IDEA

Innovations Deserving Exploratory Analysis Programs

Highway IDEA Program

Environmentally Friendly Passivating Coatings for Steel Rebars

Final Report for Highway IDEA Project 52

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INTRODUCTION

This report summarizes the findings of the first year of an ongoing investigation conducted by the Florida Department of Transportation (FDOT), in conjunction with the University of South Florida (USF) and Neely Industries. The general objective for this work is to determine the effectiveness of Inorganic Polymer Coated (IPC) reinforcing bar (rebar) in the presence of sodium chloride (NaCl). Also of interest is the potential of this coating to passivate any damage the rebar may have suffered, such as that encountered in normal handling procedures.

The effectiveness of a rebar coating depends on its ability to impede corrosion when significant levels of aggressive substances are present at the steel surface. In addition, an appropriate rebar coating must not cause any negative side effects and provide favorable impact on the life cycle cost of the structure.

TEST MATRIX

Bar variables

For this project, four different types of rebar are being investigated; (1) Inorganic Polymer Coated rebar type 1 (IPC-1), (2) Inorganic Polymer Coated rebar type 2 (IPC-2), (3) epoxy coated rebar, and (4) plain carbon steel rebar. All rebar used in this project was #4 (1/2") diameter. Neely Industries, Inc. supplied all IPC rebar, and epoxy coated rebar was obtained from a certified manufacturer (Lilly Greenbar).

Concrete Mix Variables

The concrete for this project was batched on December 3, 1998. The test matrix utilized 658 lb/yd^3 Type II cement with a target water-to-cement ratio of 0.50. No pozzolans or corrosion inhibitors were used for this project. The only additive was WRDA-64, an air entrainer and water reducer. The properties of this concrete mix are shown in Table 1.

Characterization and Control Tests

In order to establish the properties of the concrete used for these test specimens, the following tests were conducted: rapid chloride permeability (RCP) at 28 and 360 days as described in ASTM C 1202, compressive strength (ASTM C 39) at 28 and 360 days, length change (ASTM C 490), impressed current (FM 5-522), and initial chloride content (FM 5-516). The results of these tests are included in Table 1.

Test Specimens

For purposes of evaluating coating performance, only ASTM G-109 specimens were cast. This investigation focuses primarily on the passivating ability of the IPC rebar. In order to assess this feature, all specimens except the control group and one group of IPC-1 specimens had the anodes (top bar in the G-109 specimens) deliberately damaged. The specimen matrix is shown in Table 2.

Table 1. Concrete Mix Properties

BATCH DESIGN QUANTITIES (pcy)		PHYSICAL PROPERTIES		DURABILITY TESTS	
CEMENT	657.4	SLUMP (in)	9 1/2	INITIAL CHLORIDES (pcy)	0.186
WATER	328.7	AIR CONTENT (%)	4 1/4	28-DAY COMPRESSION (psi)	5433
FINE AGGREGATE	1034	CONCRETE TEMP (°F)	72	360-DAY COMPRESSION (psi)	6639
COARSE AGGREGATE	1661.1	UNIT WEIGHT (pcy)	3707.9	28-DAY RCP (Coulombs)	9654
TARGET W/C RATIO	0.5	ACTUAL W/C RATIO	0.48	360-DAY RCP (Coulombs)	7373
				IMP CURR - Days(Ohms)	18(472)

Table 2 – Specimen Rebar Descriptions

NAME	QUANTITY	DESCRIPTION
CTRL	3	Control – Black Steel Rebar
EDT	3	Epoxy-Coated Rebar w/ 0.25% Holidays (All bars)
EDB	3	Epoxy-Coated Rebar w/ 0.25% Holidays (Anode), Black Steel Rebar (Cathodes)
I1DT	3	Inorganic Protective Coating No. 1 w/ 0.25% Holidays (All bars)
I1DB	3	IPC No. 1 w/ 0.25% Holidays (Anode), Black Steel Rebar (Cathodes)
I1UB	3	IPC No. 1 without Holidays (Anode), Black Steel Rebar (Cathodes)
I2DB	3	IPC No. 2 w/ 0.25% Holidays (Anode), Black Steel Rebar (Cathodes)

