The Use of Vitreous Enamel Coatings to Improve Bonding and Reduce Corrosion in Concrete Reinforcing Steel

Sean W. Morefield¹, Philip G. Malone², Vincent F. Hock¹, Orange S. Marshall¹, Donna C. Day², Charles A. Weiss, Jr. ²,

¹. Construction Engineering Research Laboratory,
². Geotechnical and Structures Laboratory
USAE Research and Development Center
The Use of Vitreous Enamel Coatings to Improve Bonding and Reduce Corrosion in Concrete Reinforcing Steel

U.S. Army Corps of Engineers, Engineer Research and Development Center, Construction Engineering Research Laboratory, Champaign, IL, 61826-9005

Approved for public release; distribution unlimited
Overview

- Corrosion of Reinforcing Steel in Concrete
- Strategies to Prevent Corrosion
- Alkali-resistant Vitreous Enamel Testing and Results
- Ongoing Demonstration Work at CCAD
- Summary
Problem of Corrosion of Reinforcing Steel in Concrete

- Deterioration of reinforced concrete structures directly effects military readiness.
- Corrosion problems are typically related to docks, bulkheads, retaining walls and mooring structures
- U.S. has 276 inland locks, 1,914 deep water ports and 1,812 ports on inland waterways
- Estimated cost for infrastructure repair is $30M annually
Failure of Concrete with Mild Steel Reinforcement is Due to Corrosion of the Steel

- The major cause of failure in reinforced concrete is the corrosion of the reinforcing steel whether it is rebar or steel fiber
- The rusting of iron embedded in the concrete increases the volume and cracks the concrete apart
- All normal reinforced concrete (cast-in-place and precast) may have a short service life due to corrosion
Concrete Composition

- 6% Air
- 11% Portland Cement
- 41% Gravel or Crushed Stone (Coarse Aggregate)
- 26% Sand (Fine Aggregate)
- 16% Water
Cement Reactions Set Conditions

Tricalcium silicate + Water --->
Calcium silicate hydrate + Calcium hydroxide + heat

\[2 \text{Ca}_3\text{SiO}_5 + 7 \text{H}_2\text{O} \rightarrow 3 \text{CaO.2SiO}_2.4\text{H}_2\text{O} + 3 \text{Ca(OH)}_2 + 173.6 \text{kJ}\]

Dicalcium silicate + Water --->
Calcium silicate hydrate + Calcium hydroxide + heat

\[2 \text{Ca}_2\text{SiO}_4 + 5 \text{H}_2\text{O} \rightarrow 3 \text{CaO.2SiO}_2.4\text{H}_2\text{O} + 3 \text{Ca(OH)}_2 + 58.6 \text{kJ}\]

Initial pH in fresh paste is 12.5 to 13
Formation of Fe Passive Layer

Stable to pH 9
Reduction in pH in Concrete

Pozzolanic Reactions

And

Carbonation

\[ Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \]

pH drops from ~13 to ~9
Why Reinforcement Steel in Concrete Corrodes

• All chemical changes that occur after concrete hardens increase the likelihood that the steel will corrode.

• Reactions with the carbon dioxide in the air make the concrete less alkaline and remove the stable iron oxide coating that prevents the orange rust formation.

• Infiltration of chlorides from sea spray or road salt increase corrosion.

• Hollow spots around the steel expose the metal surface.

Ingress of corrosive species (into porous concrete)

Cracking and spalling of the concrete cover

Build up of voluminous corrosion products

Corrosing reinforcing steel

Porous concrete

Corrosive species may already be present in concrete from “contaminated” mix ingredients.
Increasing the Volume of the Iron Oxide Layer Cracks the Concrete

Volume Relative to Iron

- Fe(OH)$_3$·3H$_2$O
- Fe(OH)$_3$
- Fe(OH)$_2$
- Fe$_2$O$_3$
- Fe$_3$O$_4$
- FeO
- Fe

Volume Relative to Iron

6.3× Increase
Strategies to Prevent Corrosion

- Coat the reinforcement with an insulator
- Maintain the alkalinity of the surface of the steel reinforcement
- Coat reinforcement with sacrificial metal (zinc)
- Substitute a non-corroding reinforcement materials (stainless steel, fiber-reinforced polymer)
- Add corrosion inhibitors to the concrete
- Use a external cathodic protection system
- Use combinations of systems

All of the above have been tried! There are no economical solutions!
Reinforcement Developed for Stopping Corrosion

- Black steel with organic coatings such as hot fused epoxy
- Black steel with hot-dip galvanizing
- Specialty alloys such as MMFX
- Stainless steel cladding
- Solid stainless steel (316)
- Glass fiber reinforced polymer rebar (FRP)
- Black steel with vitreous enamel coating
How does Bonding Enamel Work?

- **Cement Grains**
- **Alkali-resistant Vitreous Enamel**
- **Steel Reinforcement**

Enamel protects and steel from corrosion; the cement grains hydrate and bond to surrounding concrete.
Bonding Enamel Has Serious Advantages!

- Enamel insulates the surface and prevents electrochemical effects that cause corrosion.
- Enamel covers the surface to prevent chloride contact.
- Provides a tight bond and dense cemented layer.

