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Demonstration of Reactive Vitreous Coatings on Reinforcement Steel to Prevent Corrosion and Concrete Failure

Final Report on Project F08-AR01

Sean Morefield, Charles A. Weiss Jr., Philip G. Malone, and Victor Martinez

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Demonstration of Reactive Vitreous Coatings on Reinforcement Steel to Prevent Corrosion and Concrete Failure

Final Report on Project F08-AR01

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Final report

Abstract

The Department of Defense (DoD) Corrosion Prevention and Control Program funded a project to evaluate the corrosion performance of a new vitreous reactive-silicate coating that can be bonded to steel reinforcement bars used in concrete structures. The technology was installed in pavement at Corpus Christi Army Depot (CCAD) where corrosion-induced concrete damage has contributed to costly accidents involving transport of aircraft engines. Test blocks designed and instrumented for accelerated corrosion testing were used to compare the performance of vitreous-coated bars with other types of bars. The vitreous-coated bars installed in CCAD pavement showed no sign of corrosion because atmospheric chlorides could not penetrate to reinforcement depth during the demonstration period. Test block custody was temporarily lost at the installation, during which time they were damaged and experimental controls were disrupted. When the blocks were split open for visual examination, the vitreous-coated samples had various amounts of surface corrosion on the bars and concrete traces.

An economic analysis using a conservative service-life assumption for vitreous-coated rebars projected a return on investment of 44.69 over 30 years versus materials and methods currently used at CCAD. The technology requires further refinements and testing before it could be recommended for DoD-wide implementation.

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Executive Summary

Reinforced concrete pavements comprise critical infrastructure on all Department of Defense (DoD) military installations. Corrosion is a major problem for steel-reinforced concrete as moisture and chlorides infiltrate and attack the rebar, progressively corroding the steel and promoting fractures that accelerates with normal weathering and loading. These processes result in premature failure of reinforced concrete structures, sometimes many years short of their designed service life.

A project funded under the DoD Corrosion Prevention and Control Program was performed to demonstrate and validate the performance of a new vitreous reactive-silicate coating that can be bonded to steel reinforcement bars used in concrete structures. The coating was applied to black steel rebars and installed in a reconstructed section of roadway at Corpus Christi Army Depot (CCAD), where corrosion-induced concrete damage has contributed to costly forklift accidents involving transport of refurbished aircraft engines. In addition to monitoring the pavement section for signs of corrosion damage during the performance period, researchers constructed test blocks containing vitreous-coated, epoxy-coated, and bare steel bars for taking corrosion-current measurements and comparing rebar material performance.

The vitreous-coated bars installed in CCAD pavement were tested using a three-electrode linear polarization technique, but no signs of corrosion were detected in part because there was not enough time during the demonstration period for atmospheric chlorides to penetrate the concrete to rebar depth. The test block experiments were disrupted by a temporary loss of custody at the installation so the data are compromised, but observations are documented for the record.

An economic analysis using a conservative service-life assumption for vitreous-coated rebars projected a return on investment of 44.69 over 30 years versus materials and methods currently used at CCAD. The technology requires further development and testing before it could be recommended for DoD implementation. This technology may be best suited for precast sectional work (e.g., beams, panels, columns, etc.) due to environmental and material handling factors.

Unit Conversion Factors

Multiply	By	To Obtain
cubic yards (cu yd)	0.7645549	cubic meters
feet (ft)	0.3048	meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
inches (in.)	0.0254	meters
mils	0.0254	millimeters
pounds (force) per square inch (psi)	6.894757	kilopascals
pounds (mass) (lb)	0.45359237	kilograms
ounces (liquid) (oz)	2.957353 E-05	cubic meters
square feet (sq ft)	0.09290304	square meters

1　Introduction

1.1　Problem statement

Reinforced concrete pavements are a critical infrastructure component on all Department of Defense (DoD) military installations. The material is used in all types of infrastructure, from vehicle roadways and bridge decks to airfields and heavy equipment support pads. A universal problem for steel-reinforced concrete is corrosion of reinforcement bars due to the infiltration of moisture and contaminants, such as atmospheric chlorides or road de-icing salts. As loading and weathering create cracks that allow moisture intrusion, water and chlorides act as an electrolyte that creates corrosion cells, progressively degrading the steel and, therefore, its load-carrying strength. Also, in structures with multiple steel reinforcement mats, differences in chloride infiltration at various concrete depth can create differences in electrical potential that result in macro-cell corrosion current between layers of steel. Roads and grounds rank third in total corrosion cost for DoD facilities ($282 million annually), which amounts to 10% of the total maintenance cost [Ref. 1].

Currently there is no simple solution to deterioration of reinforcing steel in concrete. Epoxy coatings on concrete have been shown to deteriorate due to delamination and cracking in five years or less, and chemical additives to concrete have proved to be of very limited use. Researchers at the U.S. Army Engineer Research and Development Center (ERDC) developed a new reactive silicate material that can be bonded to steel reinforcement bars with a layer of vitreous enamel [Ref. 2]. This innovative coating blends a hydraulically reactive silicate cement with a glass enameling frit that is fused onto the steel. The research has shown that when Portland cement is used in the vitreous formulation, the hydration reaction that occurs in cement paste is likewise observed in the cement embedded in the vitreous coating. If the vitreous coating fractures, the crack can be sealed by calcium silicate hydration products from the embedded cement in a self-healing-type reaction [Ref. 2]. Preliminary investigation of the composition and behavior of the composite Portland cement vitreous enamel formulation has confirmed the occurrence this self-healing reaction in an aggressive environment, as cement grains react with moisture in contact with them to produce a cement paste in the crack to protect the steel from

exposure [Ref. 3]. U.S. and international patents for this new technology have been applied for [Ref. 4].

In order to evaluate the potential applicability of this technology to pavements on military installations, a Corrosion Prevention and Control Program demonstration/validation project was funded to fabricate, install, and test reinforcement bars fabricated with this vitreous coating.