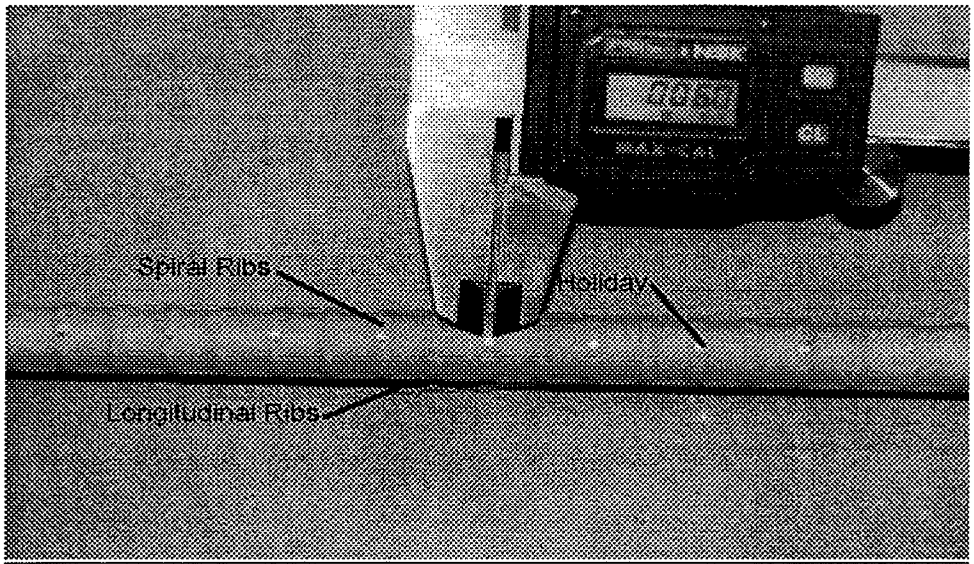
SPECIMEN PREPARATION

Bar Preparation

The IPC and epoxy rebar arrived from Neely Industries, Inc. already cut to approximately 13" lengths. At the FDOT laboratory, the necessary bars (Table 2) were intentionally damaged to model what is normally seen in construction applications. The work plan specified that it was necessary to damage 10 areas per bar. Further, the total damaged areas were required to equal 0.25% of the surface area. To achieve this, a 1/16" diameter drill bit was used. The tip of the drill bit ground down until it was flat; to simulate damage expected from scraping. The damaged areas were confined to the apex of the spiral ribs (Figure 1) on the 6 inches of rebar situated directly under the pond.

Bar Placement

The G-109 forms are constructed from high-density polyethylene plastic. No form oils or release agents are utilized. The forms are constructed so that the rebar can be secured in the proper position. Particular care is taken to ensure that the damaged areas are orientated facing the ponded surface of the specimen. The bars are placed in "as received" condition except for the deliberately damaged bars.



Concrete Batching, Casting, and Curing

The concrete was batched in a 27 cubic foot central mixer. Strict control of the water-to-cement ratio was maintained through careful measurement of all components. Additionally, aggregate moisture contribution is taken into account. All aggregates used were from FDOT approved sources and tested for proper gradation prior to batching. Quality control of the freshly batched concrete was maintained by testing for slump, air content, unit weight, and temperature (Table 1). The American Concrete Institute (ACI) certifies all personnel conducting these tests. Additional control test specimens were prepared at the time of batching for future testing. The concrete was placed into the forms in two lifts. After each lift, the concrete was vibrated for 45 seconds to assure uniformity throughout the specimens. The specimens were lightly troweled and then covered with polyethylene film and allowed to cure for 72 hours. Following this, the forms were stripped away, and the specimens were placed into a 100% humidity moisture curing room for 28 days. Finally, the specimens were removed from the moisture room and placed in plastic bags for an additional 59 days to achieve longer curing, and to prevent carbonation from occurring. This additional curing time (beyond that normally used in the ASTM procedure) was intended to increase the degree of concrete maturity before saltwater exposure was initiated. The specimens were prepared for testing before reaching the 90-day maturity point. This preparation included affixing plastic ponds to the top surface, and an application of epoxy coating, which meets all ASTM G-109 specifications, to the sides, ends, and top surface (excluding the area within the pond) of each specimen.