The cement-glass layer fused to the surface of the steel produces a bond strength that is significantly greater than that obtained with a bare steel surface (usually at least 2 to 4 times greater). All other coatings decrease bond strength.
Enameled Test Rods

• Rods can be single-coated and fired once or double coated and fired twice
• Firing temperatures were in the 745 °C to 850 °C
• Firing times ranged from 2 minutes to 10 minutes

Mild Steel Test Rods
## COMPOSITION OF CONVENTIONAL ANDALKALI-RESISTANT GROUNDCOAT ENAMELS FOR STEEL

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Conventional Groundcoat</th>
<th>Alkali-resistant Groundcoat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amount (%)</td>
<td>Range (%)</td>
</tr>
<tr>
<td>Silicon dioxide $\text{SiO}_2$</td>
<td>54.69</td>
<td>51 – 65</td>
</tr>
<tr>
<td>Boron oxide $\text{B}_2\text{O}_3$</td>
<td>12.47</td>
<td>9 – 15</td>
</tr>
<tr>
<td>Na oxide $\text{Na}_2\text{O}$</td>
<td>14.77</td>
<td>12 – 15</td>
</tr>
<tr>
<td>K oxide $\text{K}_2\text{O}$</td>
<td>1.71</td>
<td>1.7 – 3</td>
</tr>
<tr>
<td>Li oxide $\text{Li}_2\text{O}$</td>
<td>nil</td>
<td></td>
</tr>
<tr>
<td>Ca oxide $\text{CaO}$</td>
<td>4.54</td>
<td>3.5 – 5.3</td>
</tr>
<tr>
<td>Aluminum oxide $\text{Al}_2\text{O}_3$</td>
<td>8.85</td>
<td>6 – 9</td>
</tr>
<tr>
<td><strong>Zr oxide $\text{ZrO}_2$</strong></td>
<td>nil</td>
<td></td>
</tr>
<tr>
<td>Cu oxide $\text{CuO}$</td>
<td>nil</td>
<td></td>
</tr>
<tr>
<td>Mn dioxide $\text{MnO}_2$</td>
<td>0.45</td>
<td>0.4 – 0.7</td>
</tr>
<tr>
<td>Ni oxide $\text{NiO}$</td>
<td>nil</td>
<td></td>
</tr>
<tr>
<td>Cobalt oxide $\text{Co}_3\text{O}_4$</td>
<td>0.31</td>
<td>0.2 – 0.35</td>
</tr>
<tr>
<td>Phosphorus oxide $\text{P}_2\text{O}_5$</td>
<td>nil</td>
<td></td>
</tr>
<tr>
<td>Fluorine $\text{F}_2$</td>
<td>2.27</td>
<td>1.7 – 2.6</td>
</tr>
</tbody>
</table>
## COMPARISON OF AVERAGE BOND STRENGTHS

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Average Peak Force (N)</th>
<th>Std. Deviation (N)</th>
<th>Average Bond Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel fiber embedded in mortar</td>
<td>---</td>
<td>---</td>
<td>2.04 – 2.72</td>
</tr>
<tr>
<td>Steel rods, uncoated embedded in mortar</td>
<td>2,618.2</td>
<td>466.2</td>
<td>2.06</td>
</tr>
<tr>
<td>Enameled rods without portland cement embedded in mortar</td>
<td>3,497.9</td>
<td>540.8</td>
<td>2.70</td>
</tr>
<tr>
<td>Rods with enamel containing portland cement embedded in mortar</td>
<td>11,124.6</td>
<td>235.3</td>
<td>8.79</td>
</tr>
</tbody>
</table>

*3 or 4x STRONGER BOND*
Reactive Enamel Increases Strength Over Time

- Bond strength of coated rebar increases over time
- Bond strength of non-coated rebar lower, and decreases over time
Salt Water Exposure Testing

Exposure in Partly Saturated Quartz Sand with 3.5% Sodium Chloride Solution at 20 °C
Salt Water Exposure of Bare Metal and Drilled Enamel

After 72-hour Exposure

Bare metal showed rapid corrosion over full surface

Enamel steel showed corrosion only where a hole had been cut through the enamel
Salt Water Exposure at 40-days for Bare and Coated Test Rods

Results of 40-day exposure of mild steel test rods in 3.5% NaCl solution at 20 °C

Alkali-resistant ground coat enamel

Alkali-resistant ground coat enamel w/ portland cement

Cement on surface that contacted water hydrated
Salt Water Exposure at 40-days for Coated Test Rods

- SEM photomicrograph of the edge of a groove cut in the enamel to expose underlying metal.
- Rod was embedded in resin, sliced and polished to show the edges of the bare metal area. The enamel does not debond or allow capillary transfer of salt solutions.
- SEM Surface of enameled metal wire bent to produce fractures and partly wetted to produce examples of open and filled fractures.
- The reacted cement on the surface produces the irregular surface texture.
CCAD Demonstration
Cooling Tower Support
and Street Section
CCAD Cooling Tower Support

- Exposure to Atmospheric Chlorides from Gulf of Mexico
- Spalling concrete from corroding steel
CCAD Cooling Tower Support Beams
Summary

- The cement-glass interface produces a bond strength to the steel that is at least 3 to 4 times greater compared to bare steel alone.
- The cement-glass enamel hydrates in the same way as conventional cement. Morphological and chemical changes in the cement embedded in the glass is consistent with conventional hydration.
- Enameling is very effective in preventing corrosion. In testing corrosion has not been observed on the steel when the enamel is not purposely removed.
- Bonding enamel potentially can be very useful in creating reinforced concrete with an improved composite character and improved corrosion resistance.
- Work at CCAD will demonstrate the technology on a much larger scale, yielding real world load bearing and corrosion performance data.
Bonding Enamel on Reinforcing Steel Has Many Applications

- It can go into pre-cast or cast-in-place concrete
- It can be go onto steel decking for concrete floor construction
- Masonry anchors and “appliances” that have to bond to mortar can be enameled
Questions?