DO EPOXY-COATED BARS PROVIDE COST-EFFECTIVE CORROSION PROTECTION?

FHWA Highways for Life
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INTRODUCTION
Epoxy Bar Use

- Introduced in 1973
- 2nd most common strategy to prevent reinforcement corrosion
  - After increased cover
- USA, Canada, Middle East, Japan, and India

- 700,000,000 ft$^2$ of decks
  - 65,000 bridges in the US alone
  - ~600,000 ton/yr
  - 10 - 15% of all rebar
Woodrow Wilson Bridge, Virginia/Maryland

I-35 Minneapolis, Minnesota

Bridge of Honor, Ohio

Biloxi Bay Bridge, Mississippi
FIELD PERFORMANCE
Research and Performance

• Over 200 research papers
Poor concrete and poor bars

• 1986, spalls observed in Florida
  – Typically 1 x 1 ft spalls in tidal zone
• Poor concrete and poor bars
  – Bars left beside ocean
  – Highly salt contaminated concrete
  – Only 25 mm (1 in.) of cover.
  – Poor quality concrete
Minnesota Department of Transportation 2008

- Four bridges
  - 1973 to 1978
- Overall condition
  - good to very good, with no or modest levels of corrosion activity.
- Corrosion constrained joints over piers
- Amount of delamination in all decks is very low
New York State Department of Transportation 2009

• Used extensive statistical analysis of all state bridge inspection data

• Pool of 17,000 structures

  –“structural decks with epoxy-coated rebars perform significantly better than those with uncoated rebars, especially in the later years.”
2009 West Virginia Study
Lawler and Krauss

• Detailed study of six bridges built 1974 – 1976
  – Deck area: 62,000 sq ft

• After 34 -36 years
  – Total delamination: 22.7 sq ft
  – Chloride levels above threshold

• Black Bar performance
  – Repaired in 1993 with overlays
Bridge 2930, West Virginia

- Epoxy-coated bars
- Black Bars
Effect of coating thickness

![Graph showing the effect of coating thickness on various percentages. The x-axis represents thickness (mil) ranging from 2 to 18, and the y-axis represents percentage ranging from 0% to 100%. The graph includes markers at 0%, 20%, 40%, 60%, and 100%. A blue circle highlights a specific section of the graph.](image-url)
DESIGN LIFE PREDICTION
Life modeling

• Environment
• Materials
• Repair
• Design
Tuuti Model

Initiation Period

Cumulative damage

Time

Crack development

Spalling

Allowable damage before repair
INITIATION PERIOD
Tuutti Model

Cumulative damage

Initiation Period

Time
Fick’s Model

- 2\textsuperscript{nd} law of diffusion
  \[ \frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} \]

- \( C = \) concentration, \( D = \) diffusion coefficient, \( t = \) time, \( x = \) distance

\[
C(x, t) = C_s - \left[ (C_s - C_0) \cdot \text{erf} \left( \frac{x}{2\sqrt{Dt}} \right) \right]
\]
## Chloride exposure

<table>
<thead>
<tr>
<th>State</th>
<th>tons/lane mile</th>
<th>times /year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td>Illinois</td>
<td>15</td>
<td>2.4</td>
</tr>
<tr>
<td>New Jersey</td>
<td>6.5</td>
<td>2.75</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>6.25</td>
<td>0.75</td>
</tr>
<tr>
<td>Utah</td>
<td>9</td>
<td>0.1</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>30</td>
<td>8</td>
</tr>
</tbody>
</table>
Concrete permeability

- Pore structure
  - chemistry of the cement and additives
  - water-cement ratio
  - types and quantities of aggregates.

