TECHBRIEF

Multiple Corrosion-Protection Systems for Reinforced Concrete Bridge Components

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This is a summary of a Federal Highway Administration (FHWA) project that is fully documented in a separate report under the same title (FHWA-HRT-11-060).

Introduction

Epoxy-coated reinforcement (ECR) is the principal concrete reinforcing material currently in use in corrosive environments in the United States. The purpose of this study was to evaluate methods for making ECR more corrosion resistant by using multiple corrosion-protection strategies in bridge decks and bridge members in marine environments where salt, moisture, and high temperatures are prevalent.

The research was conducted using laboratory and large field test specimens, and the results were used to compare the performance of the corrosion-protection systems on the basis of chloride threshold, corrosion rate, life expectancy, and cost effectiveness. Fusion-bonded thermoset ECR was evaluated in conjunction with inorganic and organic corrosion inhibitors, bars coated with zinc prior to the application of epoxy, and chemical pretreatments and epoxy formulations that increase the adhesion of the epoxy coating to the reinforcing steel.

Approach

Corrosion-Protection Systems

This study evaluated 11 systems in which ECR was combined with another corrosion-protection system and 3 systems in which uncoated steel was combined with a corrosion inhibitor. The research included seven bar types: one uncoated and six with a fusion-bonded epoxy coating. Uncoated conventional reinforcing steel and conventional ECR served as the controls.

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The multiple corrosion-protection systems included the following:

- Conventional ECR used in conjunction with one of three corrosion inhibitors: calcium nitrite (designated DCI) and two organic inhibitors (Rheocrete® 222+ and Hycrete™, designated RH and HY, respectively).
- Bars treated with a primer coating containing microencapsulated calcium nitrite prior to coating with conventional epoxy.
- Bars with improved adhesion between the epoxy and the reinforcing steel (obtained through the use of either a zinc chromate pretreatment or one of two special epoxies designed to provide greater adhesion).
- The combination of bars coated with an improved adhesion epoxy and the addition of calcium nitrite to the mortar or concrete used in the tests.
- Bars with multiple coatings consisting of a 2-mil (50-μm) layer of 98 percent zinc and 2 percent aluminum that were, in turn, coated with a conventional epoxy.

Test Parameters and Conditions

Before corrosion testing, the researchers evaluated the bars for coating thickness and number of holidays (i.e., microscopic holes through the coating). The bars were also evaluated for coating adhesion using the cathodic disbondment test. All bars met the requirements of ASTM A775 for coating thickness, except the bars coated with calcium nitrite primer.[1] Those bars tended to have larger percentages of coating measurements below 7 and 5 mils (175 and 125 μm) than the maximum allowable values of 10 and 5 percent, respectively. Only the bars coated with the calcium nitrite primer exhibited holidays, although the number of holidays was below the maximum allowable of three holidays per meter. In the cathodic disbondment test, the average coating disbondment radius for the conventional ECR and one of the high-adhesion epoxy-coated bars was above 0.16 inches (4 mm), the maximum allowed by ASTM A775 when qualifying an epoxy.[1] However, the performance of the bars in the cathodic disbondment tests was not proven to be a predictor of performance in the corrosion tests.

The corrosion tests included rapid macrocell, bench-scale, and field tests. Specimens were autopsied at the completion of testing. In the bench-scale tests, concretes with water-cement ratios of 0.45 and 0.35 were used to evaluate some systems. In all tests, the epoxy coating was penetrated by 0.125-inch (3.2-mm)-diameter holes to simulate damage that occurs during construction.

Specimen Type and Exposure Regimes

The rapid macrocell test specimen consisted of either a bare reinforcing bar or a bar clad in mortar (mortar-wrapped). The contact surface between the mortar and the bar simulated the contact obtained between concrete and reinforcing bars in structures through the use of realistic water-cement and sand-cement ratios. Bars representing the anode and cathode were placed in separate containers. At the anode, the bars were surrounded by a simulated concrete pore solution containing a preselected concentration of sodium chloride, while the bars at the cathode were surrounded by the simulated concrete pore solution alone. The two containers were connected by a salt bridge (for ion transfer), and the test specimens were electrically connected across a single 10-ohm resistor. The voltage drop across the resistor was measured to determine the macrocell corrosion current, which was used to calculate the thickness loss of the metal. The specimens were also monitored for the open-circuit corrosion potential of the bars.

