Use of Vitreous-Ceramic Coatings on Reinforcing Steel for Pavements

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ABSTRACT

An innovative vitreous-ceramic coating for reinforcing steel that incorporates reactive calcium silicates from portland cement in an alkali-resistant glass has been shown both to increase the bond between the concrete to the reinforcing steel and to protect the steel from corrosion. The new enamel coating eliminates the weak layer that is associated with the interface between the steel and surrounding concrete. The vitreous coating is applied to the steel using the same process involved in porcelain enameling. In applying the enamel, the rod is coated with a porcelain slip containing portland cement and heated to approximately 1,562 °F (850 °C) for 5 to 10 minutes to allow the molten glass to fuse to the surface of the iron and the portland-cement component to become bonded to and embedded in the glass. The result is a tough, abrasion-resistant, hermetically-tight coating that develops the adhering properties of a portland-cement paste when contacted by fresh concrete.

Bleed water from the fresh concrete that normally produces a weak interfacial transition zone is taken up by the hydration of the surface layer of reactive calcium silicate. After only 7 days of curing, the chemical bond that forms is typically three to four times greater than that observed at the surface of undeformed, bare steel. The bond from the coated steel is as strong as the bonds between cement grains in the curing concrete. The lack of a weak interface results in the bond strength at the surface of the reinforcement increasing and not decreasing as the surrounding concrete cures and shrinks.

If microcracks develop in the coating, unreacted cement grains embedded in the glass coating will hydrate, forming calcium silicate hydrate gel, and raise the alkalinity. The self-healing effect in the glassy layer helps to protect the underlying steel.

In the construction of concrete pavement, the reactive, vitreous ceramic coating may permit shorter splices. The coating can also help insure that the shrinkage fractures that develop in pavement during curing remain within the desired tolerance limits. Since porcelain enamel does not delaminate, capillary transport under the coating does not occur. Porcelain enamels are considered the most durable and chemically-resistant coatings that can be put on steel. They can provide protection even in aggressive, high-chloride environments such as salt-treated pavement.

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INTRODUCTION

Steel reinforcement and connector elements have had a long history of development in concrete pavement. As concrete pavement designs changed from jointed plain concrete pavement (JPCP) to jointed reinforced concrete pavement (JRCP) and continuously reinforced concrete pavement (CRCP), the amount of steel reinforcement and the complexity of design has increased. JPCP used dowel and tie bars to transfer loads between individual slabs 12 to 20 ft (3.7 m to 6.1 m) long. JRCP used reinforcing steel within each slab to control cracking within longer slabs that ranged up to 50 ft (15 m) in length. CRCP uses reinforcing steel to replace the contraction joints, and while cracks typically appear every 3.5 to 8 ft (1.1 to 2.4 m), the openings are held closed by the embedded reinforcing steel. The closed cracks, with the aggregate surfaces engaged, can transfer the load with minimum bending stresses.[1-3] New developments such as the use of precast concrete panels for pavement repair and ultrathin CRCP require the use of ever more complex reinforcement system in concrete pavement[4,5]. The requirements for the steel and concrete are continuing to increase as demands for better roads and road maintenance increase.

The use of steel reinforcement in concrete pavement encounters two problems:

1. The concrete surrounding the reinforcement steel changes composition as the pavement ages. Reactions with carbon dioxide in the atmosphere lower the pH of the concrete and destroy the passive iron oxide coating at the surface of the steel that prevented corrosion. Infiltrating solutions carry chlorides from the surrounding soil or from deicing salt down to the steel–concrete interface and increase the speed of oxidation of the steel.

2. It is difficult to control bonding of concrete to steel. Where steel is used to limit the lateral movement and crack openings, the concrete should bond to the steel tightly. Where steel is used in expansion joints, the steel dowels should not bond to the surrounding concrete. While it is possible to reduce the bond with the concrete, improving the bonding has been only marginally successful. The development of ceramic bonding enamel is an effort to provide a new coupling layer for steel reinforcement.[6]

Steel reinforcement in concrete is subject to corrosion, as the natural carbonation of the surrounding concrete allows the pH to drop and the passive iron oxide layer on the steel is lost. When the reinforcement steel starts to corrode the combined volume of the steel and the iron oxides, the increasing volume of corrosion surrounding the metal will put the concrete in tension. The volume of iron oxide is six times greater than the volume of iron that is oxidized. Cracking can occur when as little as 6 percent (by mass) of the steel has been corroded.[7] The concrete over the reinforcement will crack and spall, eventually putting the pavement in a distressed condition. The problems with corroding steel embedded in concrete are present whether the steel is rebar, metal support chairs, steel fiber, or dowels. The presence of chlorides from the soil or from deicing salts, greatly accelerates the corrosion rates. Corrosion problems in paving are most obvious in reinforced concrete bridge decks, where the surface freezing conditions require frequent application of deicing salts, but on-grade paving is also vulnerable.

