 35 d
  - AASHTO T259 – 90 d
  - NT Build 492 – 0.5 to 4 d
Time-to-corrosion

![Graph showing chloride content vs. depth](image)

- At time $t = 10$ years, $C_s = 5\%$
- Chloride content vs. depth for different diffusion coefficients:
  - $D_{app} = 10^{-11}$ m$^2$/s
  - $D_{app} = 10^{-12}$ m$^2$/s
  - $D_{app} = 10^{-13}$ m$^2$/s
Chloride induced corrosion

- $C_{crit}$:
  - Dependent on type of steel
  - Dependent on concrete composition (SCM)
  - Dependent on thermodynamics

- Steel types:
  - Black rebar (ASTM A615) – $C_{crit}$: 0.4 to 0.6 wt%
  - Epoxy-coated rebar (ASTM A775) – 2x black rebar
  - Galvanized rebar (ASTM A767) – 2-5x black rebar
  - Stainless steel rebar (ASTM A955) – 10x black rebar
Forms of deterioration (microcell)

General Corrosion

Pitting Corrosion

Cao (2014), Con Build Mat
Forms of deterioration (microcell)

General Corrosion

Pitting Corrosion
Forms of deterioration (macrocell)
Forms of deterioration (Galvanic)

- When metals with different equilibrium potentials are embedded in concrete
  - Galvanized and black bar
  - Stainless steel and black bar
- Anode-cathode ratio
Corrosion resistant reinforcing steel

- Epoxy-coated (ASTM A775)
  - Epoxy coating protects steel from aggressive environment
  - Steel is not passivated by concrete
  - Damage to coating is a problem
  - Coating disbondment
  - Coating must be repaired
  - Difficult to monitor
Corrosion resistant reinforcing steel

• Galvanized steel (ASTM A767)
  – Metallic zinc coating
  – Zinc protects steel from corroding (galvanic)
  – Zinc oxides are stable in concrete

<table>
<thead>
<tr>
<th>Classification</th>
<th>Zinc Thickness</th>
<th>Weight [Mass]/Unit Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mils</td>
<td>µm</td>
</tr>
<tr>
<td>Class 1 Bar Designation No. 3 [10]</td>
<td>5.1</td>
<td>129</td>
</tr>
<tr>
<td>Class 1 Bar Designation No. 4 [13] and Larger</td>
<td>5.9</td>
<td>150</td>
</tr>
<tr>
<td>Class 2 Bar Designation No. 3 [10] and Larger</td>
<td>3.4</td>
<td>86</td>
</tr>
</tbody>
</table>

Note: The key value in this table is micrometres (µm) and is based on a zinc density of 7140 kg/m³. The other values are based on conventions using the following formulae: mils = µm × 0.03937; oz/ft² = µm × 0.0232; g/m² = µm × 7.14; and mg/cm² = µm × 0.714.
Corrosion resistant reinforcing steel

- Stainless steel (ASTM A955)
  - Chemical composition determines the corrosion resistance
  - 304, 316/316L
  - Best performance at highest cost
After corrosion initiation: monitoring

Based on Tuutti. 1982
Electrochemical potential
ASTM C876 (uncoated only)
Electrochemistry

- **ASTM C876:**
  - Low probability of corrosion: -0.2V or more positive
  - High probability of corrosion: -0.35 V or more negative
Corrosion rate

No ASTM Standard

<table>
<thead>
<tr>
<th>Corrosion current density mA/m²</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1.0 to 2.0</td>
<td>Negligible</td>
</tr>
<tr>
<td>2.0 to 5.0</td>
<td>Low</td>
</tr>
<tr>
<td>5.0 to 10.0</td>
<td>Moderate</td>
</tr>
<tr>
<td>&gt; 10.0</td>
<td>High</td>
</tr>
</tbody>
</table>

Andrade and Alonso, 2004

Corrosion kinetics

- Steel in alkaline concrete without chloride
- Steel in alkaline concrete with increasing chloride by mass of cement
- Increase in chloride content
- Steel in carbonated concrete
### Repair

<table>
<thead>
<tr>
<th>Present condition of the structure (time = $t_o$)</th>
<th>Condition of the structure expected at time $t_f$</th>
<th>Penetration of corrosion as a function of time (without repair)</th>
<th>Concrete removal</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
<td><img src="image3.png" alt="Diagram" /></td>
<td>Not required</td>
</tr>
</tbody>
</table>

Electrochemical Repair (CP, ECE, RA)

ACI Committee 222 – Corrosion of metals in concrete.