1.2   Objective

The objective of this project was to install vitreous-coated steel reinforcement bars in a section of roadway on an Army installation, along with test and control concrete blocks, to determine the technology's corrosion-prevention performance.

1.3   Approach

The demonstration site was Corpus Christi Army Depot (CCAD), located in southern Texas on the Gulf coast, where atmospheric chlorides create an aggressively corrosive environment for reinforcement steel. The field work involved two tasks:

- Installation of vitreous-coated rebars in a 14,000 sq ft section of Crecy Street on the installation
- Fabrication of test blocks in accordance with ASTM G 109-074 [Ref. 5], modified for accelerated testing, to determine the corrosion performance of the research and control rebar specimens in concrete

The CCAD Department of Public Works (DPW) recommended the selected section of Crecy Street because pavement condition there has been a factor in several handling incidents in which forklifts have dropped refurbished aircraft engines, resulting in significant damages and associated costs. This section of roadway is heavily used by forklifts carrying aircraft engines being rebuilt at the depot, and even small road damage may result in the dropping of one. These engines are typically valued at $10–20 million.

For all test specimens, the state of rebar corrosion was determined by measurement of corrosion potentials (half-cell potentials), corrosion rate measurements, and macro-cell corrosion currents. The half-cell potentials on both Crecy Street and the test blocks were measured according to the

procedures given in ASTM C 8765 [Ref. 6]. Potential measurements were taken using a portable saturated calomel electrode (SCE) as the reference.

Resistance measurements using alternating current (AC) were made to determine coating porosity, both at the point of fabrication and at the demonstration site.

2 Technical Investigation

2.1 Project overview

Production of the vitreous-coated bars at Roesch, Inc. (Belleville, IL) was observed, and resistance measurements were taken from the coated bars after fabrication. These resistance measurements were also compared to resistance measurements taken from the coated bars after delivery to the construction site at CCAD. The bars were installed in Crecy Street at CCAD and embedded into test blocks fabricated according to ASTM G 109-07 instructions, with modifications to facilitate accelerated testing during the project period. The half-cell potentials and corrosion rate measurements were monitored after initial installation, six months after installation, and one year after installation. The test blocks were scheduled to be monitored by measurement of AC resistance, half-cell potentials, and macro-cell corrosion currents after initial installation, six months after installation, and one year after installation, but this task could not be completed as planned for reasons explained in this chapter.

2.2 Installation of the technology

2.2.1 Fabrication of coated bars

The vitreous coating was applied to preformed reinforcement bars on 27–29 July 2009. Bars were steel-grit blasted for surface preparation. Hangers, spaced 32 in. apart, were welded to the 14 ft bars, and the bars were hung horizontally in the firing furnace. Firing temperatures ranged from 1,400–1,600 °F. After firing, the bars came out slightly bent. Apparently, hanging the bars horizontally resulted in an uneven temperature profile over the length of the bars, resulting in a visually good coating near the center of the bars, but poor coating quality at both ends.

Because of these difficulties, the reinforcing bars were reconfigured into 6 ft lengths and coated in a continuous manner. These bars, which could then be hung vertically, were coated in a batch furnace with minimal deformation. A two-coat process was used in which a first coat with only the vitreous component was applied. The Portland cement ingredient of the coating was applied before a second firing. These bars were considered suitable for installation. No resistance readings were taken from the 6 ft bars before shipment.

2.2.2   Crecy Street installation

Twenty-eight tons of Texas-Lehigh Type I/II LA Portland cement was mixed into sand to stabilize the base underlying Crecy Street, and installation of vitreous-coated rebars began 11 July 2009. Because the coated rebars were only 6 ft long, and since an overlap of 18 in. was required for each bar, extra labor was needed to place the reinforcing steel. The bars were placed on Crecy Street from 11–14 August 2009, and the concrete was poured on 14 and 18 August (see Figure 1).

Figure 1. Vitreous rebar in place before and after Crecy Street concrete pour.

Although many flakes of vitreous coating were seen in the rebar shipping containers, the coating on the bars appeared to be reasonably durable during placement. Concrete was placed for Crecy Street on 14 and 19 August 2009. The concrete mix design (cubic yard basis) and quality control data are as follows:

- 1 in river rock (1,900 lb)
- River sand – 0.37 in. (1,271 lb)
- Portland Type I/II LA cement (376 lb)
- Fly ash Class C (94 lb)
- Standard water (not defined) (250 lb)

Two supplemental admixtures were also used:

- Daravair* 1000 air entrainer, ASTM C 2601.18 oz/100 lb. Air entrainer was used to ease concrete placement and enhance the finish.
- Daratard* D 17 Type D (summer), ASTM C 4949.40 oz/100 lb. Retardant slows the rate of cement hydration and was used to extend concrete working time to prevent premature hydration in the summer heat.

Average compressive strength of concrete delivered to Crecy Street per ASTM C 39 was 3,880 psi (average of 15 tests after 28-day cure). The average slump was 5.0 in.

2.2.3   Test block construction

Modified test blocks were constructed at Corpus Christi, Texas, on 19 August 2009 using concrete from the same batch placed on Crecy Street that day. The ASTM G 109-07 procedure was originally created to test the effectiveness of topically applied corrosion inhibitors. In the published test procedure, the blocks are constructed as shown in Figure 2 with homogeneous uncontaminated concrete throughout. Sodium chloride solution was then applied to the top surface of the blocks in a series of wet-dry cycles until chloride contamination reached the level of the top bar and corrosion was initiated.