SPECIMEN TESTS

ASTM G-109

ASTM G-109 specifies that a 100-ohm resistor be connected across the anode and cathodes. Plexiglas plates containing the required resistor, switch, and banana jacks were fabricated. These plates allowed for additional optional testing of the specimens, while facilitating the separation of the anode and the cathodes. The testing schedule requires that a two-week wet cycle followed by a two-week dry cycle, with testing conducted in the middle of the wet cycle. The initial wet cycle began on March 15, 1999 when a 3% NaCl solution was added to each pond. The ponds were covered to prevent evaporation and concentration of the chloride solution. The specimens were allowed sit undisturbed until March 22, 1999, when the initial testing of the IPC specimens began. The following measurements were conducted with the resistor connected between the anode and cathodes: combined potential versus a saturated calomel electrode (SCE) placed in the pond and macrocell current (potential drop. The following measurements were conducted for archival purposes and possible use in an extended investigation (not reported in this document): i) with the

resistor connected: total ohmic resistance versus a titanium electrode (in the pond); ii) with the resistor disconnected and the specimens allowed to depolarize for several hours: individual bar potentials versus an SCE (in the pond), individual bar ohmic resistance versus a titanium electrode (in the pond), inter-bar ohmic resistance, and the instant-on current. All ohmic resistance measurements were conducted with a Nilsson Model 400 or similar alternating current device operating on a 2-point mode; iii) additionally, polarization resistance and electrochemical impedance spectroscopy (EIS) tests were scheduled every three months until specimen failure.

The ASTM G-109 test method requires that testing continue "until the average macrocell current of the control specimens is 10 :A or greater, and at least half the samples show macrocell currents equal to or greater than 10 :A". To assure sufficient corrosion for a visual inspection, testing then continues for an additional three complete cycles. FDOT standard practice is to continue monthly testing on each specimen until corrosion cracks develop, at which time one last complete set of measurements is taken. After completion of all final non-destructive tests, powdered concrete samples at the rebar level are collected and tested for chloride content. Finally, an autopsy is performed to assess the extent of corrosion and type of corrosion present.

In early January 2000 it was discovered that the pre-manufactured plates were mistakenly equipped with 1000-Ohm resistors. Those resistors were subsequently replaced with 100-Ohm resistors on February 14, 2000 (at exposure day ~300). It appears that this error only moderately biased the tests and did not substantially affect the relative ranking of the materials examined.

PRELIMINARY RESULTS AND DISCUSSION

The reporting period for this report concerns the testing of the ASTM G-109 specimens for the first twelve-month period of saltwater pounding. Figures 2 and 3 show the total potential and macrocell current evolution respectively for all rebar configurations. Each data set constitutes an average of three samples.

The all-black rebar control group showed the earliest and most pronounced evidence of corrosion. Two control specimens attained potentials indicative of corrosion activity (the potentials were -351mV and -310mV versus SCE) after only 4 months of exposure. Current measurements were in agreement with that trend. Upon visual inspection, it was determined that only one of these specimens had cracked.

All the coated systems showed improved performance compared to that of the black bar controls. The coated system performances may be divided into three groups as follows:

Very low corrosion: The inorganic type 1 without flaws coupled with black bar cathodes, and the flawed epoxy coupled with flawed epoxy cathodes, gave the best overall performance, with potentials well into the passive regime and very small macrocell currents throughout the entire test period. The flawed inorganic type 1 coupled with flawed type 1 bar cathodes showed relatively negative average potentials from nearly the start suggesting possible corrosion activity, but average macrocell currents were negligible during the entire reporting period.

Delayed corrosion, moderate current: The flawed epoxy and the inorganic type 2, when coupled with black bar cathodes, showed macrocell current indications of corrosion (but several times less strong that in the black bar controls) after about 200 days of pounding. Potential trends confirmed that observation.

Delayed corrosion, high current: The flawed inorganic type 1 system, coupled with black bar cathodes, did not show indications of corrosion until about 300 days of exposure. However, when corrosion started the average macrocell current was comparable to that of the black bar controls. Potential indications are also indicative of active corrosion.

The results reviewed above are preliminary and reflect a short test period dictated by contractual limits. Because of the protective effects of the coatings, evidence of corrosion activity developed so far typically in only 1 or 2 of the triplicate specimens in each category showing activity. A longer test exposure is needed to allow for useful comparison of the behavior of those systems, and also to permit ranking of the other systems that did not yet show any activity. Autopsy of test specimens after full development of corrosion would also provide an essential element for useful performance assessment. In anticipation of continuing investigation, a minimum of data acquisition activity by the FDOT laboratories has proceeded for archival purposes. Reestablishment of full data acquisition and data processing and evaluation will take place should continuation support for this project become available in the future.

