INNOVATIVE APPROACHES TO IMPROVING THE BOND BETWEEN CONCRETE AND STEEL SURFACES

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ABSTRACT

A reactive silicate layer fused onto the surface of reinforcing steel provides a coupling layer that allows a very strong bond to develop between hydrating Portland cement paste and the surface of the steel. The reactive layer eliminates the problem of a weak, low-density hydrated, layer of paste forming on the surface of the steel. Steel enameling techniques are used to bond a low-melting point glass frit onto the steel. A high melting point hydraulically reactive silicate (such as Portland cement) embedded in the bonded glass reacts with the surrounding paste and the paste adheres strongly to the coupling layer. Bench-scale pull-out tests show that the bond can be up to four times that observed with uncoated rods. The porcelain-based coating can potentially provide protection from corrosion for the coated reinforcing elements.

1. INTRODUCTION

1.1 Conventional Concrete-to-Steel Bond

Steel has been used to reinforce concrete on many levels; steel bar, fiber and corrugated sheets. Investigations of the interface between the surface of the steel and the surrounding cement paste have shown that a transition zone is produced during the hardening of the cement paste. Investigators have reported that the interface between concrete and the steel surface is influenced by the bleeding and entrapment of water against the surface of the steel and the less compact arrangement of the small cement particles (average diameter of approximately 10 µm) in the 20 to 40 µm layer adjacent to the fiber surface (Al Khalaf and Page, 1979; and Bentur et al. 1985a). In the case of steel fiber the fiber surface is often observed to be covered by a discontinuous platy layer of calcium hydroxide (Bentur et al. 1985b). The weakest zone at the paste-steel interface is reported to be associated with the porous paste zone that is 10 to 40 µm from the actual fiber surface (Wei et al., 1986). Even when a hard paste can be produced around steel, the phases at the interface are usually ferrous and ferric hydroxides that are not tightly bonded to the silicate gel in the paste (Mazkewitsch and Jaworski, 1986). Without a coupling compound on reinforcing steel, the best bonding mechanism that can be postulated is the production of an electrical double layer at the contact of the paste and the steel. Calcium, aluminum and silicon couple by electrical charges across the interface with hydroxide ions on the surface of the steel and iron atoms couple with unbalanced oxygen atoms in the paste (Mazkewitsch and Jaworski, 1986). Mlodecki (1986) describes the bond between the iron atom and a hydroxyl groups in the cement paste as a form of hydrogen bonding with the hydroxyl ion coupling with the pair of electrons that are held in the outer fourth orbit of the iron atom. It can be concluded that the bond at the steel-cement paste interface is a much lower energy bond than bonds in either adjoining phase.

1.2 Reactive Enamel Bonding Layer

The weak bonding at the steel-concrete interface can be overcome by coating the surface of the steel with a porcelain enamel that incorporates reactive calcium silicate phases that can act as a bonding layer. Steel enameling techniques are used to bond a low-melting point glass (MP = 745 to 825 ºC) onto the steel, a high melting point hydraulically reactive silicate (such as Portland cement) embedded in the bonded glass reacts with the surrounding paste and the paste adheres strongly to the coupling layer.

Enamel frits developed for application on steel can contain 10 to 15 components that control the melting point, bond strength, relative thermal expansion, fluidity, and color of the glass that adheres to the surface of the steel (American Society for Metals, 1995). By adding high melting point, partially crystalline/partially glassy calcium silicates developed in Portland cement (di- and tri-calcium silicates, calcium aluminates) and firing the mixture onto the surface of the reinforcing steel a layer that can bond strongly with the surrounding paste is developed.

The most suitable frits for use as a coupling layer are glasses developed for undercoating over mild steel. Critical components, especially cobalt and nickel, in the frit assure that the iron oxide on the surface of the steel will migrated into the enamel to form a tight chemical bond. The relative thermal expansion of the glass is designed to put the hardened glass layer into compression as the coated metal cools. The compressed inside surface of the glass layer is also mechanically locked into the irregularities on the metal surface (Danielson and Wolfram, 2003).

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 NOV 2006**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE
Innovative Approaches To Improving The Bond Between Concrete And Steel Surfaces

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
USAE Engineer Research and Development Center, Vicksburg, MS 39180

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002075., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**4**	

2. METHODS AND MATERIALS

Test specimens consisted of 6.35-mm diameter mild steel (C1018) rods cut to be 76.2 mm in length. One end of the rod was threaded to allow it to be attached to the test apparatus. The length of the rod permitted it to be embedded in mortar to a depth of 63.5 mm. The rods were furnished by the manufacturer (Alabama Specialty Products, Munford, AL) with a smooth, glass bead-blasted surface.