Reinforcing steel typically has a relatively weak chemical bond to the contacting concrete. While other composite materials like fiberglass have a strong bond from the matrix to the reinforcement, in reinforced concrete comparable strong chemical bonds are not normally achieved. Deformed steel rod is typically used to obtain mechanical anchoring, but the limitations of this approach show up when it is necessary to determine the overlap requirements for splicing rebar and the embedments required for anchoring rebar. Specifications can call for up to 45-rod diameters overlap in each splice (34 in. or 0.8 m for #6 rebar).[8] When organic polymer-coated reinforcement is used, longer overlaps are required.

Of all of the surface coatings applied to steel, silica and alumina oxide coatings are the most versatile in their methods of application (wet frit, electrostatic powder, plasma, etc.), and they can be engineered to produce excellent chemical inertness and mechanical properties. The mixed glass and ceramic coatings have been shown to have the best adherence and the best wear resistance of all the oxides. Porcelain enamel or vitreous enamel in industrial applications is a specially formulated durable glass that is fused to metal under high temperatures typically ranging from 1,100 to 1,600 °F (595 to 870 °C). The enameling process forms a layer at the interface that merges the chemical makeup of the glass and the underlying metal. The bond has many characteristics of a chemical bond and also maintains a mechanical bond due to the lower coefficient of expansion of the glass, which keeps it in a state of compression. Bond strength of 10,000 to 12,000 lbf/in^2 (69 to 82 MPa) can be obtained between steel and enamel.[9]

Vitreous enamel typically has hardness in the range of 3.5 to 6 on the Mohs scale of mineral hardness, where organic coatings are in the range of 2 to 3. Porcelain enamels can generally be engineered to produce abrasion resistance greater than the underlying metal. Generally, porcelain enamel will not fracture due to impact unless the underlying metal is permanently deformed. Porcelain coatings do not creep, and moisture generally will not penetrate under porcelain enamel.[10]

The reactive silicates in portland cement are a complex mixture and typically fuse at a temperature of 2,550 °F (1,400 °C). Firing the mixture of crystalline and glass compounds in portland cement into an enamel surface would not be expected to alter the composition of the silicates or aluminates except where the lower melting enameling glass can act as a solvent and adhere to the surface of the cement grains to form a bond.[11]

Lab-scale investigations with steel reinforcement were undertaken to demonstrate the bond strengths that can be obtained and investigate the effectiveness of the blended reactive silicate enamel in protecting steel reinforcement.

EVALUATION OF BONDING PROPERTIES

The procedure for preparing test specimens used in this investigation has been presented in detail in an earlier report and follows conventional enameling techniques[7]. Test specimens were mild steel (ASTM C 1018) rods, 0.25 in. (6.35 mm) in diameter, cut to be 3 in. (76.2 mm) long. One end of the rod was threaded to allow it to be attached to the test apparatus. The rods were embedded in mortar to a depth of 3.5 in. (63.5 mm). The rods were furnished with a smooth, glass bead-blasted surface. The surfaces were further prepared for enameling using a grit polishing and water-based cleaning technique.

The composition of the glass frit for use on steel can vary with the manufacturer. In this study, the manufacturer was asked to furnish an alkali-resistant frit that would be a suitable groundcoat for a two-firing application. Most alkali-resistant frits are similar to conventional groundcoat enamels, but contain 4 to 6 percent zirconium oxide by weight. The good performance of zirconium glasses in high-alkaline environments is believed to be due to the relatively low solubility of Zr–O–Zr species. In some applications, titania may be added to further improve the durability of the glass.[12] In some applications, for alkali-resistant glasses used in concrete, up to 13 percent zirconium oxide has been recommended.[13]

Porcelain enamels can be applied by making a slurry of frit and clay with water containing the necessary surfactants and suspending agents to achieve a stable suspension and the desired wettability and viscosity. The slip preparation used was PEMCO 06R-407 B-3 (PEMCO Corporation, Leesburg, Alabama). The test rods were coated by dipping the cleaned metal into the slip and letting the coating dry.

