Epoxy-Coated Versus Galvanized Reinforcing Steel on Bridge Decks

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Abstract— The purpose of this research is to evaluate and compare the relative merits of the two coating systems for reinforcing bars in concrete. A review is given of the nature and characteristics of both epoxy coated and galvanized steel for use as reinforcement in concrete. Also presented is an overview of the results from recent experimental work on the comparative corrosion behavior of uncoated black steel, epoxy coated steel, and galvanized steel in concrete.

Index Terms— Bridge, Coated (Black), Corrosion, Crack, Deck, Epoxy, Galvanized, Rebar, Reinforcing Steel

1 Introduction

CORROSION of bridge deck reinforcing steel is a major problem facing the transportation infrastructure. This leads to time consuming and costly repairs often including complete reconstruction and to inconvenience for the public. When the chloride ions reach the reinforcing steel, a corrosion reaction occurs which produces rust. The rust occupies a larger volume than the reinforcing steel, thus producing tensile forces within the concrete which eventually exceed the limited tensile strength of the concrete. This causes cracking that can lead to delaminations and eventual spalling. Protecting the reinforcing steel from corrosion results in a longer, lower-maintenance life for the bridge deck, as well as to lower life-cycle costs.

Corrosion is accelerated by the intrusion of chloride ions from deicing salts into the bridge concrete. The cracking associated with the corrosion of the reinforcement leads to delaminations and eventually spalling. Coated steel reinforcement has found very wide application over many years in different types of concrete construction under various exposure conditions. At present the most common coating system for steel reinforcement is epoxy coating.

Under ideal conditions, concrete provides stable, long-term corrosion protection to steel reinforcement by passivating its surface. To maintain this condition, the concrete must be sufficiently impermeable and uncracked so as to prevent the transport of chemicals such as chlorides, carbon dioxide and oxygen to the reinforcement. Corrosion problems are commonly faced under moderate-to-severe exposure conditions encounted with marine and coastal construction, chemical processing facilities, as well as bridge and highway construction.

Corrosion may also occur under less severe exposure conditions, such as those in building construction.

Coated steel reinforcement has found very wide application over many years in various types of concrete construction under various exposure conditions. The most common coating system for steel reinforcement is epoxy coating. Hot dip galvanizing has been used in a number of applications as well.

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2 Steel Corrosion in Concrete

Metal corrosion may be defined as "the undesirable deterioration of a metal, i.e., an interaction of the metal with its environment that adversely affects the properties of the metal" [17].

Significant energy must be input to reduce an ore to a metal, to manufacture steel, and to fabricate the steel products. Corrosion can be viewed as the tendency to revert the steel products to their natural, low energy state.

Corrosion of metals is an electrochemical process. It normally involves both chemical reactions and a flow of electrons.

There are four elements necessary for corrosion to occur:

1. An anode - This is the electrode where a reaction occurs to generate electrons. Corrosion occurs at the anode.
2. A cathode - This is the electrode which receives electrons. The cathode is protected from corrosion.
3. An electrolyte - This is the conductor through which ions migrate from the anode to the cathode. Electrolytes include water solutions of acids, bases, and salts.
4. A return current path - This is a metallic pathway connecting the anode to the cathode (for example, a reinforcing bar).

In structures, the anodic and cathodic site may be quite far apart.

For an electrochemical cell to operate, there must be a potential difference between the two electrodes, which may arise from almost any conceivable heterogeneity of the system. Potential differences in steel reinforcement may be caused by surface inclusions, discontinuous layers of mill scale, scratches, static and cyclic stresses, etc. Irregularities in the concrete which may create potential differences are different moisture content, differential salt concentration, cracks, variations in concrete density, etc. The irregularities in the steel reinforcing bars or the surrounding concrete produce differences in the potential between zones of the reinforcement. Calcium hydroxide, present in hardened concrete, can act as an electrolyte in the presence of moisture. Thus, with these basic requirements present, an electrochemical cell is set up and corrosion proceeds, since the steel bar itself can provide the electron conductor between the anodic and cathodic zones.

Under normal conditions, concrete is alkaline with a pH of about 12.5. In such an alkaline environment, a passivating iron oxide film forms on the steel, causing almost complete inhibition of corrosion. The presence of chloride ions creates lattice vacancies in the oxide film, thus providing defects in the film through which metal ions may migrate more rapidly and permit corrosion to proceed. Also, chloride ions reduce the pH, thus increasing the corrosion rate [18].