Figure 2. ASTM G-109 test block design.
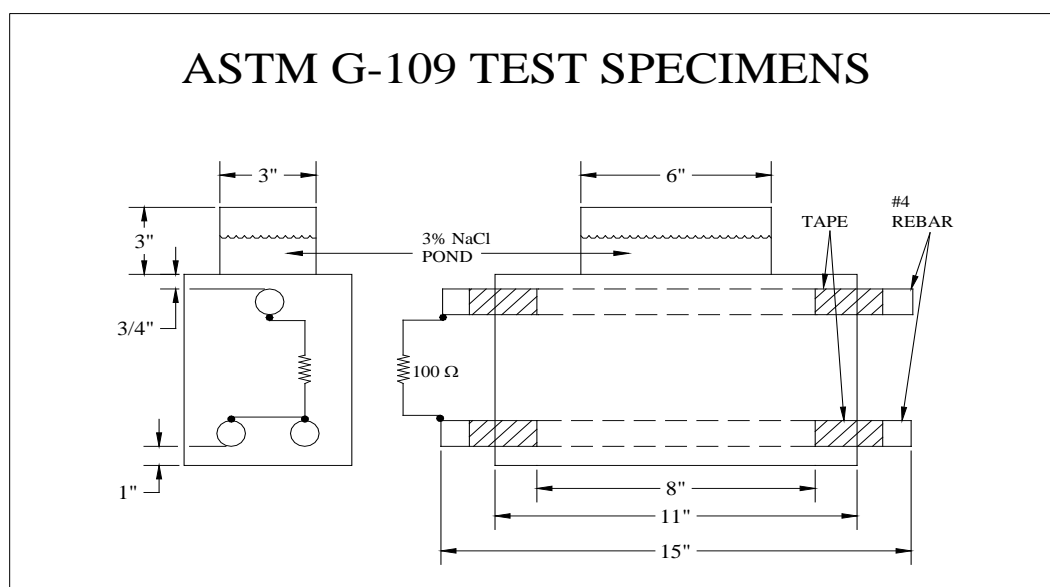
Using the published method, however, corrosion often takes several months to begin—sometimes more than a year. Therefore, the process is often modified to introduce chlorides immediately to the reinforcement bars. One method of acceleration is to cast the concrete in two lifts, with a chloride-containing top lift surrounding the top bar to set up a corrosion cell between top and bottom bars, so corrosion processes can begin in a matter of days. For the test blocks used in this project, the top lift of concrete was cast containing 10 pounds per cubic yard (pcy) of admixed chlorides in the form of sodium chloride. The pond included on top of each block was used only to hold moisture from precipitation or to wet the blocks during stretches of very dry weather. Seven test blocks were constructed using the vitreous enamel-coated rebar, seven were constructed with epoxy-coated top bars, and six used uncoated top bars.

The test blocks were originally located adjacent to Crecy Street. Unfortunately, during the first site visit on 3 November 2009, the blocks were found to have been damaged or vandalized. Wires and resistors had been ripped off of 18 of the 20 test blocks. Upon this discovery, the test blocks were then relocated to a secure area inside the fence at Grace Paving and Construction, 4237 Baldwin Street, Corpus Christi. The morning of 3 November 2009 was spent repairing and rewiring the blocks. Ultimately, the data from the test blocks was not considered reliable enough to use in the evaluation, although the blocks were split open and visually inspected for signs of corrosion.

2.3 Testing program

Initial AC resistance measurements were taken through the vitreous coating, both at the fabrication plant on 27 July 2009 and at the CCAD jobsite on 12 August 2009. AC resistance, corrosion potentials, and macro-cell corrosion currents were recorded on the ASTM G 109-07 test blocks on 3 November 2009 (81 days after installation) and on 30 August 2010 (349 days after installation). Corrosion potentials and corrosion rate measurements were taken on the vitreous-coated bars installed in Crecy Street on 3 November 2009 (81 days after installation) and on 29 April 2010 (227 days after installation). The testing methods are described below. The results are provided in Chapter 3.

2.3.1 AC resistance testing

Each AC resistance test was performed by placing a 6 x 3 in. sponge wetted with 30 gm/liter sodium chloride solution on top of the bar. AC resistance was measured between a galvanized screen on top of the sponge and the bar using a Nilsson-400 Soil Resistance Meter. The measured resistance is indicative of the porosity and number of pinpoint defects (holidays) in the coating.

AC resistance was also measured between the top test bars and the two bottom bars of the test blocks using a Nilsson-400 Soil Resistance Meter. Resistance measured in this way provides a good indication of the integrity of the coating. High resistance indicates an insulating, nonporous coating, whereas a low resistance indicates electrical contact between steel and concrete. It can be assumed that a coating with a low resistance would permit direct contact between chloride ions in the concrete and allow corrosion of the bar surface. The test setup for measuring AC resistance on a test block is shown in Figure 3.

Figure 3. Measurement of AC resistance on the test blocks.

2.3.2 Potential testing

Potentials measured indicate a probability that corrosion is, or is not occurring at the time of measurement. Rate-of-corrosion cannot be quantitatively determined from half-cell potentials. Corrosion potentials were

determined for reinforcing bars in both Crecy Street and the test blocks. Measurement of potentials on the test blocks is shown in Figure 4.