The porcelain enamel coating was fired onto steel at temperatures from 745 to 850 °C. Firing times were typically from 2 to 10 minutes, depending on the mass of metal to be heated and the size of the furnace. No attempt was made to obtain an even or smooth coating as would normally be the case for porcelain enamels for appliances, bathtubs, etc. (Figure 1). The enamel coatings had an average thickness of 0.8 mm.

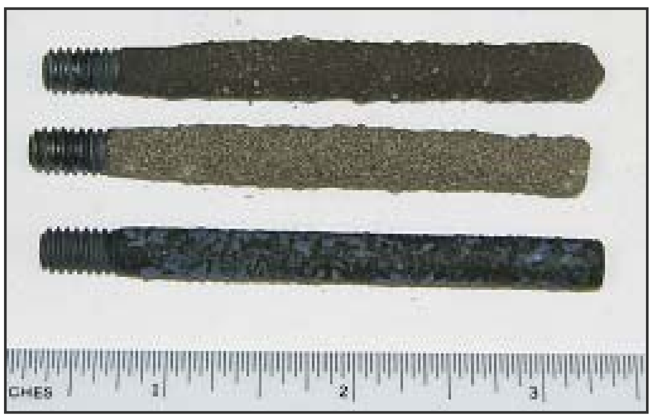

Figure 1. Examples of test rods prepared with various samples of glass frits with an outer coating of portland cement applied to the melted glass.

The enameled test rods were embedded in a mortar prepared using the guidelines presented in ASTM C 109, “Standard Method for Determining Compressive Strength of Hydraulic Mortars.” Test cylinders were prepared for each mortar batch and tested to verify the unconfined compressive strength at 7 days was within the limits recognized for this mixture design.

Each enameled test rod was inserted in a long cylinder mold, 2-in. (50.8-mm) in diameter, 4 in. (101.6 mm) long, filled with fresh mortar. The rod was clamped at the top so that a 2.5-in. (63.5-mm) length of the coated portion of the rod extended into the mortar. Each cylinder was tapped and vibrated to remove entrapped air and consolidate the mortar. The samples were placed in a 100 percent humidity cabinet at 77 °F (25 °C) and cured for 7 days. After 7 days, the test cylinders were demolded, mounted in the test apparatus, and the force required to pull the rod out of the mortar was measured using an MTS Model 810 testing machine.

The results of the pull-out testing for coated and uncoated rods are presented in Table 1. Each series of test rods were prepared and tested in triplicate. The results are presented as the average value and the standard deviation. The average bond strength is calculated as the force for pull-out distributed across the area of the metal-enamel interface.

Table 1
Comparison of Average Bond Strengths

Treatment	Average Peak Force lbf (N)	Std. Deviation lbf (N)	Average Bond Strength lbf/in^2 (MPa)
Steel fiber embedded in mortar (various published sources)	---	---	295.4-394.5 (2.0-2.7)
Steel rods, uncoated embedded in mortar	588.7 (2,618.2)	104.8 (466.2)	298.8 (2.1)
Enameled rods without portland cement embedded in mortar	786.4 (3,497.9)	121.6 (540.8)	391.6 (2.7)
Steel rods, uncoated, surface roughened by grit blasting (reported by PPEC)	--	--	595 (4.1)
Enameled rods with portland cement (acid surface preparation reported by PPEC)	--	--	797 (5.5)
Rods with enamel containing portland cement embedded in mortar	2,500.9 (11,124.6)	52.9 (235.3)	1,274.9(8.8)

INVESTIGATION OF CORROSION PROTECTION

The examination of corrosion phenomena in the bare rods, enameled rods, and enameled rods with the portland cement addition was done by exposing sets of three identically prepared rods to a 3 percent sodium chloride solution in partly saturated sand (Figure 3). The goal of the testing was to provide conditions that would promote the mode of corrosion that would occur in carbonated (nonalkaline) portland-cement concrete that was contaminated with chloride. The pH of the wet, drained sand ranged from 6.0 to 6.5, and the temperature was maintained at 77 °F (25 °C). Because of the typically high electrical resistance of the enamel, corrosion will only occur if a hole is made in the enamel that exposes the metal surface. Vitreous enamel typically has a volume resistivity of 1×10^{14} ohm·cm; therefore, intact enamel surface is an insulator. Defects were prepared in each of the coated rods. All of the enameled rods were tested using the procedure outlined in ASTM C 876 and showed potentials more negative than -0.35 copper sulfate electrode (CSE) indicating that corrosion was occurring. The test rods were examined and photographed after 72 hours of salt water exposure and again after 40 days of exposure.