CONCLUSIONS

1. All coating systems investigated provided better corrosion performance than that of the plain steel controls.

2. During the 1-year test period reported here both inorganic coating type 1with no flaws coupled to black bar cathodes, and flawed epoxy coupled with flawed epoxy, showed evidence of very low corrosion. Flawed inorganic coating type 1 coupled to flawed inorganic type 1 cathodes showed also very low corrosion currents.

3. Flawed inorganic coating type 1 coupled with black bar cathodes showed delay of corrosion initiation but comparable corrosion currents, after initiation, to those of the black bar controls.

4. Flawed inorganic coating type 2, and flawed epoxy, coupled with black bar cathodes showed delay in corrosion initiation and reduced corrosion currents compared to black bar controls.

5. Extended testing and analysis is required to complete the relative evaluation of these coating systems. Data acquisition by FDOT is proceeding at a maintenance level in anticipation of a continuation program.

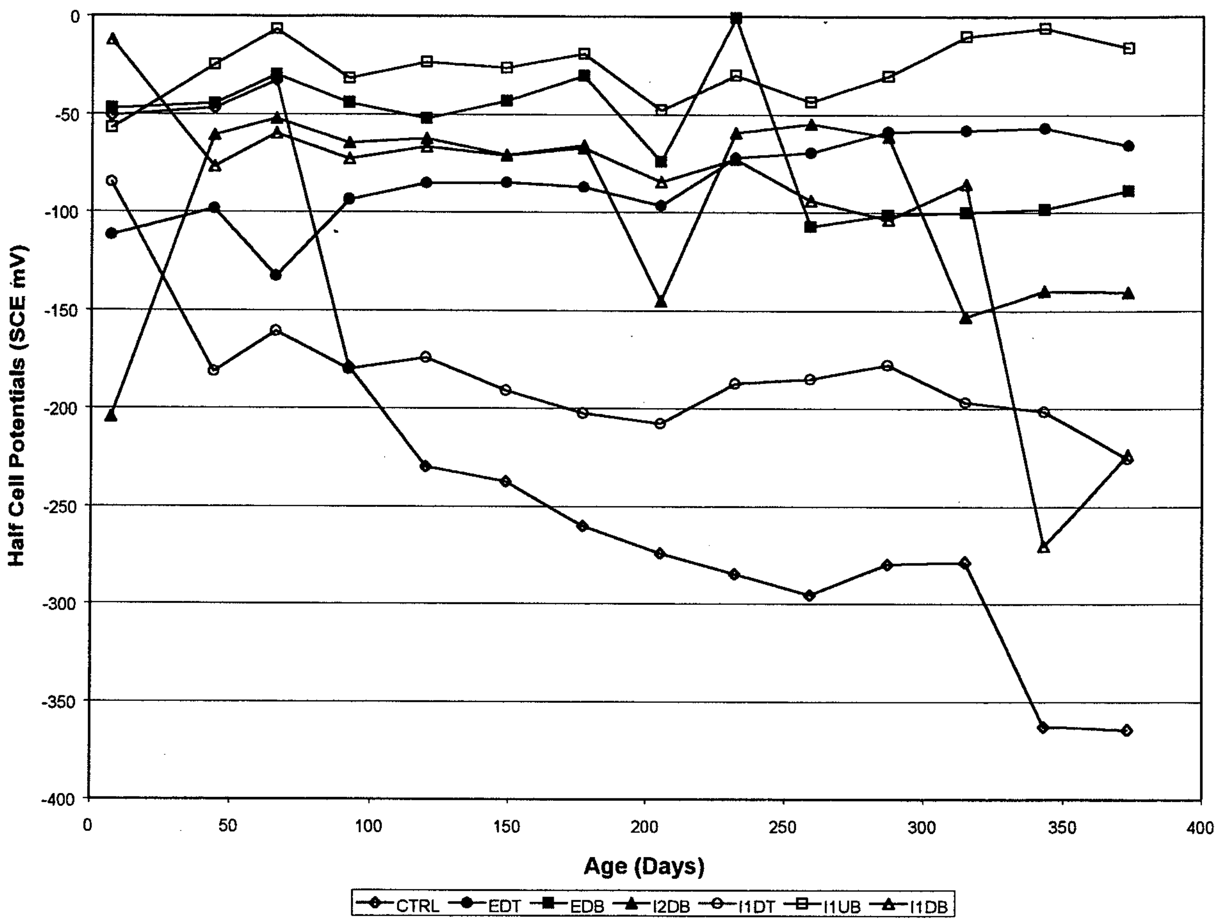


Figure 2. Combined potential (average of triplicate specimens) as function of exposure time for all rebar configurations. Refer to Table 2 for rebar designation code.