Figure 4. Measurement of corrosion potential on the test blocks.
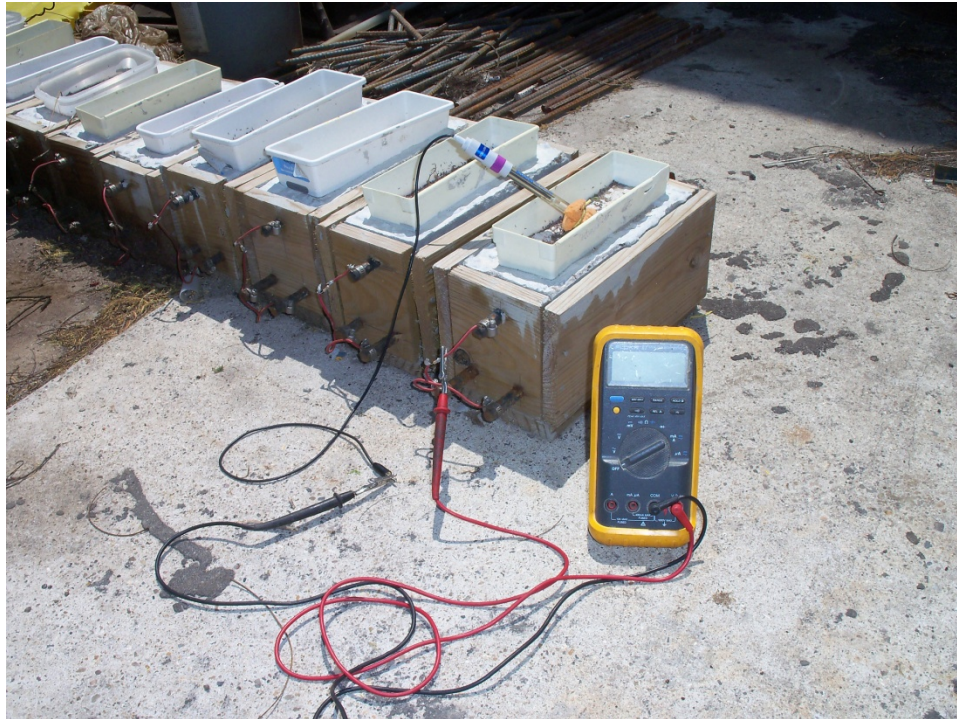
2.3.3   Onsite corrosion-rate testing

Corrosion-rate measurements were determined on Crecy Street by applying a three-electrode linear polarization technique. Using this technique, a small current was impressed on the embedded reinforcing steel using an auxiliary electrode placed on the surface of the concrete (electrode 1.) The small impressed current disturbs the equilibrium between the rebar (electrode 2) and surrounding concrete. The resulting shift in polarization of the steel was measured using a portable SCE reference electrode (electrode 3.) Polarization values were converted to corrosion rates using the Stern-Geary Equation [Ref. 7]. Corrosion rate can be expressed as a current density (mA/sq ft) or in mils per year (mpy). Corrosion rate measurements were taken on the reinforcing steel installed in Crecy Street. Photography was not permitted at the test location, but corrosion-rate measurement at a similar site is shown in Figure 5.

Figure 5. Corrosion rate measurement on concrete at a site similar to Crecy Street.
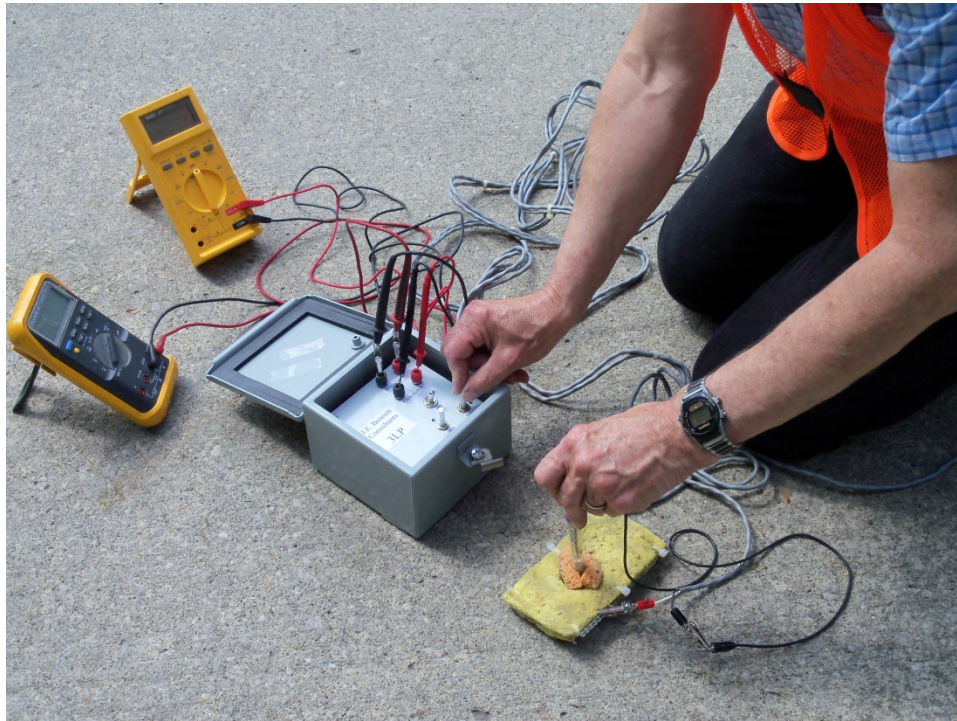
2.3.4 Macro-cell current testing

Macro-cell corrosion currents were recorded on the test blocks by measuring the current flowing between the top test bar (corroding bar), and the bottom bars in the test block that act as cathode. Corrosion currents were determined by recording the drop across a measuring resistor, which is a feature of the test block design. Corrosion currents are typically expressed in microamperes. The measurement procedure is shown on Figure 6.

Figure 6. Macro-cell corrosion current measurement setup.

2.4   Completion of field work

At the conclusion of the demonstration period, the test blocks were split open in order to visually determine the extent of corrosion on each bar. This was done by saw-cutting toward the test bar, followed by splitting the block to expose the bar trace. Any corrosion observed on each rebar trace was documented.