Examination of the test rods that were embedded in the salt water–sand mixture showed that, as expected, the enameled surfaces showed no detectable changes and the cleaned bare steel rods had begun to oxidize after 72 hours of exposure. Polished sections of rod surfaces after exposure are shown in figures 2 and 3. Note that the rods with enamel-only coating, in Figure 2, show the opaque particles that are in the slip and become part of the enamel during firing. The larger particles in Figure 3 are the portland cement particles that were fired into the surface of the enamel.

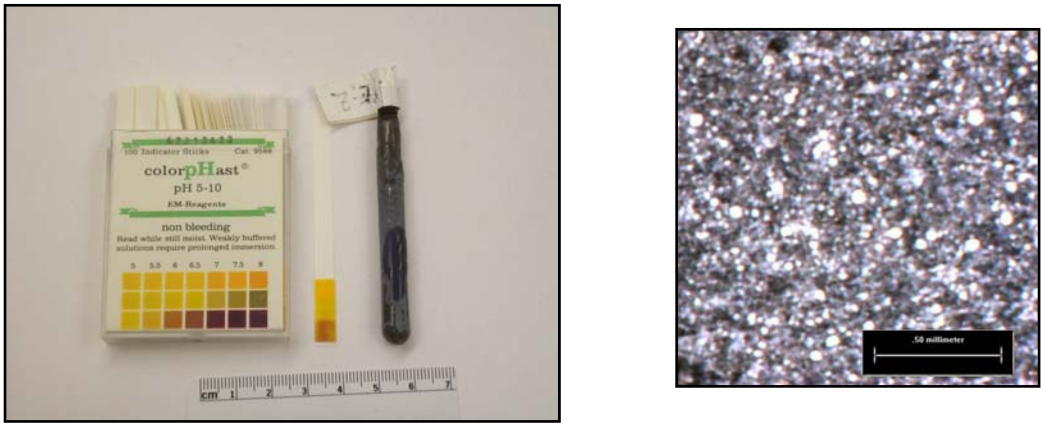

Figure 2. Enameled test rod (left) and polished section of side of rod after exposure (right). The moist pH test strip applied to the surface showed the pH of the abraded surface to be approximately 6.5.

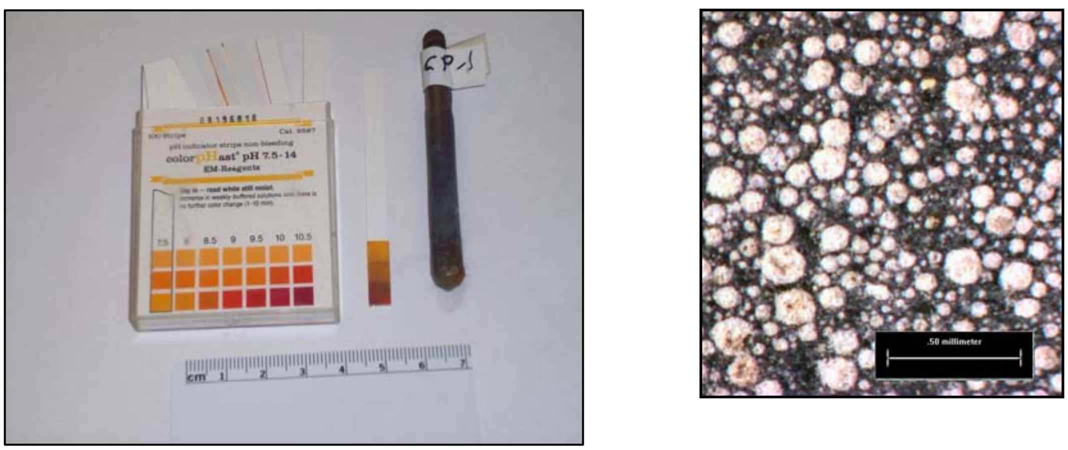

Figure 3. Enameled test rod with portland cement embedded in the glass (left) and polished section of side of rod after exposure (right). The moist pH test strip applied to the surface showed the pH of the abraded surface was approximately 10.5.

