Technical Advances in Reactive Vitreous Enamels for Reinforcing Steel in Concrete Structures

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Abstract
This paper reviews the recent progress in the commercialization efforts for this new reactive vitreous enamel technology for reinforcing steel in concrete structures. Development of optimized manufacturing methods is leading to competitive products. Improvements in corrosion resistance and structural performance are discussed with the data from demonstration projects. Additional market opportunities and potential products for future commercialization are also reviewed.

Background

Infrastructure and buildings can benefit from reduced corrosion of reinforcing steel in concrete for a number of reasons including; extended service life, structural continuity and life-cycle costs. A reactive vitreous enamel coating for reinforcing steel in concrete was developed by ERDC (U S Army Corps of Engineers) in Vicksburg, MS about 6 years ago.

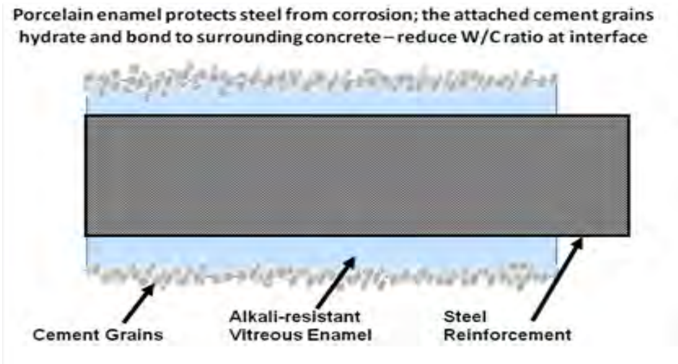
Since its invention in the late 1800's, steel-reinforced concrete has been a widely used and highly valuable building material; new designs and applications continue to arise. Reinforced concrete structures combine the tensile or bendable strength of metal and the compression strength of concrete to withstand heavy loads. Steel embedded in concrete typically develops a weak bond between the surface of the steel and the surrounding hydrated cement paste as bleed water from the cement paste accumulates at the surface of the reinforcing steel. Cement paste does not form a chemical bond with the underlying steel and the water-rich paste immediately adjacent to the steel is typically weaker than the average paste in the mass of concrete.

The difficulty in developing strong bonding for steel reinforcement in concrete can be related to the complex nature of the cement paste and the lack of bonding layer that will perform as a coupling surface. Hydrating portland cement paste is largely a mixture of calcium hydroxide, calcium carbonate, and calcium alumino-sulfate crystals in a calcium silicate hydrate gel. Over 20 chemical compounds are thought to form during the hardening of cement pastes. Investigations undertaken with steel reinforcement in conventional concrete indicate that soft crystals of calcium hydroxide are the most common material noted at the steel surface. A dense calcium silicate hydrate phase typically does not form at the surface of steel

reinforcement unless the composition of the concrete is altered to prevent segregation of the concrete at the iron-paste interface. 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. Modifications of the composition of the concrete and treatments of the steel surface to increase the strength of the bond have been only moderately successful. For example, the addition of methylcellulose to the concrete and the application of sodium silicate to the steel surface produced only a slight increase in bond strength and often the variation in bond strength has scatter that masks the modest effects of surface treatments.
Without a bonding layer on reinforcing steel, the best adhesion 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. Mlodecki 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 4th 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.

The strength of reinforced concrete is also compromised by the eventual corrosion of the steel embedded in the concrete. As the carbon dioxide from the air diffuses into the concrete it neutralizes the alkalinity of the concrete around the steel; the passive coating protecting the steel is destroyed and the steel corrodes. The corrosion products take up a larger volume than the metal and the expansion puts the surrounding concrete in tension and produces cracking. The corrosion problem is accelerated by the presence of chloride ions that can infiltrate into the concrete from sources such as road salt or sea water. Chlorides may also be present in the concrete due to contamination of materials used to proportion the concrete.

Modifying the surface of the steel to reduce the likelihood of corrosion by plating or polymer coating the steel does nothing to improve the bond strength. Galvanizing or epoxy coating may actually reduce the bond strength.