3 Discussion

3.1 Metrics

In order to equal or exceed the industry-standard technology for preventing corrosion of reinforcing steel (i.e., epoxy coating), the following metrics were established:

- AC resistance through the coating >500,000 Ω
- Corrosion potentials on Crecy Street >-276 mV$_{SCE}$ (>-350 mV$_{CSE}$)
- Rate-of-corrosion on Crecy Street <0.20 mA/sq ft (<0.10 mpy)
- AC resistance on the ASTM G 109-07 test blocks >100,000 Ω
- Corrosion potentials on the ASTM G 109-07 blocks >-276 mV$_{SCE}$ (>-350 mV$_{CSE}$)
- Macro-cell corrosion currents on the ASTM test blocks <10 μA
- No significant corrosion visible on rebar trace of split blocks

3.2 Results

3.2.1 Vitreous-coated bars as fabricated

One of the original 14 ft vitreous-coated rebars (see section 2.2.1) was examined with a 30X optical microscope for quality. The following observations were made for sections of the bar between each hanger:

- End section—coating porous with dull finish; coating loose and very friable
- Section 2—coating porous and glassy; coating ~20% debonded
- Section 3—coating glassy with some porosity; coating ~10% debonded
- Section 4—best section; coating smooth and glassy; coating <5% debonded
- Section 5—coating glassy, but porous; coating ~20% debonded
- Section 6—porous glassy coating with many holes; coating ~15% debonded

AC resistance measured on uncoated black-steel bar typically ranges from 15 to 25 Ω, whereas resistance through a good quality epoxy coating will typically be in excess of 500,000 Ω. Resistance readings taken about every 16 in. on two 14 ft bars are shown in Table 1.

Table 1. AC resistance from 14 ft as-fabricated bars at 10 test points (Ω).

	1	2	3	4	5	6	7	8	9	10
Bar 1	52	170,000	660	200,000	560,000	2,000	800	6,300	54	27
Bar 2	170	54	1,400	1,300	2,500	6,800	2,000	7,000	130	22

Resistances were generally higher toward the center of the bar than near the ends, which agree with the visual observations above. Also, resistances on Bar 2 were significantly lower than those on Bar 1, indicating poor reproducibility. Of the twenty AC resistance measurements taken, only three had a resistance greater than 100,000 Ω. Only one reading had a resistance equal to or greater than resistances commonly obtained on epoxy-coated bars (>500,000 Ω).

3.2.2 Vitreous-coated bars installed in Crecy Street

Because of problems with steel deformation during firing of the vitreous coating, the 14 ft rebars in Table 1 were not shipped to the jobsite. Instead, reinforcement design was reconfigured utilizing 6 ft bars, which were coated and shipped to Corpus Christi for installation in Crecy Street.

3.2.2.1 AC resistance

AC resistances were taken on the 6 ft bars 12 August 2009 after arrival at the jobsite, and these data are shown in Table 2. These data show great variability and generally low resistance, indicating high porosity. Of the 23 AC resistance readings taken at Corpus Christi, only two had a resistance greater than 100,000 Ω. No readings had a resistance equal to or greater than resistances commonly obtained on epoxy-coated bars (>500,000 Ω).

Table 2. AC resistance from 6 ft bars (four test points each) before installation (Ω).

		1	2	3	4
Pallet 1	Bar 1	500	470	600	740
	Bar 2	1,700	1,200	130	310
	Bar 3	80,000	380,000	330,000	
Pallet 2	Bar 4	250	13,000	10,000	30,000
	Bar 5	18,000	40,000	40,000	27,000
	Bar 6	2,500	10,000	6,000	7,500

3.2.2.2 Corrosion potentials

Corrosion potentials taken on bars installed in Crecy Street on 3 November 2009 and 29 April 2010 are shown in Table 3.

Table 3. Corrosion potential measurements from bars in Crecy Street (mV).

Location	Test Point	Potential$_{SCE}$, 3 Nov 2009	Potential$_{SCE}$, 30 April 2010
North	1	-113 mV	-24 mV
	2	-120 mV	-72 mV
	3	-199 mV	-80 mV
	4	-217 mV	-123 mV
South	5	-182 mV	-98 mV
	Average	-166 mV	-79 mV

Although a few of the corrosion potentials taken on 3 November 2009 indicate an uncertain state of corrosion on the bars in Crecy Street, most potentials in Table 3 indicate a >90% probability that no corrosion was taking place at the time of measurement. This result was expected since not enough time had passed for chloride ions to penetrate the concrete to the level of the reinforcing steel.

3.2.2.3 Corrosion rate

All corrosion-rate measurements taken on bars in Crecy Street indicate no significant corrosion at the time of the measurement, as shown in Table 4. This result was expected since there was no chloride ion in the concrete adjacent to the reinforcing steel at the time of measurement. At these rates, no corrosion damage would be expected over the next thirty-plus years. However, the rate of any corrosion processes occurring over time would be expected to increase as chloride ions penetrate the concrete cover to rebar depth.

Table 4. Corrosion rate on bars in Crecy Street.

Location	Test Point	Corrosion Rate Nov. 3, 2009		Corrosion Rate April 30, 2010	
		mA/sq ft	mpy	mA/sq ft	mpy
North	1.	0.112	0.06	0.094	0.05
	2.	0.125	0.06	0.044	0.02
	3.	0.125	0.06	0.050	0.03
	4.	0.106	0.05	0.044	0.02
South	5.	0.112	0.06	0.025	0.01
	Average	0.116	0.06	0.051	0.03

3.2.2.4 Condition of Crecy Street repairs (May 2016)

As of May 2016, the overall condition of the pavement was reported to be sound (see Figure 7). Some minor D-cracking (less than 4 in. radius) was observed by DPW personnel at some corners of the installed pavement (see Figure 8).

Figure 7. Crecy Street pavement condition as of May 2016.

Figure 8. Observed D-cracking unrelated to vitreous rebar performance.

D-cracking is a deterioration mechanism in concrete in which fine cracks run parallel to joints and cuts and propagate radially around slab corners. This crack pattern is most consistent with moisture-aggravated deterioration. It is unlikely that these cracks are related to the reinforcing bars, which are installed in a grid pattern covering the entire roadbed and not localized to slab corners.

3.2.3 Vitreous-coated bars installed in test blocks

As explained in section 2.2.3, custody of the text blocks on the installation was lost for several months in 2009. When the blocks were recovered, they were found to have been damaged to an extent that they could not be considered reliable sources of data in the context of a controlled experiment. However, the research team moved the blocks to a secure location on the contractor's property and examined the specimens at the end of the demonstration period as planned in order to see if any usable observations could be documented. A summary of the findings is presented in the Appendix for purposes of completing the project documentation, but the observations cannot be taken as valid scientific results because of experimental loss of custody and control.