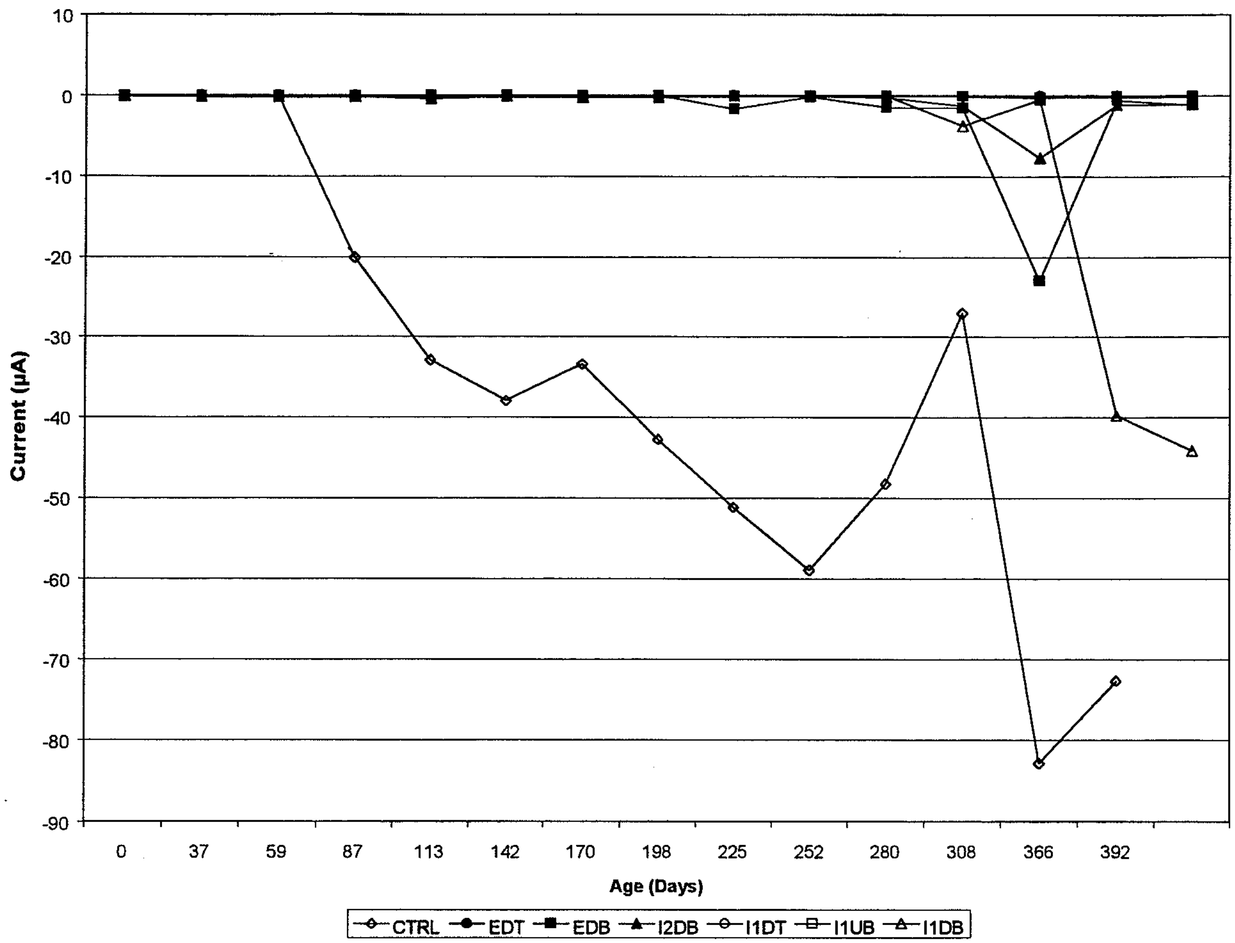


Figure 3. Macrocell currents (average of triplicate specimens) as function of exposure time for all rebar configurations. Refer to Table 2 for rebar designation code.