2.1 Preparation of Metal and Selection of Frit

The test rod surfaces were prepared for groundcoat enameling using an alkaline cleaning process followed by washing with distilled water and wiping with alcohol. The composition of the glass frit applied to the test rods varied with the manufacturer and the exact composition of most formulations is proprietary. In all cases the manufacturer was asked to furnish an alkali-resistant formulation that would be a suitable groundcoat for a two-firing application. The composition for a typical glass frit prepared for this application is given in Table 1.

Table 1. Composition Range of a Typical Alkali-resistant Groundcoat Enamel for Steel (American Society for Metals, 1995)

Constituent	Amount (%)	
Silicon dioxide SiO_2	42.02	40 - 45
Boron oxide B_2O_3	18.41	16 - 20
Sodium oxide Na_2O	15.05	15 - 18
Potassium oxide K_2O	2.71	2 - 4
Lithium oxide Li_2O	1.06	1 - 2
Calcium oxide CaO	4.47	3 - 5
Aluminum oxide Al_2O_3	4.38	3 - 5
Zirconium oxide ZrO_2	5.04	4 - 6
Copper oxide CuO	0.07	nil
Manganese dioxide MnO_2	1.39	1 - 2
Ni oxide NiO	1.04	1 - 2
Cobalt Oxide Co_3O_4	0.93	.5 – 1.5
Phosphorus Oxide P_2O_5	0.68	.5 - 1
Fluorine F_2	2.75	2 – 3.5

2.2 Application of Frit

Porcelain enamels can be applied by making a slurry of frit and thickeners with water containing the surfactants necessary to achieve the desired suspension and viscosity. The test rods were coated by dipping or flow coating the slurry onto the surface. Where Portland cement (Type I-II or Class H) and frit were fired in a two-step process, the groundcoat enamel was fired and the Portland cement was applied immediately after the test rod was taken from the furnace. The rod would then be fired briefly for a second time to fix the Portland cement to the groundcoat. When one-step applications were made, the Portland cement was mixed in a 50% proportion by volume with the frit. The cement was added to the porcelain enamel slurry and applied to the rod surface.

2.3 Firing of the Frit

The porcelain enamel coating was fired onto steel at temperatures from 745 to 850 °C. Firing times were typically from 2 to 8 minutes depending on the mass of metal to be heated and the size of the furnace. The goal was to produce a thick groundcoat enamel with the cement embedded in the surface of the groundcoat. No attempt was made to obtain an even or smooth coating (Fig. 1).

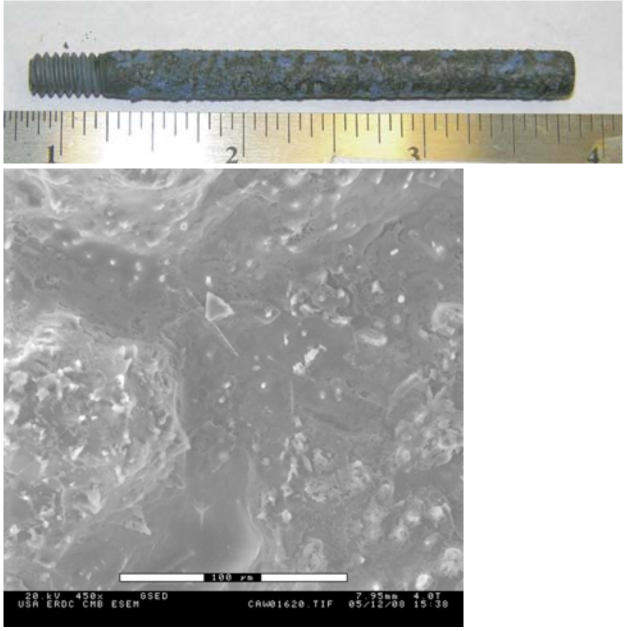

Fig. 1. Example of test rod (upper photo) prepared by firing on glass frit adding cement and firing a second time. Note the rough irregular surface on sample due to the incorporation of the Portland cement grains in the melted glass (lower photomicorgraph).