3 Epoxy-Coated Reinforcing Bars

Epoxy coating of reinforcement has been widely used since the mid-1970's to combat corrosion, particularly in salt contaminated concrete such as highway bridge decks, marine structures, etc. Epoxy coating provides good corrosion protection to steel and the coating is not consumed in performing its function. The coating is essentially inert and highly resistant to both the alkaline environment of concrete and the penetration of chlorides. The barrier protection it affords to steel is due to the complete isolation of the steel from the environment. The epoxy coating itself does not corrode.

There has been a concern expressed in some publications regarding the longevity of the protection afforded by epoxy coating in aggressive environments. A review of published reports and documents by FHWA (Federal Highway Administration), KCC (Kenneth C. Clear, Inc.), CRSI (Concrete Reinforcing Steel Institute), West Virginia DOT, NYSDOT, etc. (Reference [1-7, 12]) shows that the corrosion behavior of epoxy-coated bars depends mainly on the following factors:

1. Chloride does not penetrate the epoxy coating, but enters through a break in the coating and travels along the steel surface [1].
2. Corrosion performance of epoxy-coated bars is related to the holiday (that is, any hole or defect in the coating that permits current to pass) count and electrical resistance qualities of the coating. Electrical resistance depends upon proper film thickness, good surface preparation and low holiday counts.
3. Excellent corrosion performance is based upon final average current densities less than 0.01 mA/ft2, intermediate corrosion performance is based upon corrosion current density between 0.01 and 0.10 mA/ft2, and poor corrosion performance is based upon current densities greater than 0.10 mA/ft2 [1]. Figure 1, “Correlation between Holidays per Foot and Corrosion Current Density (mA/SF)” in reference [13] indicates that epoxy-coated bars with less than 1-2 holidays per foot exhibit excellent corrosion protection.
4. Holidays are the dominant factor in determining the corrosion performance of the reinforcing bars. Holidays can be produced at bar marks, bending induced cracks, damage during handling at the coating applicator's plant, damage during bending at the fabricator's plant, damage during transport and installation, and due to inadequate film thickness.
5. A coating is consistently thinner at the edge of a deformation than in the areas between the deformations. Thin films can contribute to poor corrosion performance as it influences holiday formation.
6. High holiday count, non-specification bars (i.e., with coating not per specifications) provide poor corrosion protection to the steel.

To assess the corrosion protection provided by epoxy coatings on steel reinforcement in bridge decks, NYS DOT selected a sample of 14 bridges in age from 7 to 12 years for field survey and laboratory analysis of deck cores [3]. The results presented in “Approximate Reinforcement Cost” table in reference [22] indicate that the corrosion of the epoxy coated steel reinforcement was not significant and the protection provided by epoxy coatings appeared satisfactory.

The results from a condition survey conducted by West Virginia DOT on a number of existing bridge decks is reported in [2]. Both, the decks with epoxy coated and black steel rebars, are of comparable age. As “Expected Service of Reinforcing Bars” table in reference [22] indicates, decks with uncoated rebars exhibited vastly greater amount of delaminations than those with epoxy coated bars.

Based on field and laboratory test data, ASTM A775 and ASTM D3963 specifications require the following:

- Film thickness to be from 8 to 12 mils.
- Bar mark holidays are to be included in the count and must be repaired.
- Bending-induced cracks must be repaired.
- Repairs must be made in applicator's plant on handling damage, at the fabricator's plant on all fabrication or handling damage, and at the construction site by the contractor.
- Bars are permitted to have an average of no more than 2 holidays per foot and as much as 2% damaged areas as long as the individual damaged spots are smaller than 1/4x1/4 in.

Epoxy coating that satisfies the above requirements is noted to provide good corrosion protection to steel reinforcement.

