FINAL REPORT

TESTING OF SELECTED METALLIC REINFORCING BARS FOR EXTENDING THE SERVICE LIFE OF FUTURE CONCRETE BRIDGES: SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

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ABSTRACT

This report summarizes the major conclusions drawn from its companion reports, which described investigations conducted using a stainless steel–clad bar, selected stainless steel bars (304, 316LN, and duplex 2205), and a carbon steel bar in concrete and in simulated concrete pore solutions (with various concentrations of chloride and pH) to assess the comparative corrosion resistance of the clad bar.

The most important conclusion is that stainless steel cladding serves as an excellent protection for the carbon steel core. The clad bars and the solid stainless steel bars tolerated the same concentration of chloride ions without corroding, a level that was at least 15 times more than the corrosion threshold for carbon steel bars. Simple cost comparisons demonstrated that the clad bar is also a cost-effective reinforcement for extending the service life of future concrete bridges. Based on its excellent corrosion resistance and reasonable price, the study recommends that the clad bars be used in the construction of new concrete bridges in Virginia as long as the mechanical and physical characteristics of the bars are at least equivalent to those specified by the American Society of Testing and Materials in ASTM A 615.

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INTRODUCTION

The combination of concrete and reinforcing steel provides a strong and yet relatively inexpensive material that has been widely used for a long time in the construction of roadways and bridges. However, the permeable nature of concrete and its tendency to crack allow for intrusion of chloride ions from deicing salts or seawater into exposed concrete areas. Eventually, the chloride ions accumulate in the concrete to a threshold level that, in the presence of oxygen and moisture, is sufficient to initiate corrosion of the carbon steel bars. The resulting corrosion products cause the concrete to rupture internally, which, in turn, leads to the deterioration of many concrete bridges, often long before their design life is reached. This problem has placed a tremendous financial burden on many state and local transportation agencies in maintaining their bridges. The latest estimate of the annual cost of corrosion to the nation's highway bridges, including steel and concrete, is $8.3 billion.[1]

Given the very harsh service environments to which many bridges will be exposed, building new reinforced concrete bridges that will be free of reinforcement corrosion is extremely difficult, but not impossible. The achievement of this goal would require the use of a combination of measures such as:

- corrosion-resistant reinforcement
- adequate depth of concrete cover over the reinforcing bars
- low-permeability concrete
- use of a corrosion inhibitor as an admixture
- application of waterproofing membranes or sealants to the exposed concrete
- application of cathodic protection at the time of construction.

Each measure has technical merits, practical disadvantages, and associated costs. Some investigators have advocated that the combined use of low-permeability concrete, adequate concrete cover, and a corrosion inhibitor in the concrete is sufficient to provide long-term protection from reinforcement corrosion. This may be true if the concrete does not crack during service. However, concretes do crack, some even at an early age. When cracking occurs, the reinforcing bars may be left unprotected. Therefore, in the final analysis, the use of a corrosion-resistant reinforcement will still be the most direct and prudent solution to the costly problem of corrosion. In fact, if a corrosion-resistant bar were available and used, all the other measures might be unnecessary.

The use of protected bars, in the form of epoxy-coated carbon steel bars, in combination with a thicker concrete cover and concrete with a low water-to-cement ratio (w/c) had been adopted by many state transportation agencies by the early 1980s. Because of these measures, the majority of the concrete bridge decks built since then has remained free of corrosion.[2] In contrast, in bridges built with uncoated carbon steel bars, corrosion typically occurred in only 5 to 10 years in areas where deicing salts were used. However, the epoxy coating has weaknesses (e.g., a susceptibility to abrasion damage arising from careless handling by workers at construction sites and rubbing by aggregates and vibrators during concrete placement and degradation caused by prolonged exposure to ultraviolet rays at the sites) that are expected to limit its long-term effectiveness. The estimates for the additional service life attained with epoxy-coated bars range from 5 to 25 years. Therefore, to achieve the design-life goal of 100 years (for major bridges), better reinforcing bars made of tough and intrinsically corrosion-resistant materials are needed.

Bars made of fiber-reinforced plastic where the fibers are either glass or graphite have the potential to be such a material. These materials have their advantages and disadvantages.[3] They are not susceptible to chloride-induced corrosion, but glass fibers are susceptible to attack by the high alkalinity of concrete. This necessitates the use of the proper resin and care in production so that none of the fibers is exposed or the use of the more expensive graphite fibers. These materials have high tensile strength, but they tend to absorb moisture into the resin matrix, and a reduction in mechanical strength is a major concern. They also have a very low tensile modulus, which limits their application to only short spans and close bar spacing; the latter offsets the advantage of a low specific gravity, with the bars weighing only one fourth as much as steel bars. Because these new composite materials do not have a long performance history for reference, whether they have long-term durability under traffic loading and continuous exposure to changing natural elements will remain the primary question for a while.