Cathodic protection

Sacrificial anodes

Impressed current

CP current direction

Steel (cathode)

concrete

anode

H₂O

O₂

OH⁻

H₂O

OH⁻

O₂

e⁻
Electrochemical Repair (CP, ECE, RA)

- **ECE**: Electrochemical chloride extraction
- **RA**: Concrete realkalisation

- Cl\(^-\) transported to anode (+)
- Promotion of cathodic reaction: production of OH at the rebar surface = higher alkalinity

Typically: 1 A/m\(^2\) concrete
Voltage 10 to 40 V DC
Duration: 1-2 weeks
Cracks in CRCP

- Transverse cracks are present in CRCP
- Cracks allow faster ingress of CO$_2$ or Cl
- Concrete quality governs the rate of degradation
- Longitudinal cracks should be avoided
Cracks in concrete

- Cracks can reduce the service life significantly if too wide
- The maximum allowable crack width is dependent on the exposure conditions (de-icing salts)
- In some cases, cracks narrower than can be healed (depending on the environment and concrete composition)
Cracks in concrete

- Cracks in tensile zone
- Crack width (surface)
- Secondary cracks
- Large cracks at the surface promote the formation of secondary cracking
- Influence of secondary cracks on concrete-steel interface and corrosion

Table 4.1—Guide to reasonable* crack widths, reinforced concrete under service loads

<table>
<thead>
<tr>
<th>Exposure condition</th>
<th>Crack width</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>in.</td>
</tr>
<tr>
<td>Dry air or protective membrane</td>
<td>0.016</td>
</tr>
<tr>
<td>Humidity, moist air, soil</td>
<td>0.012</td>
</tr>
<tr>
<td>Deicing chemicals</td>
<td>0.007</td>
</tr>
<tr>
<td>Seawater and seawater spray, wetting and drying</td>
<td>0.006</td>
</tr>
<tr>
<td>Water-retaining structures†</td>
<td>0.004</td>
</tr>
</tbody>
</table>

* It should be expected that a portion of the cracks in the structure will exceed these values. With time, a significant portion can exceed these values. These are general guidelines for design to be used in conjunction with sound engineering judgement.

† Excluding nonpressure pipes.
Effect of cracks on corrosion

![Graph showing the relationship between crack width and accumulated pit area or volume. The R² values are 0.94 and 0.97 for area and volume, respectively.]
Conceptual model for cracked concrete

- Sound concrete
- Cracked concrete
- Cracked concrete with secondary cracks

Chloride ingress

Cover depth, x

Steel reinforcement

Graphs showing chloride content vs. depth for different conditions:
- Sound concrete: $w_k / w_{\text{limit}} = 0$
- Cracked concrete: $w_k / w_{\text{limit}} < 1.0$
- Cracked concrete: $w_k / w_{\text{limit}} = 1.0$
Durability & Service Life (ACI 365)

- **Durability** is the ability of a *structure or its components* to maintain serviceability in a given environment *over a specified time*.
- **Service life** is an *estimate* of the *remaining useful life* of a structure based on the current rate of deterioration or distress, assuming continued exposure to given service conditions *without* repairs.
Service life

• **Technical service life** is the time in service until a defined unacceptable state is reached, such as spalling of concrete, safety level below acceptable, or failure of elements.

• **Functional service life** is the time in service until the structure no longer fulfills the functional requirements or becomes obsolete due to change in functional requirements.

• **Economic service life** is the time in service until replacement of the structure (or part of it) is economically more advantageous than keeping it in service.
Requirements

• Buildings, Infrastructure
  – structures, SL →50 ..100 year (Limit state)

• How to obtain 100 y service life?
  Service life design

• How to maintain old structures?
  Remaining service life
  – materials! composition, production, protection, repair, restoration
  – understand degradation mechanisms..
Corrosion prevention strategies

**Owner**
- Establish durability requirements for the pavement
- Performance specification specific to each project
- Discuss with consultant on material selection
- Establish criteria for corrective action

**Contractor**
- Understand durability requirements for employed materials
- Qualify concrete mixtures beyond compressive and tensile strength
- Take extra precautions with handling of special reinforcing steel types
Take aways

• Rule of 5’s
• Preventing corrosion in CRCP is achievable
• Maintaining corroding CRCP is possible
• Smart design → easier, faster, cheaper
• Structural & Materials blend (economics too)
• Monitoring is key
• Repair as an alternative to extend SL
• SL of every structure can be extended (cost!)
53rd Annual ACPA Meeting 2016

CRCP - Reinforcement Corrosion Considerations

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