Examples of the effect on a bare steel rod and an enameled rod after 40 days exposure is shown in figures 4 and 5. Active corrosion was noted where steel was exposed to the salt-water saturated sand (left), and the build-up of iron oxide cemented the adjacent quartz sand to the surfaces of the bare steel rods (Figure 4). Enamel rods both with and without the portland cement addition showed no active corrosion where the enamel was present to protect the steel. Enamel does not debond, and studies with intentionally created defects that exposed the surface of the steel resulted in only local limited occurrence of corrosion. Figure 6 shows an optical photomicrograph of a polished section through an enameled test rod that had been drilled to remove the enamel. Note that the enamel does not delaminate or allow capillary transfer of fluids under the enamel.

Figure 4. Corrosion on bare steel surface (left) and on enameled steel after 40 days of exposure in salt-water saturated sand. The corrosion of the bare steel cemented sand to the rod.

Figure 6. Exhibition of evident corrosion of bare steel surface (left) and not evident on enameled steel containing portland cement after 40 days of exposure in salt-water saturated sand. The corrosion of the bare steel cemented sand to the rod. A powdery, alkaline deposit formed from the hydration of the exposed portland cement.

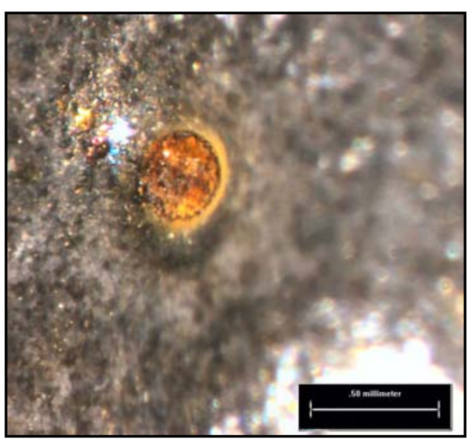

Figure 6. Optical photomicrograph of the edge of a hole drilled in the enamel to expose underlying metal. Rod sample was exposed to 3.5 percent NaCl solution for 40 days to produce corrosion. The enamel does not debond or allow capillary transfer of salt solutions.

Portland cement bonded to the surface of the enamel hydrates when the coating contacts fresh cement, but unhydrated cement grains are embedded deeper in the enamel. If the enamel is cracked, the exposed grains will hydrate on contact with infiltrating moisture. The calcium silicate hydrate gel formed by the hydration reaction fills the crack and produces a self-healing effect. Figure 7 shows a cracked enamel surface that has been partly wetted to produce open and filled fractures.

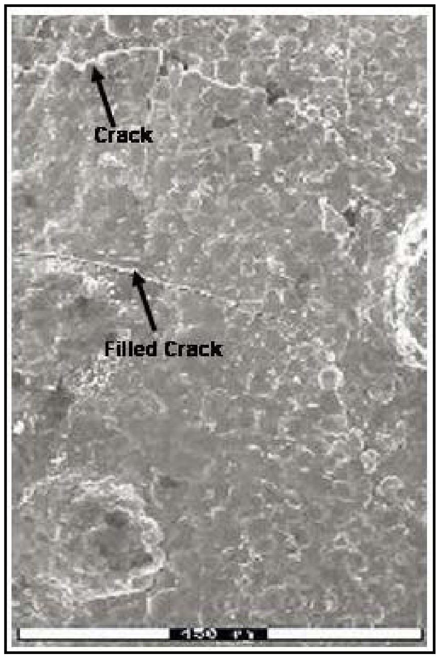

Figure 7. Surface of enameled metal wire bent to produce fractures and partly wetted to produce examples of open and filled fractures. The reacted cement on the surface produces the irregular surface texture.

SUMMARY

The investigation of steel reinforcement with bare steel, enameled steel, and enamel steel with embedded portland cement has shown the following:

1. The bond between the surface of reinforcing steel and concrete can be significantly increased by using a hydraulically reactive silicate fused into a layer of vitreous enamel fired onto the steel. The bond strength is increased by a factor of over three times over that developed with bare steel or with vitreous enamel only.

2. An intact coating of vitreous enamel or glass-ceramic composite coating can prevent corrosion of the underlying steel when conditions in the surrounding mortar or concrete would normally promote oxidation.

3. Enamel coating will corrode if the enamel is removed, but the corrosion is limited to the exposed metal and delamination and capillary effects were not observed.

4. The cement embedded in the enamel hydrates when exposed to water and controls the pH on the surface of the coated metal. Potentially, cracks in the ceramic-glass composite can maintain an elevated pH and inhibit the corrosion of any exposed steel.

5. Vitreous enamel application is a mature technology, and potentially glass-ceramic coatings can be used to protect and improve the performance of any steel reinforcement element used in concrete pavement including steel fiber, bar, welded mesh, and dowels.

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