Alternatives with a realistic prospect of immediate application are bars made of materials with properties that have been well known for some time, such as particular grades of austenitic and duplex stainless steels (304, 316, 2205, etc.). Such bars have been used recently in concrete bridges.[4] In addition to being very corrosion resistant, they have mechanical properties comparable to those of conventional carbon steel bars, which means their use in bridge decks would virtually be a direct substitution. Unfortunately, the cost of stainless steel is very high, about $2.30/lb (installed) compared to $0.50/lb (installed) for carbon steel bars, and has been the major obstacle to their wide acceptance by transportation agencies.

Economically viable alternatives to solid stainless steel bars are bars made of a carbon steel core protected by a cladding made of a stainless steel. Since the stainless steel cladding is tough, it does not have the inherent weakness of the organic coating used in the epoxy-coated bars. The data from a recent limited investigation of clad bars funded by the Federal Highway

Administration as part of a major investigation of many types of reinforcing bars, have suggested that these bars could be as resistant to chloride attack as solid stainless steel bars.[5] Costing slightly more than twice the cost of carbon steel, this material is extremely attractive.

To verify the preliminary data and thereby open the way to the wide use of clad bars, an investigation was conducted at the Virginia Transportation Research Council, with the cooperation of the Materials Science Department of the University of Virginia.[6,7]

PURPOSE AND SCOPE

The primary objective of this investigation was to ascertain whether the chloride corrosion threshold of stainless steel–clad bars is considerably higher than that of carbon steel bars and, thereby, whether such bars when used in concrete bridge decks would lengthen considerably the service life of such structures before corrosion could occur. The methods, results, conclusions, and recommendations of the investigation are detailed elsewhere.[6,7] This document presents a summary of the conclusions and recommendations.

The time frame of the study was limited to 2 years.

METHODS

Stainless steel–clad bars; other bars made of alloys such as stainless steels 304, 316LN, and 2205; and carbon steel bars were embedded in concrete blocks, which were then set outdoors and exposed to weekly cycles of ponding with a saturated salt solution for 3 days followed drying for 4 days.[6] In addition, the same materials (with the exception of the stainless steel 2205) were exposed to different simulated concrete pore solutions of various pH and chloride ion concentrations.[7]

Except for the accelerated exposure to salt, the test concrete blocks were intended to provide a realistic simulation of the environment that typically surrounds embedded reinforcing bars. In contrast, the solutions, because of their higher electrical conductivities (that enhance corrosion) than found in typical concrete, provided a harsh, or worst-case, test environment for the various bars. This was intended to allow for an estimate of the chloride corrosion thresholds for the various bars (especially the more corrosion-resistant bars) within the limited study period in the event tests in the concrete blocks could not. Different electrochemical techniques were used to monitor quantitatively the behavior of the different bars during the exposures. Details are provided in previously published reports.[6,7]

FINDINGS FROM THE LABORATORY INVESTIGATION

- *The defect-free stainless steel–clad bars were virtually as corrosion resistant as the solid stainless steel bars tested. In addition, the corrosion resistance of the three solid stainless steel bars tested was not significantly different.* After almost 2 years of weekly accelerated and severe salt exposure of test concrete blocks, the embedded clad bars and the stainless steel bars (304, 316LN, and duplex 2205) evidenced no electrochemical indication of corrosion (in terms of macrocell current, corrosion rate, and open-circuit potential). The carbon steel bars corroded as early as 90 days after exposure began. These findings support the preliminary findings of the FHWA-funded investigation.[5] In solutions, the clad bars the and the solid 316LN stainless steel exhibited similar electrochemical properties (e.g., open-circuit potentials, E-vs-log(i) function, and pit repassivation potentials).

- *The clad bars, similar to the stainless steel bars, tolerated at least 15 times more chloride than the carbon steel bars were able to tolerate*. The estimated average chloride concentrations in the concrete blocks at the depth of the top bars when the embedded carbon steel bars began to corrode and at the end of the investigation (700 days) were about 0.0350% and 0.520% (by weight of concrete), or 1.38 lb/yd^3 and 20.5 l/yd^3, respectively. Testing in solutions showed that the chloride thresholds for the clad bars and the 316LN stainless steel bars were at least 16 and 24 times, respectively, that of the carbon steel. The slight difference in the resistance was attributed to possible differences in the alloy compositions of the stainless steel cladding and the 316LN.

