

Summary Report:
**CORROSION RESISTANT
REINFORCING STEEL
IN CONCRETE**

In 2013, a Master's of Science Thesis was prepared by David Beh at the University of Utah on the corrosion resistance of various reinforcing bar systems¹. The purpose of the research was "to compare the available reinforcing materials and to show the effect of supplementary cementitious materials on the resistivity of the concrete, which will increase the time to corrosion initiation and extend the propagation period." Testing was conducted using "Florida Method of Test for An Accelerated Laboratory Method for Corrosion Testing of Concrete Using Impressed Current."²

MATERIALS EVALUATED

The following reinforcing steel materials were chosen for evaluation:

- Carbon-steel (ASTM A615)
- Epoxy-Coated Steel (ASTM A775)
- Duplex Stainless Steel (ASTM A955)
- Stainless Steel-Clad
- Mid-chromium Steel (ASTM A1035)

The bar size used was #4 or #5.

For the epoxy-coated reinforcing steel, three conditions were tested: "end cut", "pinhole", and "mash." The pinhole specimen is designed to simulate a "holiday" or defect during manufacture and the "mash" and "end cut" specimens are meant to simulate improper handling procedures.

The duplex stainless steel bars meeting ASTM A995 and carbon-steel bars meeting ASTM A615 were tested as-received. The duplex stainless steel bars had 22 percent chromium, 4.8 percent nickel and 3.1 percent molybdenum.

The stainless steel-clad bars were tested in 3 conditions; as-received, end cut, and a pinhole. The stainless-clad bars had an average thickness of the cladding of 690 μm . The cladding met ASTM A276 and is classified as 316L.

The mid-chromium steel was manufactured by MMFX and met ASTM A1035.

The data suggest that even improperly handled and placed epoxy-coated reinforcing steel is the superior choice for designers looking to achieve 100-year life cycles.

PROCEDURES

The scope of the Florida DOT test method states: "This procedure is an accelerated laboratory method of testing reinforced concrete for corrosion protective properties. The method was designed to compare various concrete mixes, but can also be used to investigate concrete protective coatings, and rebar claddings and coatings."

Mixture proportions for the research were consistent with those used for bridge decks using a water cementitious ratio of 0.45. One mixture only contained Type I/II cement (OPC), while the other second mixture was a ternary blend containing 20% replacement by weight of the cement of class F fly ash and 20% replacement of slag cement.

Reinforcing bars were cast into the center 4" x 8" cylinders with 1.75" of cover and the specimens were cured at room temperature for approximately 24 hours before being removed from the mold and then allowed to cure in a moist room for 28 days (Fig. 1).

After curing, the exposed bars in the specimens were connected to the positive terminal of a DC power supply with a voltage of 6V and the negative terminal of the power supply was connected to a #5 bar placed at the bottom of the tank (Fig. 2). The amperage was measured on a daily basis was measured until a visible crack formed or a large current increase was measured (~1 mA or greater). Each specimen was tested for 60 days or until failure.



Figure 1
Visual comparison of ternary vs OPC specimens containing carbon-steel bars.

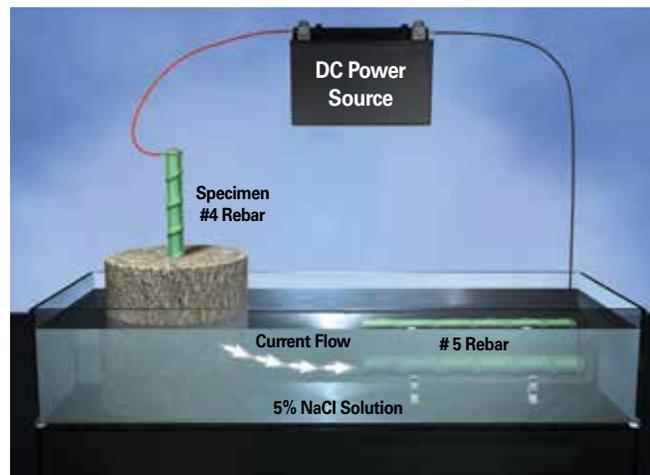


Figure 2
Test schematic for impressed current test (Florida DOT, 2004).