3.3 Lessons learned

3.3.1 Testing

In order to test and quantify the effectiveness of technology designed to mitigate the corrosion of reinforcing steel in concrete, the technology should not be demonstrated in chloride-free concrete. Given the typical concrete cover and quality of concrete, it may take several years for chlorides to migrate through the concrete cover to the level of the reinforcement and initiate corrosion. In that connection, in demonstrations of corrosion-mitigation technologies for reinforced concrete, it would be beneficial to design accelerated testing specimens using concrete with chloride content that emulates real-world chloride concentrations which affect embedded rebar after extended periods of exposure.

3.3.2 Fabrication

To be fully effective in mitigating corrosion of reinforcing steel in concrete, the vitreous coating must be largely free of porosity and pinhole-type defects. In order to gain maximum benefit from this technology, coated bars must have electrical resistance as high and uniform as possible along their entire length. Typical ways of measuring resistance involve using AC or direct current (DC) methods prescribed for epoxy coatings. These ASTM standard tests serve as reasonable methods for testing vitreous coatings. ISO* standards for related enamel coatings may also be applicable as quality control/quality assurance metrics, but they were not used in this project.

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* ISO is International Organization for Standardization, Geneva, Switzerland.

4   Economic Summary

The original Return on Investment (ROI) calculation included in the proposed Project Management Plan (PMP) was based on the replacement of two reinforced concrete support structures for chiller units at Corpus Christi Army Depot. The demonstration as implemented replaced a 14,000 sq ft section of road at Corpus Christi Army Depot, so the economic analysis starts from a slightly different set of assumptions and management cost data than the original PMP. The underlying technology, environment, benefits, and potential aging and failure mechanisms remain the same.

4.1   Costs and assumptions

Cost of vitreous-coated reinforcing steel, although not firmly established, has been estimated to be about $0.50–0.60 per pound of steel [Ref. 8]. This does not compare favorably with the established cost of epoxy-coated reinforcing steel of $0.15 per pound of steel [Ref. 9]. To be economically beneficial in terms of material first costs, the price of vitreous-coated steel would need to be substantially lower than that of epoxy-coated steel, or else performance would need to help reduce the overall life-cycle cost.

There are two significant benefits to investment in this technology: improved corrosion resistance and decreased lap-splice length.

Corrosion resistance is calculated based on the increased resistance of the coating compared to the industry-standard epoxy coating. The recorded corrosion-rate estimates for the demonstrated vitreous-coated steel rebar indicated no significant corrosion damage would be expected over the next thirty-plus years. However, as noted in Chapter 3, corrosion of steel in concrete is a strong function of chloride concentration, but the chloride level in the demonstration pavement was low at the time of measurement because chloride infusion is long-term process. For this analysis it was conservatively assumed that although the concrete was manufactured and constructed to industry standards, the chlorides will at some point penetrate to the surface of the rebars and shorten the lifespan.

The assumption of decreased lap splice length is based on prior pullout strength testing, which showed that the yield strength in shear is four to eight times greater that of bare steel alone for the same geometry [Ref. 10]. This permits the use of much smaller lap splices for the same structural

design, which is conservatively estimated to require 15% less bar overlap than bare steel and 30% less overlap than epoxy-coated steel. This represents a significant potential economy for future projects using this technology. The return on investment calculation below does not incorporate this savings component, however, since the lap splice lengths were varied in order to test their performance in the field. Also, the length of individual bars used in this project was significantly shorter than the industry standard due to prototype manufacturing conditions. (With smaller bar lengths, more splices are required, thus negating the cost advantage of shorter splices.) However, future applications using longer bars will incorporate these savings.

The 14,000 sq ft section of roadway at CCAD was used as the basis for the calculations in both the baseline and alternative cases.

Alternative 1 (Current Technology). Using present construction methods and materials, including epoxy-coated rebar, this section of road has a history of severe corrosion damage occurring within five years of replacement. As noted in section 1.3, this section of roadway is heavily used by forklifts carrying aircraft engines being rebuilt at the depot, and even small road damage may result in the dropping of an engine. A destroyed engine cost can easily exceed the entire pavement-replacement project cost using current technology. Individual aircraft engines cost $10 to $20 million each. In the five years before this project, several incidents involving degraded pavement at the demonstration site caused significant damage and costs to refurbished engines. The loss of one engine valued at $10 million due forklift handling accidents specifically caused by road cracks, potholes, or degradation-related surface irregularities would represent an average annual cost of $2 million. It is assumed that the CCAD coastal proximity will continue to impose a high-chloride, high-humidity environment that drives the five-year lifespan of roadways constructed using current reinforced-concrete technology. This alternative represents a complete replacement of the road using historical replacement values of $450,000.

Alternative 2 (Demonstrated Technology). For the demonstrated technology, the starting point is the projected thirty-plus year service life based on the corrosion rate readings on the steel (see section 3.2.2.3). It is assumed that the chlorides will, over time, migrate and reach the steel, and

that there are some holidays in the coating resulting from fabrication, handling, or placement conditions. It is difficult to model these complex environmental and material factors quantitatively, so it is conservatively assumed that actual rebar service life will be half of what was projected based on the corrosion-rate readings. Thus a full replacement cost is incurred at Year 15, and is estimated at $500,000. It is anticipated that as this technology matures, and manufacturing volume capabilities increase, the cost of the coating per pound of steel will decrease significantly. However, the cost to remove the old roadbed, prepare the sub-base, and to procure the raw materials for the concrete—i.e., the majority of project costs—will remain largely constant. The $80,000 decrease in cost (about 14%) in Year 16 comes from performing the roadwork strictly as a replacement project; eliminating the scientific monitoring and analysis costs; and having fewer reporting requirements and associated costs.