4 Galvanized Reinforcing Bars

Hot dip galvanized reinforcement has been used by a number of agencies and its usage grows. Zinc coating on iron and steel products has been used over many years for corrosion protection of exposed structural steel and other consumer products. It has been used over 60 years for corrosion protection of steel reinforcement. Zinc coating provides barrier protection by isolating the steel from the local environment. It has higher chloride tolerance than black steel and it takes longer time to depassivate zinc than black steel. In addition to this, galvanized coating provides an extra measure of corrosion protection because of its inherent sacrificial nature. In this case, the coating behaves anodically while the steel is cathodic, and local damage to the coating can be tolerated as long as the exposed steel remains fully cathodic with respect to the coating. The total life of a galvanized coating in concrete thus consists of the time taken for the zinc to depassivate, plus the time taken for the dissolution of the coating.

There is considerable controversy concerning the advantages of using galvanized reinforcement in concrete exposed to harsh environments such as bridge decks or marine structures. Several laboratory and field studies have been performed in connection with galvanized reinforcement in concrete. The studies frequently contradict one another, and evaluation of data generally results in different opinions regarding measured or expected performance of galvanized reinforcement:

1. Substantially higher longevity has been found over regular mild steel rebars in some situations, but only slightly better, equal or even worse performance has been found in other exposures [8-10].
2. Under certain conditions, zinc can reverse in polarity and may cause accelerated corrosion of black steel. Some examples of exposure conditions leading to reversed polarity in zinc are the following:
   - Waters high in carbonates increase this tendency.
   - When black steel in salt contaminated concrete begins to corrode and is electrically interconnected to galvanized steel in relatively low salt concrete, then the "reversed polarity" zinc might cause the black steel to have accelerated corrosion [13].
   - A comparison study on the performance of galvanized reinforcing steel and conventional black steel reported in [14] indicates the following. Galvanizing only the top mat reinforcing steel is very detrimental, resulting in corrosion rates twice as high as those for all black steel.
3. The corrosion product of zinc coated steel reinforcing bars embedded in concrete containing large concentrations of chloride ions is zinc hydroxychloride. This corrosion product occupies over 3.5 times the volume of the original zinc and involves expansions far greater than that for the usual zinc corrosion product (zinc oxide) [8].

Reference [9] reports on study undertaken in 1981 to investigate the protection galvanized coating provides to reinforcing steel in concrete bridge decks subjected to chlorides introduced by deicer salt application. Eight bridges built between 1967 and 1975 were selected. Electrical potential readings numerically higher (more negative) than -0.50 volts and measurements of chloride ion contents higher than 1.8 lbs/yd^3 were used as an indication of active corrosion. The results from this investigation show that the galvanized coating has experienced superficial to mild corrosion. See “Size Designations of Reinforcing Bars” table in reference [27].

The benefit in the use of galvanized versus plain reinforcing steel in concrete subjected to salt contamination was the objective of the research presented in [13]. The main variables in the study were the amount of cement per cubic yard, the method of curing of the specimens (moist and steam curing), and the type of reinforcement (black and galvanized steel). The initiation of corrosion was measured by the use of Saturated Calomel Electrode (SCE) as an active half-cell potential. For black steel, a reading of -0.35 volts or more versus the reference electrode was taken to indicate that corrosion is active. For galvanized steel, a reading of about -0.85 volts or more was used as an indication of active corrosion. Figures 2 through 5 and “Average Days to Active Corrosion and Concrete Cracking” table in reference [13] presents the average number of days to initiation of corrosion and concrete cracking caused by either the corrosion of steel or zinc. The results from the study indicate that the time to initiation of corrosion of galvanized and black steel in comparable concrete environments is similar regardless of cement factor or method of curing.

Shop-bent galvanized reinforcing bars meeting the requirements of ASTM standards A-143 and A-615 are expected to perform better than epoxy coated and black reinforcing bars under high traffic volume and in concrete exposed to extreme environments such as bridge decks or marine structures. However, it appears that the requirement for shop bending of galvanized reinforcing bars may create an issue with local unions who perform field bending of reinforcing bars. Galvanized reinforcing bars are not recommended for projects involving only patching or repairs mixing existing black rebars and newly placed rebars as well as reinforced concrete in mild environments such as building construction. We recommend that the implementation of galvanized rebars be based on the NYS DOT Standard Specification, Section 709.