Bench-scale tests included southern exposure and cracked beam tests. Both tests consisted of small slabs of concrete containing two mats (top and bottom) of reinforcing steel that were electrically connected across a 10-ohm resistor. A simulated 12-mil (0.3-mm)-wide crack was placed parallel to and above the top reinforcing bars using a stainless steel shim during fabrication of the cracked beam specimens. The shim was removed shortly after the concrete set. The southern exposure test specimens had no cracks. For both bench-scale tests, the slabs were subjected to a 7-day alternate ponding and drying regime, with ponding at 73 ± 3 °F (23 ± 2 °C) for 4 days and drying at 100 °F (38 °C) for 3 days. Prior to drying, the solution was removed from the upper surface. The ponding and drying regime continued for 12 weeks. Then, the specimens were subjected to continuous ponding for 12 weeks at 73 ± 3 °F (23 ± 2 °C), after which the alternate ponding and drying regime began again. The two regimes continued for 96 weeks. The specimens were monitored for macrocell corrosion current and corrosion potential. Selected bench-scale specimens were also monitored for total corrosion current using the linear polarization resistance test.

Field test specimens consisted of concrete slabs with two mats of reinforcing bars that represented bridge decks but had a 1-inch (25-mm) cover to shorten the time to corrosion initiation. The field test was designed to obtain a measure of the performance of corrosion-protection systems under realistic exposure conditions. Like the bench-scale specimens, some field test specimens were uncracked and some had simulated cracks directly above and parallel to select reinforcing bars. A dam made of weatherstripping was attached to the upper concrete surface to hold a salt solution that was ponded on the specimens every 4 weeks. Corrosion measurements were obtained for a minimum of 250 weeks. Salt was applied to the specimens at the same annual rate used for bridge decks in Kansas.

Results

The test results indicate that the corrosion losses on the damaged areas on ECR (all systems) were generally higher than but of a similar magnitude to the average corrosion losses exhibited by uncoated conventional reinforcing steel. The relatively higher losses on the damaged areas may be because the losses recorded for uncoated conventional steel represent values that are averaged over the full contact surface, all of which may not be corroding. Superior performance was observed over the 15-week test period for the mortar-wrapped macrocell specimens containing ECR. These results are in concert with the results for epoxy-coated bars in the bench-scale tests, which indicate that, due to the natural variation in chloride concentration within concrete, all damaged areas on ECR do not come in contact with high chloride contents at the same time. When uncoated steel was used, however, a portion of the unprotected steel is expected to undergo corrosion. As a result, a higher average chloride content was required to initiate corrosion in ECR with a damaged coating than for uncoated conventional reinforcement.

In terms of overall performance, the use of concrete with a lower water-cement ratio provided an advantage for both uncoated and coated reinforcement in uncracked concrete due to its role in delaying penetration of chlorides and limiting access of oxygen and moisture to the steel. The same advantage was not apparent in all cases for cracked concrete. Concrete with a lower water-cement ratio resulted in a lower corrosion rate for uncoated steel but not for damaged ECR.

As observed in other studies, increasing the adhesion between the epoxy coating and reinforcing steel did not provide an advantage over conventional ECR.[2]

In uncracked concrete, the use of corrosion inhibitors and the use of the primer coating containing calcium nitrite provided added protection for damaged ECR. In general, the lower the water-cement ratio, the better the protection. Of the systems incorporating a corrosion inhibitor, bars with the calcium nitrite primer coating under the epoxy coating and conventional ECR cast in concrete with one of the organic inhibitors (specifically, HY) provided improved performance, although the relative advantages were lower for cracked concrete than for uncracked concrete.

The test results for the bars with multiple (zinc-epoxy) coatings indicate that the zinc helped to protect the underlying conventional steel. This protection, however, was obtained through the sacrificial loss of zinc. The multiple-coated bars exhibited relatively high corrosion rates compared to conventional ECR in the bench-scale tests but performed in a similar manner to conventional ECR in the field tests in both uncracked and cracked concrete.

The test data were combined with chloride measurements on bridges in Kansas to evaluate the systems' life expectancy and cost effectiveness, expressed in terms of time to first repair and the present value of initial construction and repair costs over a 75-year design life. Comparisons were based on a bridge with a 150-ft (46-m) span and 36-ft (11-m) width. The deck thickness was 8.5 inches (219 mm). Calculations were based on a 75-year economic life using costs from Kansas and South Dakota.