The annual cost savings is estimated at $2,000,000 per year in avoided costs due to fewer accidents while handling refurbished aircraft engines and parts on this stretch of roadway. As estimated for the baseline technology scenario above, this assumption is based on avoiding one accident involving an aircraft engine (valued at $10 million) every 5 years. It is understood that there will still be the potential to incur handling accidents due to operator error and other factors. For the purpose of this calculation we assume that only those accidents that arise from road damage are eliminated.

4.2 ROI calculation

Using the OMB Circular A-94 [Ref. 11] in spreadsheet format (Table 5) and the above assumptions for the next 30 years, the projected ROI for this demonstration is 44.69.

The majority of the savings comes from cost avoidance due to the criticality of the road surface as it relates to sensitive equipment handling.

Table 5. ROI calculation.

Return on Investment Calculation

Investment Required	**580**
Return on Investment Ratio	**44.69** **Percent** **4469%**
Net Present Value of Costs and Benefits/Savings	**169** **26,090** **25,921**

A Future Year	B Baseline Costs	C Baseline Benefits/Savings	D New System Costs	E New System Benefits/Savings	F Present Value of Costs	G Present Value of Savings	H Total Present Value
1	450			2,000		2,290	2,290
2				2,000		1,747	1,747
3				2,000		1,633	1,633
4				2,000		1,526	1,526
5				2,000		1,426	1,426
6	450			2,000		1,632	1,632
7				2,000		1,245	1,245
8				2,000		1,164	1,164
9				2,000		1,088	1,088
10				2,000		1,017	1,017
11	450			2,000		1,164	1,164
12				2,000		888	888
13				2,000		830	830
14				2,000		776	776
15				2,000		725	725
16	450		500	2,000	169	830	660
17				2,000		633	633
18				2,000		592	592
19				2,000		553	553
20				2,000		517	517
21	450			2,000		592	592
22				2,000		451	451
23				2,000		422	422
24				2,000		394	394
25				2,000		368	368
26	450			2,000		422	422
27				2,000		322	322
28				2,000		301	301
29				2,000		281	281
30				2,000		263	263

5   Conclusions and Recommendations

5.1   Conclusions

No corrosion-rate measurements taken on bars installed in Crecy Street indicated any significant corrosion at the time of the measurement. At the measured rates, no corrosion damage is expected over the next thirty-plus years. This conclusion is based on the low level of chlorides at the time of measurement. Service life could be reduced as chlorides diffuse into the pavement and accelerate concrete deterioration. Because reinforcement steel is a relatively small component of total reinforced concrete project costs, the cost premium of vitreous-coated bars over epoxy-coated bars can be more than paid back over the life of the system using the methods practiced in this demonstration.

Measurements and observations showed more variation in results among rebars than desirable, indicating that some coating porosity and damage occurred during the coating and handling processes. These flaws result in more vulnerability to corrosion than would be expected when the fabrication and handling methods have matured.

5.2   Recommendations

5.2.1   Applicability

At this time, recommendation of the demonstrated technology must be accompanied with a significant caveat. At the time of this project, the coating process produced a result that was subject to flaking and coverage irregularities that might create corrosion sites on otherwise-protected bars. Therefore, prospective users should research the state of the market before specifying the technology. Additionally, users should inspect individual bars during installation for coating flaws that leave bare steel exposed. Nevertheless, the technology should be considered for applications where pavement degradation due to corrosion presents a high risk of equipment, vehicle, or financial loss, particularly in environments with high chloride content.

However, there are many other applications for which this technology could be considered for long-term cost savings. Of particular interest are precast sectional items such as beams, columns, and panels, which are typically fabricated indoors and under stricter tolerances, in conditions where

more care can be taken to avoid coating damage during handling. The calculated cost savings for such alternate applications may not be as high as projected for the demonstrated application, but concrete structural members using vitreous-coated rebar should have a service life significantly longer than those fabricated using bare steel or galvanized rebar.

5.2.2   Implementation

To facilitate awareness of this emerging corrosion-mitigation technology throughout the DoD civil engineering community, a description of it is recommended for incorporation into Unified Facilities Guide Specification UFGS 03 20 00.00 10, *Concrete Reinforcing* [Ref 12]. A new subsection on vitreous-coated rebar can be added to Section 2.3, "Reinforcing Steel," to include language pertaining to manufacturer quality control, acceptance testing on site, handling, and installation.

Vitreous coatings for steel reinforcement materials show promise for reinforced-concrete applications in severely corrosive environments where accelerated corrosion damage can lead to serious equipment damage and/or financial losses. However, broader DoD-wide implementation recommendations should be postponed until coating methods are shown to consistently produce more uniform steel-coverage results and long-term corrosion performance can be rigorously validated in a fully controlled, industry-accepted testing program.

5.2.3   Future work

Future development of this technology should seek to refine the coating process to reduce variations in porosity and substrate coverage. Also, to more rigorously validate corrosion performance and service-live projections, additional testing should be performed using significantly more aggressive chloride concentrations, and imposing tighter controls and chain of custody over test specimens. Rebar-pullout strength testing would also be recommended.

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Appendix: Test Block Observations

This appendix summarizes the findings of the ASTM G 109-07 (2007) block tests. As reported in sections 2.2.3 and 3.2.3, experimental control of the test specimens on the installation was temporarily interrupted and the blocks were damaged, so the results cannot be considered valid. The following observations are offered in the interest of completing documentation of the project.

AC resistance

AC resistance was measured between the top bar and the bottom bars in each test block using a Nilsson-400 Soil Resistance meter. The resistances for the epoxy-coated bars were relatively high, but not as high as typically measured. An epoxy-coated bar without any holidays or defects in the coating should have a resistance >100,000 Ω, such as that recorded on Test Block 6. The resistances for the uncoated black steel bars were low, <1,000 Ω, as expected. The resistances for the vitreous-coated bars averaged 1,260 Ω on 3 November 2009, 1,595 Ω on 29 April 2010, and 1,460 Ω on 30 August 2010. Although better than uncoated block bar, this relatively low resistance indicates a degree of porosity which can be expected to result in vulnerability to corrosion.