The NYS DOT requires that at least 95% by mass of the galvanized reinforcing bars are shop bent. When using cast-in-place concrete, this requirement may create an issue with local unions who do field bending of rebars. The epoxy coated rebars currently in use by the Authority, can be bent in the field or in a shop. The NYS DOT, Region 11 and the NYC DOT were contacted to discuss their experience with galvanized reinforcing bars. The NYC DOT has used galvanized rebars only on one project - the reconstruction of the arch span of the 3rd Avenue Bridge, where pre-cast panels were used. To date, the NYS DOT, Region 11 has not used galvanized rebars. The galvanized reinforcing bars for project TB-65 will be shop-bent.

5 Comparison of the Two Coating Systems

Epoxy coated bars require special handling and treatment on site. Galvanized bars do occasionally chip or scratch during handling. If the damaged areas are small they do not require repair because of the self-healing properties of galvanizing. Repairs are needed for larger damaged areas, using at least two coats of a zinc rich paint.

Pullout testing reveals that the ultimate bond strength of epoxy coated bars is some 17% less than that for black steel and for galvanized bars is comparable or up to 31% greater than for equivalent black steel reinforcement. Section 5.11.2.1.2 in ASSHTO [19] specifies modification factors increasing the tension development length, l_d, by a factor of 1.2 or 1.5 for epoxy coated bars.

The most significant differences between the performance of epoxy coated and galvanized reinforcement in concrete concern the method of corrosion protection afforded to the steel and the longevity of that protection.

Since galvanized coating has higher chloride threshold compared to black steel in concrete, there will be a delay in the initiation of corrosion of the zinc. After the zinc is depassivated, corrosion process initiates during which dissolution of the zinc layer occurs followed by corrosion of the rebars once the coating is consumed. Therefore the main limitation of galvanized coating is its reduced service life during which the coating is consumed. The results of some investigations suggest that the galvanized coating delays the corrosion initiation by roughly 5 years when compared to black steel [11].

Epoxy coating, on the other hand, protects reinforcement because of the complete isolation of the steel from the environment, with no sacrificial component. However, when the coating has holidays, corrosion commences because there is no further protection afforded to the steel.

As per ASSHTO [19] "reinforcing bars... in concrete which may be expected to be exposed to airborne or waterborne salts, shall be protected by an appropriate combination of epoxy and/or galvanized coating, concrete cover, ...". NYS DOT Standard Specifications [20] state that "...reinforcing steel for concrete structures may be either epoxy-coated or uncoated".

Epoxy coating for steel reinforcing bars is included in the Approved List, Materials and Equipment for Use on NYS DOT Projects [21]. No reference to galvanized reinforcing bars is made in the NYS DOT documents, [20] and [21].

6 Conclusion

Neither epoxy coating nor galvanizing can assure complete prevention of corrosion of reinforcement in concrete over long periods of exposure. However, coated reinforcement is expected to have longer life than black steel reinforcement under equivalent circumstances. Therefore, reinforced concrete components utilizing coated reinforcing bars are expected to have a longer life and lower life-cycle costs than those with black (uncoated) reinforcing.

The study has indicated no conclusive evidence for one of the two coating systems being superior to the other in an overall sense. However, based on engineering judgement, epoxy coating manufactured and handled according to the specifications cited is expected to afford better protection to the rebars than galvanized coating, and provide a longer life and lower life-cycle costs for the reinforced concrete components. Continued use of epoxy coated reinforcing bars, rather than adoption of galvanized reinforcing, is therefore recommended for the Authority at this time.

It should be noted that coating of reinforcing bars is intended to mitigate problems already existing with reinforced concrete components. It is prudent to avoid or minimize such problems in the first place, by preventing water and contaminants from penetrating the concrete components. This can be done by using proper structural as well as temperature and shrinkage reinforcing, good quality concrete with low permeability and, for bridge decks, special overlays and waterproofing membranes.

"Approximate Reinforcement Cost" table compares the cost and "Expected Service of Reinforcing Bars" table illustrates the expected service life for different types of reinforcing bars as provided in reference [22]. The NYS DOT has determined these values from information gathered from industry sources, university research studies and professional journals. While most of the values listed in "Expected Service of Reinforcing Bars" table in reference [22] represent the average service life of the reinforcing bars, the value for black reinforcement is too low. Ten years of service life may occur only if the black reinforcement is imbedded in low quality concrete with substandard concrete cover and is subjected to a very corrosive environment.

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