Cost-Effective Methods for Improving the Corrosion Resistance of Concrete

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Constraints

• Available resources
  – Don’t have unlimited funds
  – Don’t wish to continually repair
Chloride

- Deicing salts
- Marine waters

- Mechanism
  - iron chloro-complex (green rust)
  - expansion

Not well understood!

Courtesy W.R. Meadows
Carbonation

$\text{CO}_2$ reacts with cement

Carbonated concrete
Reinforcing Steel in Concrete

Chloride

carbonation

pH >13
CONCRETE MODIFICATION
Concrete Modification

- Reduce permeability
- w/cm (<0.40)
- Pozzolans
  - silica fume (< 5%)
  - fly ash (< 30%)
  - slag cement (< 50%)

New materials, such as polycarboxylate help improve concrete
Corrosion Inhibitors

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

- **Improves chloride threshold**
  - Dependent on the dosage

- **212.3R-10: Report on Chemical Admixtures for Concrete**
BAR MATERIALS
Types

- 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
- A934: Purple or Grey
- Most widely used and researched material
- Significant material improvements over 37 years
- **Over 70,000 bridges**
  - ~ 2500 per year
Galvanized Reinforcing

- ASTM A767
- 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
  – Excellent: 316, 2205, 2304
  – Fair: 2201, 3Cr12
• “Stainless steel isn’t”
  – Roper 1986
• ?? bridges
Other Materials

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

- Initiation Period
- Propagation Period
- Corrosion Starts
- Damage

Time

Damage
Laboratory Tests

- Voltmeter
- 10 Ohm
- 15% NaCl solution
- 19 mm (3/4 in.)
- Crack
- 178 mm (7.0 in.)
- 152 mm (6.0 in.)

Cracked Beam (CB) Specimen
Corrosion Thresholds

- Kansas University Study for KDOT and FHWA

- 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
Propagation Period

- Cracked Concrete
- Black bars: 14 years
- Corrosion inhibitor: 33
- Epoxy-coated bars: 50
- ECR + Corrosion inhibitors: 63
- Stainless steel: > 100
PERFORMANCE
West Virginia 2009

Deck with both epoxy and black bar sections
West Virginia 2009

Black - Delaminated concrete after 17 years

Epoxy - No delaminations after 34 years

Deck with both epoxy and black bar sections
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.
PA deck condition 2010
1973 - 1983

Repairs likely

Percent of Ratings vs. NBI Grade
PA deck condition 2010
1973 - 1983

Epoxy – 3x less likely to exhibit low deck ratings
Florida Bridges with ECR

After Sagues et al.

5 structures
Poor bars
Poor concrete

290 structures
Good bars
Good concrete

Percent Damage

Age (years)

0 2 4 6 8 10

0 20 40 60 80 100

After Sagues et al.
Stainless in Marine (1)

- Progreso Pier (1940)
- Generally good performance

- “serious laminated corrosion on the visible reinforcement and the reinforcement area was reduced to approximately 60 – 70%.”
Stainless in Marine (2)

- 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

http://farm3.static.flickr.com/2718/4389549311_eb08812cb4.jpg
COST EFFECTIVENESS
Life-Cycle Cost Analysis (LCCA)

• Calculate net present value
  – Determine initial and repair costs
  – Timing of repairs
  – Discount rate
    • No consensus as to the appropriate value
    • 3 to 5 percent are commonly recommended
Is stainless in the budget?
Life Cycle Cost

ECR provides lowest life cycle cost

$/yd^2

- Uncoated: $444
- Epoxy: $237, $207
- Stainless: $319
- Inhibitor + Black: $308 - $432
- Inhibitor + epoxy: $224 - $242
OTHER FACTORS
Sustainability

• Pozzolans
  – reduce carbon footprint
  – post-industrial waste

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

• Processing Energy
  – Stainless steel > epoxy-coated or galvanized bars
Availability

• Pozzolans
  – East of Mississippi

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

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

• Stainless steel reinforcing
  – limited manufacturers
  – substantial lead times
  – Identification/theft

• Other Products
  – Proprietary
  – Lead times
  – Bent bars
CONCLUSIONS
Summary And Conclusions

• Wide choice in the selection of materials for corrosion protection
• Low water-cement ratio
• Pozzolans
  – Cracks should be repaired
• Epoxy-coated bars
  – Proven protection over 40 years
• Stainless
  – Cost, performance

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

http://www.deldot.gov