- *When the bars are embedded in concrete, defects in the cladding may not necessarily lead to corrosion of the exposed carbon steel*. Although actual defects were not observed in different batches of clad bars coming from the U.K. plant and in samples from the only U.S. manufacturer, the effect of defective (or damage in) cladding was investigated. Clad bars with holes intentionally drilled through the cladding to expose the carbon steel core showed corrosion activity in solutions, clad bars with similar defects that were embedded in concrete did not show any corrosion activity, even after 700 days of weekly severe salt exposure cycles. Similar absence of indication of corrosion activity was also observed of embedded clad bars with cuts of 1.0 in through the cladding and subjected to 364 days (so far) of the same severe salt exposure.[8] This difference may be attributed to the facts that the electrical conductivity of concrete is typically orders of magnitude lower than that of solutions and that corrosion rate is highly influenced by the electrical conductivity of the surrounding medium or solution. It is possible that, in concrete, a cladding defect has to reach a threshold size before corrosion of the underlying carbon steel core can occur at a sustained level.

- *As predicted, corrosion can occur on the exposed carbon steel at the cut ends of clad bars.* Test in solutions indicated that the chloride corrosion threshold of the exposed carbon steel core at the cut ends of clad bars was similar to that of solid carbon steel bars (i.e., Cl^--to-OH^- molar ratio of 0.68). In addition, tests of different methods for sealing the ends showed welding the ends with stainless steel to be the least effective and epoxy coating the ends to be associated with various degrees of improvement.

- *Using a combination of a more corrosion-resistant bar (such as clad or the solid stainless steel bar) for the top-mat reinforcement in a bridge deck and the cheaper, but corrosion susceptible, carbon steel bars for the bottom mat is risky.* The appearance of a "reversed" macrocell current in many of the test concrete blocks with such bar combinations demonstrated that sufficient chloride ions will eventually reach the bottom reinforcement mat to cause the carbon steel bars to corrode long before the top bars.

COST COMPARISONS OF BARS

For any new material to be widely accepted, it must be shown to be more cost-effective than existing materials. Thus, the new clad bar must meet this requirement. To facilitate a simple cost comparison, consider a hypothetical concrete bridge deck to be built in Roanoke, Virginia, using the Virginia Department of Transportation Class A4 concrete mix (see Table 1) to provide a concrete cover of 2.75 in. As Figure 1 shows, it is possible to estimate the age or length of service of this hypothetical bridge deck when the chloride ions at the depth of the first-mat bars will reach a particular concentration level. This may be done by assuming that the transport of chloride ions in concrete follows Fick's second law of diffusion and using the diffusion coefficient predicted for such a concrete mix (adjusting for the effects of temperature and the age of the structure), the prevalent concentration of chloride at the concrete surface, and the rate of chloride application for a bridge in the Roanoke area; the two latter variables are available in a database developed elsewhere.[9]

Based on Figure 1, it would take approximately 34 years for the chloride ions in the concrete surrounding the top-mat reinforcement to reach a concentration of 0.0350% (1.37 lb/yd^3), the threshold for initiation of corrosion on carbon steel bars. Since the clad bars and the stainless steel bars are able to withstand at least 15 times more chloride, the chloride content in the concrete will be far from approaching this level, even when the structure reaches 150 years.

Life cycle cost analysis requires making assumptions on service life, discount rate, the values of future deck repair cost, disruption cost caused by future repair or replacement work, etc. For the purpose of comparison, instead of using life cycle cost, it is simpler to use the cost associated with any given bar for each service year before corrosion begins, which can be calculated with far fewer assumptions (see Table 2). Among the four types of bars considered, in

Table 1. A Hypothetical Concrete Bridge Deck

Dimensions of Concrete Deck	
Clear concrete cover	2.75 in
Overall thickness	9.0 in
Concrete Mix Design	
w/cm	0.45
Fly ash content	25%
Diffusion Coefficient (at 28 days)	1.05×10^{-11} m^2/s
Deicing Salt Exposure Condition	
Geographical location	Roanoke, Virginia
Type of exposure	Urban highway bridge