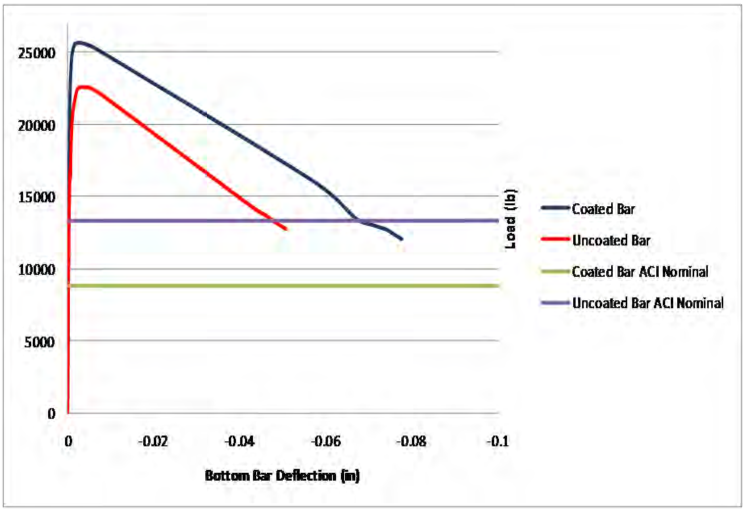
This present study examines effects that can be produced by fusing a porcelain enamel to a reinforcing steel surface prior to embedding the steel in a wet concrete structure. This new approach is different from previous coating technology in that porcelain enameling can firmly bond a reactive silicate phase to the steel and develop an outer layer of cement grains capable of bonding to the surrounding hydrating cement paste. The schematic above shows the glass coating on the steel and the portland cement grains attached to the glass, which are available to hydrate and bond with the concrete structure when it is poured.

Current Initiatives and Results

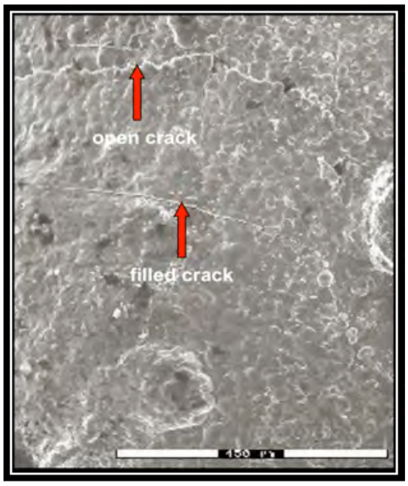
Our focus today is in producing and testing reactive vitreous enameled parts as follows; steel reinforcing bar (rebar), wall ties & anchors, steel fiber and steel sheet. Progress in each area will be reviewed in detail

Rebar – The picture below shows porcelain enamel coated rebar samples prior to some of the testing that has been performed. For reactive vitreous enameled rebar there have been two studies completed in the past 2 years. One study was conducted by the University of Louisville, Department of Structural Engineering in cooperation with several PEI members, SQM North America, Ferro Corporation, Porcelain Industries, Inc., KMI Systems, Inc. and EIC Group. The other work was by the Missouri University of Science and Technology in cooperation with Pro-Perma Engineered Coatings LLC who has licensed the patented coating to make the samples for testing. Both studies involved testing of ¾ inch diameter rebar under a number of conditions plus the construction of a test strip of 14,440 square feet of roadway at the Corpus Christi Army Depot in Texas. While there are no published results yet from the roadway there is data from laboratory testing.

The great news is that this reactive coating exhibits an increase in the strength of the reinforced concrete structure in comparison with uncoated or epoxy coated rebar. Results of ASTM A994 testing show great improvement in the pullout force as follows; P/E coated rebar 26.1 kips and uncoated rebar 22.7 kips with epoxy coated rebar rated at 15.1 kips. The data predict a reduction in required embedment length with P/E coated rebar requiring 15% less than uncoated rebar and about 60% less than epoxy coated rebar. For corrosion performance testing in a modified ASTM C867 test (which employs a 3.5 % NaCl solution at 20˚C for 40 days) we observed no corrosion for P/E coated bars while the uncoated bars showed significant corrosion. In addition, when the Porcelain Enamel coating was deliberately chipped, local corrosion occurred but corrosion did not undercut any of the porcelain enamel coating (i.e. there was no delamination) around the chip.

