Corrosion Mitigation Systems for Concrete Structures

Vector Corrosion Technologies
Outline

- Concrete Corrosion
- Corrosion Evaluation
- Impressed Current Cathodic Protection
- Galvanic Protection
- Electrochemical Treatments
Concrete in Society

- Concrete is the most widely used man-made product in the world
- 6 Billion tons per year (3 - 4 Billion yd$^3$)
- Production of 1 ton of cement produces approx 1 ton of CO$_2$
  - (CO$_2$ Production ~ 1 Billion tons / yr)
- Production of 1 ton of steel produces ~ 2 tons of CO$_2$
  - (CO$_2$ Production ~ 200 Million tons / yr)
Responsible Use of Concrete

- Despite the environmental impact, concrete is one of the most environmentally friendly materials available if it is used properly.
- Concrete is extremely durable and has the ability to last for many years.
  - Design of long lasting structures
  - Repair/rehabilitate to maintain in service
Corrosion in Reinforced Concrete

- Corrosion is the single most important problem in concrete structures
- NACE estimates the cost of corrosion (in the USA) to be approximately 400 Billion!!!
- It’s estimated that 25-30% of this cost is attributed to corrosion of concrete structures
Corrosion Cell in Concrete

Fe → Fe^{2+} + 2e^{-}

Fe^{2+} + 2Cl^{-} → FeCl_{2}

FeCl_{2} + 2OH^{-} → Fe(OH)_{2} + 2Cl^{-}

2Fe(OH)_{2} + \frac{1}{2}O_{2} → Fe_{2}O_{3} + 2H_{2}O

\frac{1}{2}O_{2} + H_{2}O + 2e^{-} → 2OH^{-}

Fe\gamma_{3}O_{4} → Fe_{\gamma_{3}}O_{3}

Cathode

Anode
Corrosion Ravaged Columns
Chicago, Illinois
Patch Accelerated Corrosion

Potential Difference Between Patch and Chloride Contaminated Concrete Results in Accelerated Corrosion
New Corrosion Sites

Underside of Parking Deck

Bridge Deck
Corrosion Services

- Evaluation and Testing
- Monitoring
- Technical Site Services
- CP System Design
- System Installation
Visual Inspection

- Identify areas of visual damage
  - Rust stains on surface
  - Cracks
  - Spalls
  - Exposed steel

- Note exposure conditions and other observations
Delamination Survey

- Performed as per ASTM D4580
- Locate areas where concrete has lost bond with rebar and delaminated concrete which has not yet spalled
- Also known as “Sounding”
  - Hammer test
  - Chain drag
Chloride Sampling and Analysis

• To determine chloride content at various levels within the concrete

• Chloride content can be performed on concrete cores or dust samples
Chloride Thresholds

- 0.2% by weight of cement (ACI)
- 0.031% by weight of concrete
- 1.2 lb Cl⁻/yd³ of concrete (0.71 kg/m³)
- These code guidelines are rather simplistic
- Different concrete conditions have different thresholds: wet or dry concrete, prestressed, etc.
- In reality corrosion activity is progressive and based on the Chloride / Hydroxyl Ratio (Cl⁻/OH⁻)

### Chloride Limit for New Construction (ACI 222R)

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Prestressed</td>
<td>0.08</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Reinforced Wet</td>
<td>0.10</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Reinforced Dry</td>
<td>0.20</td>
<td>0.15</td>
<td>0.15% by weight Cement</td>
</tr>
</tbody>
</table>

Section 1

Section 2
pH Testing

- Mainly to determine amount of carbonation
  - Can also be used to determine some types of chemical contamination
- 1% phenolphthalein in alcohol or 50/50 mixture of distilled water and alcohol
- Generally perceived to indicate pH of > 9.5
- “Rainbow” types also available
Depth of Cover Survey

- To determine the average depth of concrete covering the rebar within the structure
- Compare depth of rebar with results of chloride and carbonation testing
- Performed using Micro Covermeter
Rebar Continuity

- Verify electrical continuity of the steel
  - Discontinuous steel may pose problems for cathodic protection

- Typical Criteria
  - Less than 1 mV or
  - Less than 1 ohm resistance
Corrosion Potential

- To determine the probability of corrosion by measuring the potential (voltage) of the reinforcing steel
- Uses a reference electrode:
  - copper-copper sulfate
  - silver-silver chloride
- Performed as per ASTM C876-91
Beam Corrosion Potential

Distance from South End, ft

Potential, mV CSF

Feb-05
Apr-05

Probability
Low
50-50
High

Spaces 22 through 36
Damaged Post-Tension Cables
PT Corrosion Evaluation
## PT Corrosion Evaluation