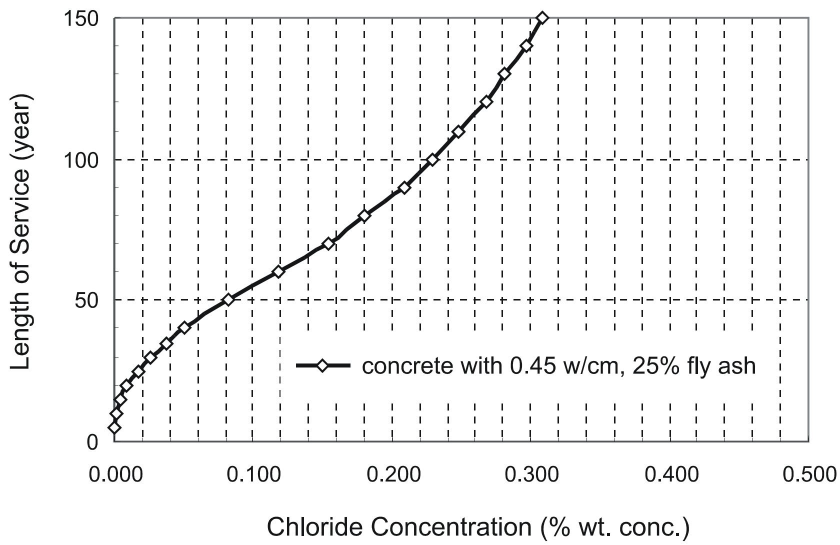

Figure 1. Length of Service Required for Chloride Ions at the Depth of Top-Mat Bars (2.75 in) to Reach a Given Concentration in the Hypothetical Concrete Deck (0.025% Cl^- by weight of concrete = 1.00 lb/yd^3)

Table 2. Simplified Comparison of Semi–Long-Term Costs Associated with Use of Different Bars

Item	Carbon Steel Bar	Epoxy-Coated Bar	Clad Bar	Stainless Steel Bar
Total deck area (ft^2)	31,145	31,145	31,145	31,145
Amount of bars required (lb)	218,040	218,040	218,040	218,040
Unit cost of bars ($/lb) installed	0.50	0.60	1.10	2.30
Total cost of bars ($)	109,020	130,820	239,840	501,490
Projected length of service before corrosion occurs (yr)	34	39	> 150	> 150
Effective cost of bars, before corrosion ($/yr-$ft^2$)	0.10	0.11	< 0.05	< 0.11

semi–long term, the clad bars would cost the least, less than $0.05/$ft^2$ per service year before corrosion begins, followed by the stainless steel bars, the carbon steel bars, and the epoxy-coated bars.

The cost of the epoxy-coated bars is based on the assumption that the bars provide only 5 additional years over the bare carbon steel bars. As mentioned earlier, estimates of the additional protection provided by the epoxy coating to the carbon steel bars range from 5 to 25 years. Bridge owners may make their own estimate and apply it to estimating the cost of using the coated bars, realizing that for every 5 years corrosion is delayed on epoxy-coated bars, the rate of return is $0.01/$ft^2$ per service year. At this rate, for the semi-long-term cost of using epoxy-coated bars to drop to $0.05/$ft^2$ per service year, the bars have to hold for 79 years before corrosion sets in, which is a very unlikely scenario.

There is no doubt that a complete life cycle cost analysis that includes factors such as the cost of future repairs and other costs associated with traffic disruption, which would be incurred if carbon steel and even epoxy-coated bars were used, would make clad bars even more favorable.

RECOMMENDATIONS

1. *VDOT should proceed with the use of stainless steel–clad bars as reinforcement in the top and bottom mats of new concrete bridge decks, especially in major bridges and urban bridges that carry heavy traffic.* Because they can tolerate considerably higher concentrations of chloride in the concrete without showing any sign of corrosion and are reasonably affordable, clad bars can be a cost-effective means for reducing or virtually eliminating reinforcement corrosion in future concrete bridges that are expected to be exposed to high levels of deicing salt. Their use will significantly lengthen the service life of future concrete bridges and reduce maintenance costs. The prospect of achieving a design life of at least 100 years, without major repair, is realistic with the use of clad bars and should not be ignored.

2. *To facilitate implementation of the previous recommendation, specifications for clad bars should be established to ensure that their mechanical and physical characteristics are at least equivalent to those specified in ASTM A 615 for carbon steel bars.* In addition to the standard requirements, such as tensile strength, elongations, deformation, cladding thickness, bending, etc., the specifications should include a provision for sealing the ends of the bars and assurance of the integrity of the cladding. It has been suggested by some that the exposed carbon steel core at the ends of a clad bar represents only a minor issue. (The total area of all bar ends in a typical bridge deck is estimated to be only approximately 0.2% of the total lateral area of all the bars.) In addition, it is possible that the potential stress exerted by corrosion product forming at the vertical end of a bar on the surrounding concrete would not be as detrimental as the stress exerted by corrosion product forming at the lateral surface of a bar on the concrete above it, which is comparatively thinner. Regardless, it is prudent to seal the ends of the clad bars even with a two-part epoxy mix while more effective means are being identified.

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