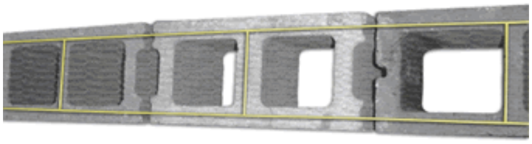


The data generated shows the reduction in development length and bar overlap requirements for reinforced concrete structures: these data allow us to market/promote/sell the technology based on better performance and lower costs of reinforcing steel in comparison with other types of rebar – uncoated (raw steel), epoxy coated, galvanized, metal clad, etc. In addition, supporting ancillary tests will enable the determination of the metallurgical effects of the porcelain enameling process heat treatment (firing) of the steel in terms of any specific changes in stress/strain performance or loss of yield strength. These tests will also allow evaluation of the performance of the coating and its adherence to the steel when the metal is strained; at what level of strain does the coating crack and/or separate from the metal. It has been postulated that low strain levels will only produce "micro-cracking" which will be subsequently filled by the internally distributed portland cement grains as they hydrate – the hydrated portland cement will fill these micro-cracks and thus seal them. Scanning electron microscopy (see picture) is being used to investigate these self-healing effects of the C_3S - porcelain enamel composites.



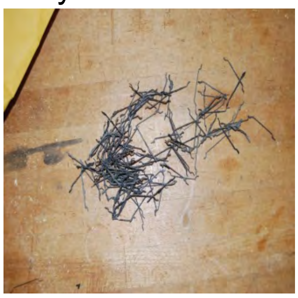
Embedded cement grains hydrate forming calcium silicate gel in fractures

These studies are leading to the accumulation of data and information needed by the building code and infrastructure authorities to start the process necessary to modify their structural equations and calculations to account for the structural performance of the reactive porcelain enamel coated reinforcing steel – helping us achieve our objective of building code approval.



Wall Ties and Anchors – This type of product is the fastest to the marketplace opportunity for our porcelain enameling industry since these are parts that can and would be made is manufacturing processes very similar to what we currently are producing. In the construction industry these products are often called "appliances" and they are used to connect and stabilize the connections of one surfaces or structure to another. For example; joint reinforcement between layers of concrete block, ties to connect brick veneer walls to the interior concrete block wall, ties to connect stud walls to brick or concrete block walls or anchors in floors to connect to walls. All of these types of construction, although designed to drain water away, experience a significant flow of water that contacts the wall ties – rusting and loss of structural integrity is a real problem. In all of these cases the dual advantages of the corrosion protection and the improved steel-to-concrete bond of the reactive porcelain enamel coated reinforcing steel improves the performance of these products and lengthens the life of the structures.

Steel Fiber – Steel, Nylon, polypropylene and other organics are used in many construction projects. Although the use of fiber reinforcement in poured concrete slabs is not a new technology, it has only seen limited success since the fibers do not actually bond to the concrete structure. Thus, when stressed, the fiber pulls out rather than deforming so cracks are not stopped on this micro level and they continue on to catastrophic failure. Steel fibers are also problematic since they cannot remain near the finished concrete surface due to rusting problems. The opportunity which is currently under investigation at the University of Louisville is a reactive porcelain enamel coated fiber to solve the rusting problems and improve the structural engineering performance of the fiber so it will deform when stressed and stop cracking. Once successful, these porcelain enamel coated fibers will stop virtually all cracking in pre-cast pipe, beams and structures plus all slab-on-grade concrete for floors, parking lots, driveways, etc.



Steel Sheet – There is a need in the marketplace to provide a moisture and radon gas barrier for concrete floors. A real solution will be porcelain enameled steel sheet which can be placed within the concrete floor to provide a barrier to the penetration of liquids and gasses. Again the corrosion protection and the structural bond of the steel to the concrete will be significant advantages for the use of porcelain enamel coated steel in this application.

Future Activity

PEI members who supply frit or equipment plus our enamelers all have expertise to further the performance of reactive P/E coated reinforcing steel for concrete. There is work to be done on: 1) enamel chemistries to achieve even better fired adherence to the steel, 2) more efficient coating application processes and 3) development of new heat treatment methods. PEI, including our material suppliers and our porcelain enamelers, sees a large number of potential steel products that can benefit from this reactive porcelain enamel technology.

This is the most exciting new technology and opportunity to come along for the porcelain enamel industry in recent years. PEI and many of our member companies are fully committed to doing all we can to further the development and commercialization of this technology. We have been actively involved in additional development and the publication of numerous technical papers. For anyone with questions, comments, suggestions or a desire to become involved, please contact the PEI office at (+1 770-676-9366) or on the web at (www.porelainenamel.com) – you can also contact any of our member companies.

Acknowledgements

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