Corrosion Resistant Rebar

97th AASHTO Subcommittee on Materials
Burlington, Vermont
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Acknowledgements


• VCTIR, VT, UVa, FHWA, VDOT Structure & Bridge Division, and VDOT Materials Division
INTRODUCTION: From ECR to CRR

- Complete section loss inside an epoxy coating was first observed in Florida in bridge substructures in 1988 (1). Research concluded that the rate of corrosion of epoxy coated reinforcement (ECR) is greater than for black bar in concrete 2 to 8 ft above sea level in marine environments (1).
INTRODUCTION: Field Observations

Epoxy Looses Adhesion with Age, VTRC Report 06-R29 (2)

parapet repair @ 19 years
INTRODUCTION: I-81 Closure Pour Failure

- ECR across a leaking construction joint corroded and failed in 17 years on I-81.
- Rebar section loss varied from none to 100%.
INTRODUCTION: Route 123 Bridge Deck

- ECR does not perform well in leaking construction joints and cracks that are typically found in high performance concrete decks.
INTRODUCTION: Route 123 Bridge Deck continued
INTRODUCTION: Route 123 Bridge Deck continued

Deck Constructed with MMFX2

- Total Chloride at Bar Depth
  - Uncracked Location
    ▪ 0.380 lb/yd³
  - Cracked Location
    ▪ 2.404 lb/yd³

*High quality concrete only helps in-between the cracks.*
INTRODUCTION Continued

• To achieve longer lasting bridges major efforts have been devoted to improving the quality of concrete but little attention has been devoted to using longer lasting reinforcement.

• High performance concrete used today can provide a bridge service life of more than 75 years as currently recommended by FHWA.

• However, ECR cannot provide adequate corrosion protection for structures designed for a 75-year+ service life because the ECR coating deteriorates with time in the moist environment of a bridge deck.
INTRODUCTION Continued

• VDOT Bridge-deck reinforcing steel type is changing
  *Coated* ➔ *Alloyed*

• Higher performance concrete needs higher performance steel rebar

• Methodology for accepting CRR is important
  – testing for alloying
  – mechanical properties
  – corrosion resistance
March 2010 Instructional and Informational Memorandum

• GENERAL SUBJECT: Corrosion Resistant Reinforcing Steels (CRR)
• NUMBER: IIM-S&B-81.4
• SPECIFIC SUBJECT: Plan Modifications for Projects with CRR
• Divides CRR into 3 Classes
  – Solid Stainless Steel (ASTM A955/A955M)
  – Stainless Clad (AASHTO MP 13M/MP 13-04)
  – Low Carbon/Chromium Steel (ASTM A1035/A1035M)
• All projects advertised after September 1, 2010 shall be with CRR.
CRR Levels

- **Level 1: Improved Corrosion Resistance Bars**
  - MMFX2, 2101LDX (S32101)

- **Level 2: Moderate Corrosion Resistance Bars**
  - Stainless Steel Clad, 2304 (S32304)

- **Level 3: High Corrosion Resistance Bars**
  - EnduraMet33 (S24000), EnduraMet32 (S24100), 304 (S30400), 316L (S31603), 316LN (S31653), 2205 (S31803)

*With VDOT approval CRR from a higher level may be substituted.*
## CRR for Functional Classification

<table>
<thead>
<tr>
<th>Classification</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeway</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Rural Principal Arterial</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Rural Minor Arterial</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Rural Collector Road</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rural Local Road</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban Principal Arterial</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Urban Minor Arterial</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Urban Collector Street</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban Local Street</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
CRR Requirements

• Low-carbon chromium bars, such as MMFX2, must meet the requirements of ASTM A1035/A1035M

• Stainless steel clad bars must meet the requirements of AASHTO designation: MP 13M/MP 13-04 †

• Solid stainless steel bars must meet the requirements of ASTM A955/A955M. This would include UNS designations S24000, S24100, S30400, S31603, S31653, S31803, S32101, S32304 †

† NOTE: All bars with a stainless steel surface in levels 2 and 3 must be pickled.
Lessons Learned: Why is it Important to Understand these Different Alloys?

- **Old Specification**
  - One Rebar Grade – ASTM A615 Grade 60
  - Differentiated by color
    - Grey (galvanized)
    - Green/yellow/purple (epoxy-coated)
    - Black
Lessons Learned: Why is it Important to Understand these Different Alloys?

• New Specification
  – Multiple alloy grades
    • ASTM A955 – multiple grades of stainless steel bar
    • ASTM A1035 – MMFX2, etc.
    • AASHTO MP13 – Multiple grades of stainless steel clad bar
  – Range of Characteristics
Lessons Learned: Visual Assessment of Different Bars

- Different Types of Bars Can Look Similar

**Carbon steel**  **MMFX2 Duracor**
Lessons Learned: Visual Assessment of A Single Bar Type

The Same Type of Steel Can Look Very Different
Lessons Learned: Manufacturers Markings

Same bar markings, yet different alloys
Lessons Learned: Magnetic Response

<table>
<thead>
<tr>
<th>Bar</th>
<th>MMFX</th>
<th>Black</th>
<th>2101</th>
<th>2304</th>
<th>2205</th>
<th>End32</th>
<th>304</th>
<th>316</th>
</tr>
</thead>
<tbody>
<tr>
<td>Res†</td>
<td>0.16</td>
<td>0.85</td>
<td>0.91</td>
<td>1.3</td>
<td>2.7</td>
<td>&gt;25</td>
<td>&gt;25</td>
<td>&gt;25</td>
</tr>
</tbody>
</table>

†Response measured using coating thickness gage
Lessons Learned: Handheld XRF Analysis

• Warm up + calibration less than 10 min.
• Alloy identification in seconds
• Alloy type, % confidence of alloy ID, list % elements detected, and confidence limit per element detected
Lessons Learned: Visual Bar Assessment

Care must be taken when accepting bars at the jobsite based on visual assessment and markings.