<table>
<thead>
<tr>
<th>Classification</th>
<th>Potential for Corrosion</th>
<th>Moisture Content (kg/kg)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Very Low (Very Dry)</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>2 Dry</td>
<td>Low (Dry)</td>
<td>0.001 &lt; 0.003</td>
</tr>
<tr>
<td>3</td>
<td>Moderate (Dry/Wet)</td>
<td>0.003 &lt; 0.007</td>
</tr>
<tr>
<td>4 Wet</td>
<td>High (Wet)</td>
<td>0.007 &lt; 0.010</td>
</tr>
<tr>
<td>5</td>
<td>Very High (Very Wet)</td>
<td>&gt; 0.010</td>
</tr>
</tbody>
</table>
Post Tech Cable Break Detection
Impulse Magnetization with Scanner
Bridge Deck Scan
Key Issues Re Corrosion

• Remove concrete from full circumference of all reinforcing steel.
• Remove corrosion by-products from steel
• Expand area of patch outside area of active corrosion (clean steel).
Electrochemical Corrosion Mitigation Systems

- **Impressed Current Systems**
  - Permanent D.C. power supply forces current flow from anode to reinforcement (cathode)

- **Galvanic Systems**
  - Sacrificial metal corrodes to provide protective current

- **Electrochemical Treatments**
  - Temporary D.C. power supply and anodes
  - Passivate corrosion by changing the environment around the reinforcement
  - Electrochemical Chloride Extraction or Re-alkalization
Impressed Current Cathodic Protection

**Distributed Anodes**

- Concrete Overlay
- Concrete
- Rebar
- Embedded Anode

**Point Anodes**

- Concrete Overlay
- Concrete
- Rebar
- Permanent DC Power Supply
- Slot Cut for Wiring Anodes

**Discrete Anodes**

- Drilled Holes

**Permanent DC Power Supply**
Impressed Current CP

- Outside power source required
- High level of control
- System monitoring and maintenance required
Bok Tower
Lake Wales, FL

- Historic Bell Tower
- Dedicated in 1929 – by President Calvin Coolidge
- Masonry encased steel frame
- Marble and coquina exterior
Bok Tower

- Moisture intrusion caused corrosion of steel beams
- Corrosion damage of exterior stone
- ICCP with discrete anodes installed to protect steel frame
Bok Tower

- Discrete anodes placed in ½ in. diameter holes
- 32 in. spacing above and below beams
- Installed from the interior through brick masonry
Bok Tower

- Remote monitoring and control of power
- Minimal disruption
- Minimal impact on appearance
Galvanic Protection Systems

- Two different metals are connected in same electrolyte (concrete)
- More “active” metal = anode
- More “noble” metal = cathode
- Anode corrodes to protect cathode
- Natural reaction
  - no external power required
- Safe for prestressed concrete
Potentials and Current Flow

Partial Galvanic Series

<table>
<thead>
<tr>
<th>Metal</th>
<th>Voltage</th>
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<tbody>
<tr>
<td>Zinc</td>
<td>-1100 mV</td>
</tr>
<tr>
<td>Steel in concrete</td>
<td>-200 mV to -500 mV</td>
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</tbody>
</table>

*Typical potentials measured with respect to copper-copper sulfate electrode
Types of Galvanic Systems

- Embedded Discrete Anodes
- Embedded Distributed Anodes
- Externally Applied Anodes
  - Zinc Sheets
  - Zinc Metalizing
Point Anodes
Point Anodes Protection
(Typically for Halo Effect)

Concrete Repair

Point Anodes

Area of Influence

Existing Chloride Contaminated Concrete
Activation Technology

**Alkali Activated**

- High pH is corrosive to zinc but not to steel
- Allows zinc anodes to provide protection to reinforced concrete over time
Installed Galvanic Anode

Anode Galvanically Protects Surrounding Rebar
Discrete Galvanic Anodes

Installing anodes around the perimeter of the repair.
Discrete Galvanic Anodes

Bridge Deck - Chip and Patch Repairs.
Colorado DOT – Greeley, CO
NYSDOT Maintenance
Bridge Deck Repair
Post Tension Anchor Repairs
Watergate Complex, Washington, D.C.
Slab Replacement
Brookline Blvd. Garage
Pittsburgh Parking Authority
Bridge Widening Corrosion Prevention
Point Anodes for Sound Concrete

- Embedded anode for corrosion control
- Installed into drilled holes
- Protect sound but contaminated areas
- Corrosion “hot spots”
Galvanic Protection with FRP Strengthening, Coastal Condominium
NYSDOT Bridge Maintenance
Fort Covington, NY
Distributed Anodes

Concrete Repair

Distributed Anodes

Base Concrete

Area of Influence
Distributed Anode System
Abutment Repair Detail With Galvanic Protection

- Replace Joint Seal
- Approach Slab
- Existing Bridge Deck
- ± 6-in SCC Facing
- Galvanic Strip Anodes
- #5 @ 18” OC EW ECR
- #5 ECR Dowels
Past Practice for Repairs

• Slab would be temporarily supported

• Abutments would be replaced

• Requires closure or part-width construction
Options

- **Do Nothing**
  - Not a feasible alternative for deficient bridges on the interstate system

- **Repair bridge**
  - With appropriate repair, most of these bridges have remaining service life