2.4 Preparation of Test Mortar

The enameled test rods were embedded in a mortar prepared using the guidelines presented in ASTM C109, Standard Method for Determining Compressive Strength of Hydraulic Mortars (ASTM, 2001). The proportion of the standard mortar was one part cement (Type I-II) to 2.75 parts of standard graded sand. The water-to-cement ratio was maintained at 0.485. Test cylinders were prepared for each mortar batch and tested to determine the unconfined compressive strength at 7 days was within the limits recognized for this mixture design (Kosmatka and Panarese, 1990).

2.5 Preparation and Testing of Embedded Rods

Each enameled test rod was inserted in a 50.8-mm in diameter, 101.6-mm long cylinder mold filled with fresh mortar. The rod was clamped at the top so that a 63.5-mm length of the coated portion of the rod was under the mortar. Each cylinder was tapped and vibrated to remove entrapped air and consolidate the mortar. All samples were prepared as triplicates. The samples were placed in a 100% humidity cabinet at 25 °C and cured for 7 days. After 7 days, the test cylinders were de-molded and then mounted in the test apparatus and the force required to lift the rod out of the mortar was measured using an MTS Testing Machine Model 810 (Material Testing Systems, Eden Prairie, MN).

3. RESULTS

Table 2 summarizes the results of the pull-out testing for coated and uncoated (control) rods. Data from each series of test rods are presented as the average value and the standard deviation for the three replicates.

The bond between the concrete and steel in the uncoated control rods on an average failed at 584 pounds force (lbf). The glass enameled rods showed bond strengths that were similar to those of uncoated rods. The rods enameled with the mixtures of glass and Portland cement required three to four times the force (1755 lbf to 2483 lbf) used to break the bonds between the concrete and steel on the uncoated rods.

Failure surfaces on the rods with the composite glass frit-Portland cement coating showed failures at both the glass-metal interface and inside the surrounding concrete (Fig. 2). Where the failure occurred on the surface of the metal; small metal fragments pulled from the surface of the test rod could be observed on the glass adhering to the concrete.

Fig. 2. Mortar cylinder split after testing to show the surface of the glass adhering to the hardened mortar and the clean surface of the metal test rod. Examination of the surface of the glass showed fragments of metal embedded in the glass.

One sample enameled using the mixed glass-Portland cement frit (FL enamel) came out of the pull-out test with the rod stretched, indicating the bond strength was approaching the limit at which it could be reliably measured using this test protocol. Comparable results were noted on a sample prepared using the mixed glass-Portland cement frit (FD enamel) where the test rod failed at the first screw thread at the top of the rod. The coarser ground cement (Class H) produced weaker bonding that the finer-ground cement (Type I-II) after the same 7-day curing time.

Table 2. Results of Pull-Out Tests of Uncoated and Enameled Rods

Sample	Firing	Average Peak Force Required (lbf)	Std. Deviation (lbf)	Location of Failure Surface	Remarks
Control (uncoated)	--	584.4	104.1	Metal surface	
Enameled w/o Portland Cement	Single	581.1	116.0	Enamel surface	
Enameled w/Type I-II cement (T enamel)	Twice	1754.7	281.0	Metal surface	
Enameled w/Portland Cement (FL enamel)	Single	2034.9	369.0	Metal surface and mortar	One rod stretched
Enameled w/Portland Cement (FD enamel)	Single	2483.2	52.5	Metal surface and mortar	One rod broke under tension
Enameled w/Class H cement (P enamel)	Single	1526	173.0	Metal surface and mortar	Coarse ground slow setting cement

CONCLUSIONS

The results of this investigation have indicated that:

1) A composite enamel composed of a hydraulically reactive component such as found in Portland cement and a commercial enameling fit can produce a coating that can significant improves the ability of metal to bond to mortar or concrete.
2) A conventionally formulated glass-only enamel applied to steel produced a bond strength in mortar that was comparable to that developed by uncoated steel.
3) Fine-ground, rapidly hydrating cements develop higher 7-day bond strengths than the coarser-ground cement tested.
4) Reactive enamels (enamels containing a hydraulically reactive component) can potentially be used on a variety of steel reinforcement materials (rebar, fiber and steel sheet metal) to improve the bond from concrete to steel and further studies may demonstrate the enamel provides corrosion protection.

ACKNOWLEDGMENTS

This investigation was undertaken as part of Basic Research Program conducted under Work Unit AT22, Task AR011. The authors wish to acknowledge the assistance of Dr. W. Allen Roberson, Chief of the Concrete and Materials Branch, USAE ERDC.

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