Corrosion potentials

Corrosion potentials were taken on the top bars in the test blocks by placing a portable SCE half-cell on top of the concrete over the bars. Potentials were measured on each test block about two hours after rewiring on 3 November 2009, and again on the morning of 4 November 2009, as shown in Table A1. Potentials taken on the test blocks on 29 April 2010 and on 30 August 2010 are shown in Table A2 and Table A3, respectively.

Table A1. Corrosion potentials on top bars
in ASTM G 109-07 test blocks, 4 November 2009, mV$_{SCE}$.

Epoxy coated			Vitreous coated			Uncoated		
Block	11/3/09	11/4/09	Block	11/3/09	11/4/09	Block	11/3/09	11/4/09
1.	-59	-147	8.	-80	-250	15.	-308	-455
2.	-69	-209	9.	-101	-206	16.	-266	-415
3.	-223	-261	10.	-69	-191	17.	-271	-395
4.	-166	-263	11.	-45	-170	18.	-149	-323
5.	-136	-240	12.	-103	-254	19.	-233	-442
6.	-12	-124	13.	-125	-270	20.	-304	-443
7.	-69	-221	14.	-267	-397			
Avg	-105	-209	Avg	-113	-248	Avg	-255	-412

Table A2. Corrosion potentials on top bars
in ASTM G 109-07 test blocks, 29 April 2009, mV$_{SCE}$.

Epoxy coated		Vitreous coated		Uncoated	
Block No.	mV vs. SCE	Block No.	mV vs. SCE	Block No.	mV vs. SCE
1.	+37	8.	-203	15.	-170
2.	+34	9.	-20	16.	-169
3.	-53	10.	-40	17.	-120
4.	-28	11.	+21	18.	-123
5.	-35	12.	-197	19.	-176
6.	-9	13.	-59	20.	-131
7.	-41	14.	-157		
Average	-14 mV	Average	-94 mV	Average	-148 mV

Table A3. Corrosion potentials on top bars
in ASTM G 109-07 test blocks, 10 August 2010, mV$_{SCE}$.

Epoxy coated		Vitreous coated		Uncoated	
Block No.	mV vs. SCE	Block No.	mV vs. SCE	Block No.	mV vs. SCE
1.	(broken wire)	8.	-80	15.	-206
2.	+36	9.	-20	16.	-245
3.	+6	10.	+4	17.	-255
4.	(broken wire)	11.	+36	18.	-75
5.	-3	12.	-157	19.	-36
6.	(broken wire)	13.	-45	20.	+22
7.	+8	14.	-6		
Average	+12 mV	Average	-38 mV	Average	-133 mV

Potentials taken in April and August 2010 were significantly less corrosive than those measured in November 2009, which might be attributable to test block dryness at the time of measurement. Data indicate little or no tendency for corrosion at the time of measurement for the epoxy-coated and vitreous-coated bars, and an uncertain state of corrosion for the uncoated bars.

Interior examination of test blocks

ASTM G 109-07 test blocks were split open on 30 August 2010, near the conclusion of the demonstration, to visually inspect interior rebar condition. Three blocks containing each type of bar were selected for examination. The top surface of the blocks were cut with a saw down to the top reinforcing bar. Then each block was split with a chisel to reveal the rebar trace. The results of the examinations are as follows:

- Test Block 1 (epoxy-coated bar): No rust
- Test Block 4 (epoxy-coated bar): No rust
- Test Block 6 (epoxy-coated bar): No rust
- Test Block 8 (vitreous-coated bar): Rust present on ~20% of rebar trace
- Test Block 12 (vitreous-coated bar): Rust present on ~10% of rebar trace
- Test Block 14 (vitreous-coated bar): Rust present on ~25% of rebar trace

- Test Block 15 (uncoated bar): Rust present on ~50% of rebar trace
- Test Block 18 (uncoated bar): Rust present on ~20% of rebar trace
- Test Block 20 (uncoated bar): Rust present on ~35% of rebar trace

Split blocks with epoxy-coated, vitreous-coated, and uncoated reinforcing bars are shown in Figure A1, Figure A2, and Figure A3, respectively.

Figure A1. Rebar trace of uncoated bar in Test Block 15.

Figure A2. Rebar trace of epoxy-coated bar in Test Block 4.

Figure A3. Rebar trace of vitreous-coated bar in Test Block 8.

In addition, test blocks containing uncoated bars had small corrosion cracks above the reinforcing bars near the ends of the blocks at the conclusion of the test. These cracks were caused by expansion of the bars from an

accumulation of corrosion products. An example of these corrosion cracks is shown in Figure A4. None of the other test blocks was cracked at the conclusion of the demonstration.

Figure A4. Corrosion crack above uncoated bar on Test Block 16.

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14. ABSTRACT

The Department of Defense (DoD) Corrosion Prevention and Control Program funded a project to evaluate the corrosion performance of a new vitreous reactive-silicate coating that can be bonded to steel reinforcement bars used in concrete structures. The technology was installed in pavement at Corpus Christi Army Depot (CCAD) where corrosion-induced concrete damage has contributed to costly accidents involving transport of aircraft engines. Test blocks designed and instrumented for accelerated corrosion testing were used to compare the performance of vitreous-coated bars with other types of bars. The vitreous-coated bars installed in CCAD pavement showed no sign of corrosion because atmospheric chlorides could not penetrate to reinforcement depth during the demonstration period. Test block custody was temporarily lost at the installation, during which time they were damaged and experimental controls were disrupted. When the blocks were split open for visual examination, the vitreous-coated samples had various amounts of surface corrosion on the bars and concrete traces.

An economic analysis using a conservative service-life assumption for vitreous-coated rebars projected a return on investment of 44.69 over 30 years versus materials and methods currently used at CCAD. The technology requires further refinements and testing before it could be recommended for DoD-wide implementation.

15. SUBJECT TERMS

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