RESULTS

The time to failure was determined when a crack was detectable by visual means or when there was a large increase in current. Results obtained are shown in **Table 1**.

Table 1: Results

Bar Type	OPC			Ternary Mixture	
	# Failing	Time at failure (days)	Observation	# Failing	Observation
Carbon-Steel (ASTM A615)	2/3	40 - 42	2/3 failed during test period	0/3	No corrosion
Stainless Steel-Clad As received and pinhole	3/3	12 - 20	Severe corrosion visible	0/3	Corrosion visible
Duplex Stainless-Steel (ASTM A955)	3/3	19 - 20	Severe corrosion visible	NR	NR
Mid-chromium Steel (ASTM A1035)	3/3	19 - 20	Severe corrosion visible	0/3	No corrosion
Epoxy-Coated Steel (ASTM A775) Pinhole	0/3	N/A	No corrosion	0/3	No corrosion
Epoxy-Coated Steel (ASTM A775) Mash	0/3	N/A	No corrosion	0/3	No corrosion
Epoxy-Coated Steel (ASTM A775) End-cut	0/3	N/A	Some visible corrosion	0/3	Some visible corrosion

NR = not reported

The results demonstrated that specimens in OPC mixture specimens corroded faster than their ternary mixture counterparts. Further, the following results were reported for the bars in the OPC mixture.

- Two out of the three carbon-steel bars in the OPC mixture failed during the test period. There was a jump in the current at the failure time of around 40 and 42 days of testing (Fig. 3). The third specimen did not fail during the period. Severe corrosion was visible.

- The stainless steel-clad bars failed in 12-20 days. All three of the stainless steel-clad bars in the OPC mixture failed during the test period. Severe corrosion was visible at the end of the test. Both the as-received condition and the pinhole condition for the stainless-clad bars in an OPC mixture performed similarly during the test.
- The ASTM A955 stainless steel bars failed soon after the stainless-clad bars, failing in 19-20 days.
- All three of the mid-chromium steel bars (ASTM A1035) in the OPC mixture failed during the test period and severe corrosion was visible.
- The epoxy-coated reinforcing steel in the OPC did not exhibit a jump in corrosion current (Fig. 4).
- The epoxy-coated reinforcing steel in the pinhole condition (Fig. 5) and mashed condition (Fig. 6) showed no signs of corrosion. The end cut epoxy-coated reinforcing steel showed



Figure 5
Epoxy-coated reinforcing steel (pinhole) in OPC after impressed current test.

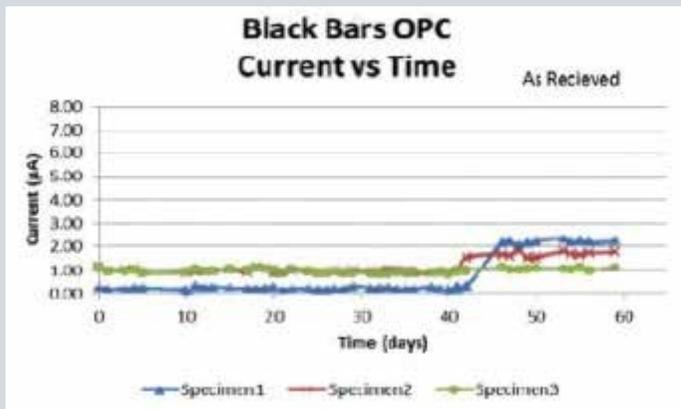


Figure 3
Carbon-steel bars in OPC current vs time.