- For w/c of 0.42
  - Lawler and Krauss ~ 0.15 in$^2$/yr,
  - Life-365 ~ 0.43 in$^2$/yr [16].
Effect of cracks

- Most models do not consider the effect of cracks
Corrosion threshold

- Typical 1.2 lb/yd$^3$
- Azad 1.0 to 2.1 lb/yd$^3$ chloride ion by weight of concrete.
# Effect of variability

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumption 1</th>
<th>Assumption 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover (in.)</td>
<td>2.8</td>
<td>3.2</td>
</tr>
<tr>
<td>Permeability (in.in/year)</td>
<td>0.15</td>
<td>0.075</td>
</tr>
<tr>
<td>Surface chloride (lb/cu yd)</td>
<td>10</td>
<td>7.5</td>
</tr>
<tr>
<td>Assumed threshold (lb/cu yd)</td>
<td>1.2</td>
<td>1.5</td>
</tr>
<tr>
<td>Calculated time to corrosion initiation (years)</td>
<td>11</td>
<td>42</td>
</tr>
</tbody>
</table>
Propagation period

- Dependant on:
  - temperature
  - oxygen availability
  - cathode areas
  - concrete resistivity

- Black bars
  - standard 5-year

- Epoxy-coated bars
  - Standard 20 years
  - significantly influenced by the availability of cathodic areas
  - very conservative
Tuuti Model

- Initiation Period
- Crack development
- Spalling
- Allowable damage before repair

Cumulative damage vs. Time
Repair timing

- Amount of deterioration
- Funding and labor
- Condition of the superstructure
- Volume of traffic
- Rate of physical deterioration

- 18 structures in Kansas
  - damage 1.0 to 29.8 percent of the deck surface
Durability of Repairs

- Need to develop durability databases
  - Significantly influence models
    - 10 year period for patch repairs
    - 20 years for an overlay
Tuuti Model
LIFE CYCLE ANALYSIS
LIFE CYCLE COST ANALYSES

• Not a straightforward procedure.
  – economic principles
  – bridge repair techniques, costs, and effectiveness
  – good costing database
  – most likely alternatives
  – good knowledge of how a bridge behaves over the long term.

• Poor decisions can result if the user applies the wrong assumptions.
Cost of repair

• Significant portion of the total cost comes from incidental costs
  – mobilization
  – traffic control
  – repairs and improvements to other parts of the bridge

• Kansas
  – Averaged $12/sf
    • minimum of $3/sf
    • maximum of $26/sf
Discount Rate

- Office of Management and Budget (OMB)
  - 2010: 2.8% for a 30 year program
  - 1982: 7.9%

- Low discount rates favor materials with high durability requiring little or no maintenance

- Present value of a $100 repair in 60 years, the present values will be $19 or $1, respectively
Which one to choose?

Range of Costs

- **316 SS**
  - $25,25,15,25$
  - $10,25$
- **304 SS**
  - $15,20$
  - $7.5,20$
- **SCR**
  - $25,25,15,25$
  - $10,25$
- **MMFX-II**
  - $25,25,15,25$
  - $6,9,4.5,9,3,9$
- **ECR**
  - $12,15,9,15,6,15$
  - $3,15$
- **Black w/HPC**
  - $1.5,5,1.5,5,1.5,5$
  - $3,15$
- **Black**
  - $1.5,5,1.5,5,1.5,5$

Service Life Inputs shown:
- $C_T$ in lbs./yd.$^3$, $t_p$ in yrs.

Discount rate=2.7%, Overlay life=15 yrs

Annualized Life Cycle Cost ($)
INITIAL COSTS
CONCLUSIONS
Selection Factors

• Experience
  – 700,000 bridges already in existence in North America.

• Initial cost.
  – Corrosion can go away – at a premium
  – Epoxy-coated bars have already provided 40 year design life in 1970s concrete for minimal cost
Dealing with uncertainty

• *Everything is vague to a degree you do not realize till you have tried to make it precise*

• Any product can be made cost effective, dependent on the assumptions.
  – Black reinforcing bars become cost effective if the discount rate is high.
Conclusions

• Designers and specifiers should consider the experience gained from 65,000 structures containing epoxy-coated bars over the past 37 years.

• Epoxy-coated bars have already demonstrated almost a 40-year design life in 1970s concrete.

• Epoxy-coated bars provide cost-effective corrosion protection.