– A magnet can be used as a rough sorting method to differentiate between magnetic and non-magnetic alloys.

– Handheld XRF devices can be useful in determining alloy composition.

– ASTM needs to revise the standards that govern the bar markings and include a requirement that markings be added that indicate the type of steel.
Lessons Learned: Uniaxial Tensile Results from Various CRR Bars
### Lessons Learned: Examples of Percent Reduction in Cross-Section

<table>
<thead>
<tr>
<th>Bar</th>
<th>Black Steel</th>
<th>SS Clad</th>
<th>Endura met 32</th>
<th>MMFX LN</th>
<th>316 LN</th>
<th>Dura Corr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red.(%)</td>
<td>7.5</td>
<td>21.5</td>
<td>35.8</td>
<td>38.5</td>
<td>48.5</td>
<td>52.6</td>
</tr>
</tbody>
</table>
Lessons Learned: Examples of Elongation Results

<table>
<thead>
<tr>
<th>Bar</th>
<th>MMFX Corr</th>
<th>Dura Corr</th>
<th>Black</th>
<th>SS Clad</th>
<th>2304</th>
<th>2205</th>
<th>Endura met 32</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elong. (%)</td>
<td>8</td>
<td>10</td>
<td>12</td>
<td>19</td>
<td>20</td>
<td>28</td>
<td>39</td>
</tr>
</tbody>
</table>
Lessons Learned: Example of Influence of Relative Rib Area in Beam End Test

Relative Rib Area Makes A Difference

Black: 
Rr = 0.80, 
NX (clad): 
Rr= 0.53
Lessons Learned: Route 360 Over Banister River, Halifax County

- Void between clad layer and black steel core
- Deep groove along the rolling direction
- Rust does not penetrate through the stainless cladding
- Uneven clad layer
Lessons Learned: Material Properties

• Lesson Learned → Knowledge of the material properties and how each bar will interact with the concrete is important.
  – Alloying changes not only the corrosion resistance, but other material properties as well.
  – With several companies producing different types of bars, features vary and can result in different responses when loaded to failure
    • Differences in relative rib area
    • Debonding of clad from steel
Lessons Learned: Steel Cost

- Alloyed steels are sensitive to alloy costs and some are more sensitive than others (3).
- Steels with lower nickel and molybdenum content provide greater price stability (3).
Lessons Learned: Bridge Cost

• The initial cost of CRR is a function of the reinforcement specified and ranges from about $0.33 up to $3.50 per pound.
• The additional initial cost of solid stainless CRR is typically less than 5 percent of the total project cost.
• The cost of one deck overlay far exceeds the extra cost of solid stainless reinforcement.
Lessons Learned: ASTM A955

- ASTM A955-06a
  Such analysis shall meet the chemical composition requirements specified in Table 2, Specification A 276, or other referenced specification or stainless steel alloy.

- A955-09b & A955-10
  Such analysis shall meet the chemical composition requirements specified in Table 2 by the purchaser.

- A955-11
  6.2 The chemical composition agreed to between manufacturer and purchaser shall conform to the requirements in Table 1 of Specification A276.

Loss of ASTM A276 decreased the number of UNS designated stainless steel products by nearly 93%
Lessons Learned: ASTM A1035

- ASTM A1035-09

<table>
<thead>
<tr>
<th>Element</th>
<th>max, %&lt;sup&gt;A&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.15 %</td>
</tr>
<tr>
<td>Chromium</td>
<td>8.0 to 10.9 %</td>
</tr>
<tr>
<td>Manganese</td>
<td>1.5 %</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.05 %</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.035 %</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.045 %</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.50 %</td>
</tr>
</tbody>
</table>

<sup>A</sup> Maximum unless range is indicated. Percentages refer to weight percentages.

Chromium content range listed eliminates candidate materials with a content greater than 10.9%
Lessons Learned: A1035 & A955 vs MP 18M

• AASHTO MP 18M

<table>
<thead>
<tr>
<th>Element</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.15%</td>
</tr>
<tr>
<td>Chromium</td>
<td>9.2% (Minimum)</td>
</tr>
<tr>
<td>Manganese</td>
<td>2.0%</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.20%</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.045%</td>
</tr>
<tr>
<td>Silicon</td>
<td>1.0%</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.030%</td>
</tr>
</tbody>
</table>

• Greatly increases number of candidate bars that a DOT could evaluate, include some ASTM A955 bars
Summary

• VDOT continues to move forward with implementing CRR
• Visual assessment can not be relied on to determine bar type
• Steel fabricator markings cannot be relied on to identify the type of steel.
• Magnetic sorting provides a quick and easy method for differentiating between magnetic and nonmagnetic alloys.
• X-ray fluorescence provides a practical, and much needed, method for positively identifying bars.
Summary continued

• Relative rib area should be monitored as it varies from producer to producer.

• Uniaxial tensile tests provide the stress-strain behavior, elongation and reduction in cross-section upon fracture can significantly vary for different CRR alloys.

• Corrosion and mechanical testing of CRR is necessary to identify the most cost effective bars with acceptable properties.
Summary continued

• Simple quality control measures need to be established to ensure VDOT receives the corrosion protection and mechanical properties it expects

• VDOT should evaluate using VTM for their acceptance criteria while pursuing a single CRR test method via AASHTO
  – Simplify Number of Standards Needed
  – Ensure Consideration of Important CRR Traits
References


† Note, the majority of this presentation is based on this report
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Thank You