Protecting Concrete Structures Against Corrosion Damage

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Can we balance performance vs cost?

We can stop corrosion, but can we afford it?
What causes corrosion?

- Deicing salts
- Marine Salts
- Carbonation
How does reinforcing steel corrode in concrete?

- Chloride
- Carbonation
- pH >13
What are the common protection methods?

• Slow chloride penetration
  – concrete modification

• Stop chloride from entering the concrete
  – Surface treatment

• Increase chloride threshold and/or reduce corrosion rates
  – Corrosion inhibitors and bar types
Methods to slow penetration

• w/cm (<0.40)
• Pozzolans
  – silica fume (< 5%)
  – fly ash (< 30%)
  – slag cement (< 50%)
• Internal water-proofing
  – admixtures
Effect of w/c on diffusion coefficient

Lower w/c leads to lower diffusion rates

Sherman, McDonald, Pfeifer, PCI 1996
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Common surface treatment methods

• Overlays
  – Iowa low slump, latex modified, silica fume
• Elastomeric membranes
• Penetrating sealers and crack repair
Overlays offer the opportunity to “start again”
Surface sealer

- NCHRP 244
  - alkyl alkoxy silane
- Typical results
  - Water Weight Gain
    - 88% reduction
  - Absorbed Chloride
    - 82% reduction
What are corrosion inhibitors?

• Added to concrete to improves chloride threshold

• Materials
  – calcium nitrite *
  – amine carboxylate
  – amine-ester
  – alkenyl carboxylate

• Typical dosage 2 to 4 gal/yd³

Less effective in cracks
Effectiveness of calcium nitrite

![Graph showing the effectiveness of calcium nitrite on total corrosion. The graph plots total corrosion (months * microohm/cm/cm) against months in NaCl. There are three conditions: Control, 3% NaCl, and reinforcing steel in a concrete lollipop. The graph indicates that calcium nitrite significantly reduces corrosion compared to the control. Berke 1987 is referenced for the data.](image)
Available bar materials

• Epoxy-coated
  – ASTM A775, A934
• Galvanized
  – ASTM A767
• Stainless Steel
  – ASTM A955
• Others
  – A1035 – Low carbon, chrome
  – A1055 – Dual Clad
  – Glass Fiber
Epoxy-coated Reinforcing Steel

• A775: Green
  – Bent after coating
  – Most widely used and researched material
  – Significant material improvements over 37 years
  – Over 70,000 bridges
    • ~ 2500 per year

• A934: Purple or Grey
  – Bent before coating
Galvanized Reinforcing

• ASTM A767
  – Bent before or after coating
• Develop oxide layer for protection
  – Dependant on cement and zinc chemistry
  – Microstructure may significantly affect performance
• Only 1050 bridges
  – ~ 40 per year
Stainless Steel Reinforcing

- ASTM A955
- Chemistry/microstructure
- Care when fabricating
- ?? bridges

http://tiny.cc/xrv4j
Other Materials

• Single source or proprietary
  – ASTM A1035/3CR12
    • Low chromium
    • Low grade stainless steels
  – ASTM A1055
    • Epoxy and zinc layers
  – Glass and Basalt fiber bars
Lee 2011

- FHWA Turner Fairbanks labs
- 12 different bar types
- Damage to epoxy, zinc layers
- 15% NaCl solution wetting and drying
- 2 years of testing
Lee 2011 (FHWA)
Corrosion Resistant Bars

• Excellent:
  – A775 Epoxy
  – A1055 Dual Clad
  – Stainless Clad
  – Stainless 2304
  – Stainless S24100 (?)
  • Enduramet 32

• Good:
  – A767 Galvanized

• Fair:
  – A1035 (MMFX 2)
  – S2201
  – 3CR12
  – Stainless S24100 (?)

• Poor:
  – Stainless S41003
  • Dual Phase 12% Cr
  – A615 Black

“...epoxy-coated bar placed in both mats yielded excellent corrosion resistance similar to stainless steel bars.”
2011 Kansas University Study

- Long-term testing for FHWA and KDOT
- Corrosion thresholds
  - Black reinforcing: 1.6 (lb/yd\(^3\))
  - Corrosion inhibitors: 0.8 – 3.0
  - Galvanized: 2.6
  - Epoxy-coated reinforcing: 7.3
  - Stainless 2205 reinforcing: 26.4

O’Reilly et al. 1987
Propagation Period

- Cracked Concrete
  - Black bars: 14 years
  - Corrosion inhibitor: 33
  - Epoxy-coated bars: 50
  - ECR + Corrosion inhibitors: 63
  - Stainless steel: > 100

O’Reilly et al. 1987
Life Cycle Cost

ECR provides lowest life cycle cost

\[
\text{Uncoated: } \$444/\text{yd}^2 \\
\text{Epoxy: } \$237 \\
\text{Stainless: } \$319 \\
\text{Inhibitor + Black: } \$308 - \$432 \\
\text{Inhibitor + Epoxy: } \$224 - \$242
\]

O’Reilly et al. 1987
New York State Department of Transportation 2009

- Statistical analysis of 17,000 structures
- Structural decks with epoxy-coated reinforcement perform significantly better than those with uncoated reinforcement, especially in the later years.
West Virginia 2009
West Virginia 2009

Black - Delaminated concrete after 17 years

Epoxy - No delaminations after 34 years

Deck with epoxy bars performing significantly better than black bar sections
PA deck condition 2010
1973 - 1983

Repairs likely
PA deck condition 2010
1973 - 1983

Epoxy – 3x less likely to exhibit low deck ratings compared with black or galvanized.
Stainless in Marine

• Magnetic Silencing Facility, Point Loma

• Losses of stainless steel cross-section exceeded 50 percent

• The reinforcement is inadequate for its environment
  – despite being of stainless steel composition, which has generally been considered superior in marine concrete
OTHER FACTORS
Can we build sustainably?

• Pozzolans
  – reduce carbon footprint
  – post-industrial waste

• Recycled Content
  – Epoxy-coated and galvanizied bars >95%
  – Stainless Steel >75%

• Processing Energy
  – Stainless steel >> epoxy-coated or galvanized bars
Are these materials available?

• Galvanizing
  – Experience
  – Bar lengths (40 ft)
  – Chromate treatment

• Epoxy-coated
  – Bar lengths (60 ft)
  – Widely available

• Stainless steel reinforcing
  – Limited manufacturers
  – Substantial lead times

• Pozzolans
  – East of Mississippi

• Other Products
  – Proprietary
  – Lead times
  – Bent bars
SUMMARY AND CONCLUSIONS
Summary

• Wide choice of materials
  – Combinations are better than individual choices

• Overall performance is not the only criteria
  – Sustainability
  – Initial and life-cycle cost
  – Availability

http://www.deldot.gov
Recommendations

• Concrete Permeability
  – Low water-cement ratio
  – Pozzolans
  – Treat Cracks

• Surface Ingress
  – Overlays
    • permit renewal
  – Silane sealers

• Bar selection
  – Epoxy-coated bars
    • High performance
    • Low initial and life cycle costs
    • Sustainable
  – Stainless
    • Cost
    • Chemistry
    • Availability