- **Replace bridge**
  - Not cost-effective to remove a good slab
I-75 Ohio DOT
Forms installed
Completed repair
Kirkwood Road – Protective Current

Galvanic Current

Temperature, degree F

Date

May-05 Aug-05 Oct-05 Jan-06 Apr-06 Jul-06 Oct-06 Jan-07 Apr-07 Jul-07 Oct-07 Jan-08

Galvanic Current, mA

Temperature
Kirkwood Road Performance

<table>
<thead>
<tr>
<th>Date</th>
<th>Temp</th>
<th>mA/m²</th>
<th>Polarization</th>
<th>Instant Off</th>
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<tbody>
<tr>
<td>5/6/05</td>
<td>37.7</td>
<td></td>
<td></td>
<td>654*</td>
</tr>
<tr>
<td>7/20/05</td>
<td>13.9</td>
<td>346</td>
<td></td>
<td>1000</td>
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<tr>
<td>8/16/05</td>
<td>87</td>
<td>12.9</td>
<td>333</td>
<td>987</td>
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<tr>
<td>10/26/05</td>
<td>54</td>
<td>5.4</td>
<td>394</td>
<td>1048</td>
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<td>12/7/05</td>
<td>51</td>
<td>3.2</td>
<td>339</td>
<td>993</td>
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<td>5/1/06</td>
<td>57</td>
<td>7.5</td>
<td>335</td>
<td>989</td>
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<td>12/20/06</td>
<td>40</td>
<td>4.3</td>
<td>500</td>
<td>1154</td>
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<td>5/30/07</td>
<td>79</td>
<td>7.5</td>
<td>446</td>
<td>1100</td>
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<tr>
<td>9/20/07</td>
<td>75</td>
<td>9.7</td>
<td>484</td>
<td>1138</td>
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</table>

* Native Potential

Cathodic Protection Criteria: Polarization > 100 mV or Inst. Off > 850 mV
Galvanic Strips In 8
Bridge Deck Overlays
Lake County, OH
Surface Mounted Zinc Anode

- High purity zinc foil
- Conductive adhesive
- Supplied in rolls
- Applied to concrete surface and connected to reinforcing steel
Surface Applied Zinc Sheet Application
ZincSheet Column Protection
Galvanode Zinc Tape

NY DOT

I-890 E over Little Circle
Prestressed Concrete Balcony Protection
Clearwater Beach, FL
Activated Arc Spray Zinc
Hospital Parking Garage
Galvanode ASZ+
Activated Arc Spray Zinc
Pile Protection Systems

- Impressed Current
  - Titanium Mesh with FRP
- Galvanic Protection
  - Zinc Mesh with FRP
  - Distributed Anode Strips

Used in conjunction with RC overbuilds, FRP jackets, or nylon bags.
ICCP Jackets
Galvanic Jackets
Electrochemical Treatments
Electrochemical Treatments

- Address the cause of the problem
- Passivates active corrosion
- Temporary treatment process
- No system left in place to maintain
Electrochemical Chloride Extraction (ECE) From Salt Contaminated Concrete
ECE Treatment Process
ECE Treatment Process
ECE Treatment Process
ECE Treatment Process
ECE Treatment Process
ECE Treatment Process
Norcure Chloride Extraction System
Historic Bridge (1933)

- Idaho’s Largest single span (210’) conc. arch bridge
- Cost $74,000 to build
- Corrosion Evaluation in 2004
  - Concrete Arches & Main Piers (below drains) had most severe corrosion
  - Corrosion Potential between -.1 to -.45 V
  - Chlorides between .2 to 5.3 lbs/cy
  - Recommended ECE for Arches & Piers
MAIN OBJECTIVES

• Preserve & Protect historic structure for future generations

• Improve Safety for traveling motorists
Potential Mapping Grid
Electrochemical Chloride Extraction

• Began July 20, 2006
• Completed September 14, 2006
• Treated Approximately 8,000 sf
• Temporary process, so no system left in place
• Addressed the source of the problem by reducing chlorides & increasing pH around rebar
• Minimal Aesthetic Impact
• Allowed structure to be rehabilitated rather then replaced.
• Also placed discrete XP+ anodes in patches
Electrical Cathodic Connections to Steel Reinforcing
Project of the Year

REPAIR AND PRESERVATION OF THE HISTORIC RAINBOW BRIDGE
Valley County, Idaho

Vector Corrosion Technologies
Wesley Chapel, Florida
Electrochemical Chloride Extraction (ECE) From Salt Contaminated Concrete
Re-alkalization of Carbonated Concrete

Anode Electrolyte Reinforcement

Na\textsubscript{2}CO\textsubscript{3} \& NaHCO\textsubscript{3}

Concrete

Reinforcement
Norcure® Re-alkalization & ECE

Reagan National Airport Facade
Washington, DC
Summary

• Large Range of Options Available for Marine Structures
• Mitigation strategies can be
  – Global, targeted, or localized in nature
• Final system selection
  – Existing condition, exposure conditions, service life requirements, maintenance considerations, budget
Thank you!