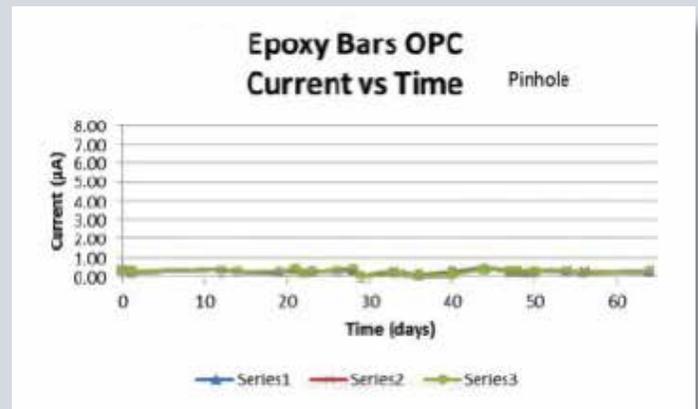


Figure 4
Epoxy-coated reinforcing steel in OPC pinhole current vs time.

signs of corrosion at the damaged site of the bar.



Figure 6
Epoxy-coated reinforcing steel (mashed) in OPC after impressed current test.

For the bars in the ternary mixtures containing fly ash and slag cements, the following results were reported.

- None of the carbon-steel bars in the ternary mixture failed during the test period.
- None of the three stainless steel clad bars in the ternary mixture failed during the test period. Corrosion products were visible but the cylinders did not crack during the test period.
- None of the three stainless steel-clad bars in the ternary mixture failed during the test period. Corrosion products were visible but the cylinders did not crack during the test period.
- None of the mid-chromium steel bars in the ternary mixture failed during the test period and no corrosion products were visible when the specimens were cracked open.
- None of the epoxy-coated reinforcing steel end-cut condition cast into the ternary bars failed during the test period. Corrosion products were visible; however, the specimens did not crack during the test period.

CONCLUSIONS

The following conclusions were reached by Beh, based upon the research:

- The data suggest that even improperly handled and placed epoxy-coated reinforcing steel is the superior choice for designers looking to achieve 100-year life cycles.
- The epoxy-coated reinforcing steel showed the best performance of the products evaluated. Even with pinholes and meshes, the epoxy-coated reinforcing steel showed no signs of corrosion.
- The end-cut condition for epoxy-coated reinforcing steel showed signs of corrosion after the test period. As long as the contractor repairs any cut ends per the manufacturer's recommendations, concrete reinforced with epoxy-coated reinforcing steel should yield the longest life structures of the bars investigated regardless of the permeability of the concrete mixture used.
- The ternary mixtures yielded better test results for all of the steel tested.
- The data suggest that carbon-steel bars, with proper coverage and the right concrete mixture, can produce long life structures even under high demand conditions.
- The carbon-steel bars did not perform well in the OPC mixtures made with Type I/II cement, but performed surprisingly well in the ternary concrete mixture.
- The stainless steel-clad bars did not perform well with either concrete mixture. The specimens showed pitting and heavy section loss when cast in the OPC mixtures.
- The stainless steel-clad specimens cast in the ternary mixture began to show signs of deterioration.
- The mid-chromium steel bars meeting ASTM A1035 did not perform well in the impressed current test and some of the specimens showed more severe deterioration than their carbon-steel counterparts.
- Designers and contractors should use caution when specifying mid-chromium steel bars.
- Using a low permeability concrete with proper cover will add extra protection should there be an issue with the protective coating.
- In order to achieve the proper design life, the author recommends that designers explicitly and concisely specify proper materials and procedures for the exposure conditions of the structure.

REFERENCE

1. Beh, D., *Corrosion Resistant Concrete Using Corrosion Resistant Steel*. 2013, The University of Utah, p. 84.
2. Florida Department of Transportation, *Florida Method of Test for An Accelerated Laboratory Method for Corrosion Testing of Reinforced Concrete Using Impressed Current*, FM 5-522, 2000.