Data analysis for time to first repair for the 11 systems evaluated in this study is shown in figure 1. All of the systems incorporating ECR provided a longer time to first repair than the systems incorporating conventional reinforcement. Conventional reinforcement without a corrosion inhibitor provided the shortest time to first repair, approximately 17 years. The time to first repair progressively increases with the addition of organic corrosion inhibitor RH, DCI, and organic corrosion inhibitor HY. The bridges with systems incorporating uncoated bars required two or three repairs during a 75-year design life. In contrast, the systems incorporating coated reinforcement required a single repair over 75 years. Of the epoxy-coated systems, conventional ECR, along with the three systems providing increased adhesion between the epoxy and the steel and one system with an organic inhibitor (specifically, RH) provided nearly identical predicted times to first repair (55 years). The other systems, DCI, organic corrosion inhibitor HY, the bars with the calcium nitrite primer coating under conventional epoxy, and the multiple-coated bars, provided somewhat longer predicted times to first repair at 64, 58, 64, and 56 years, respectively. As shown in figure 2, the costs over 75 years for the systems incorporating conventional reinforcement were higher than those containing ECR, and the costs for the individual systems incorporating ECR were similar.

Conclusions

The following conclusions were reached as a result of this study:

- Conventional fusion-bonded epoxy coatings significantly improve the corrosion resistance, life expectancy, and cost effectiveness of reinforcing steel in severe climates, such as in the case of bridge decks requiring application of deicing chemicals.
- Coated bars with damaged coatings initiate corrosion at chloride contents within concrete

Figure 1. Time to first repair.

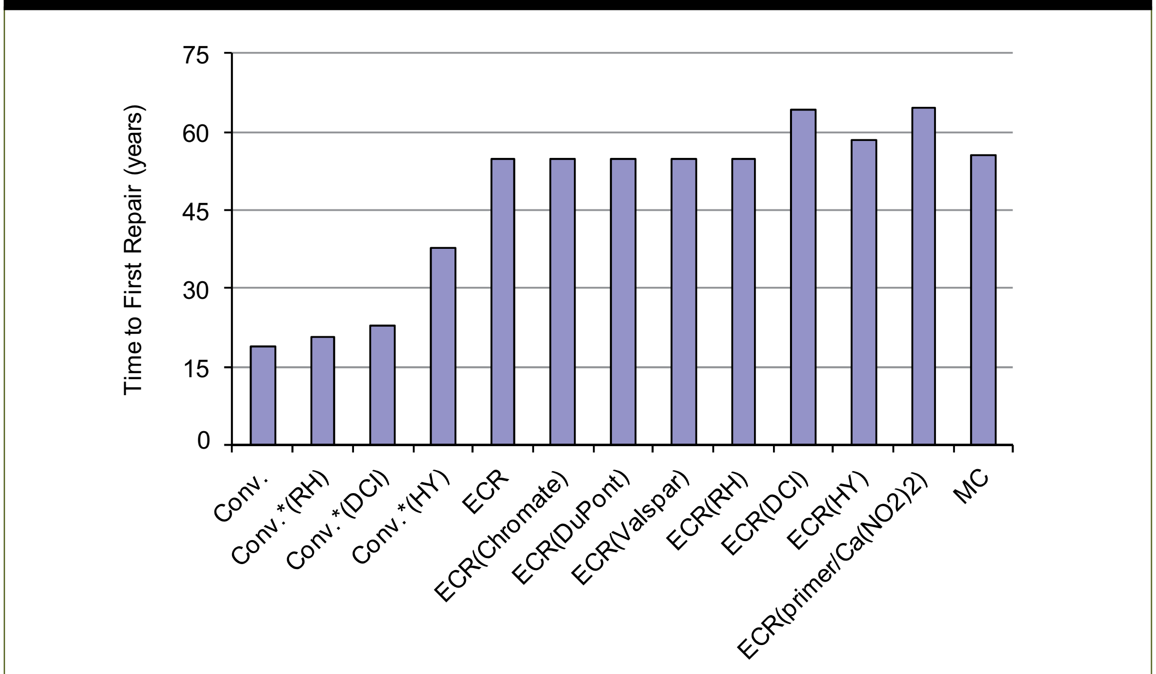
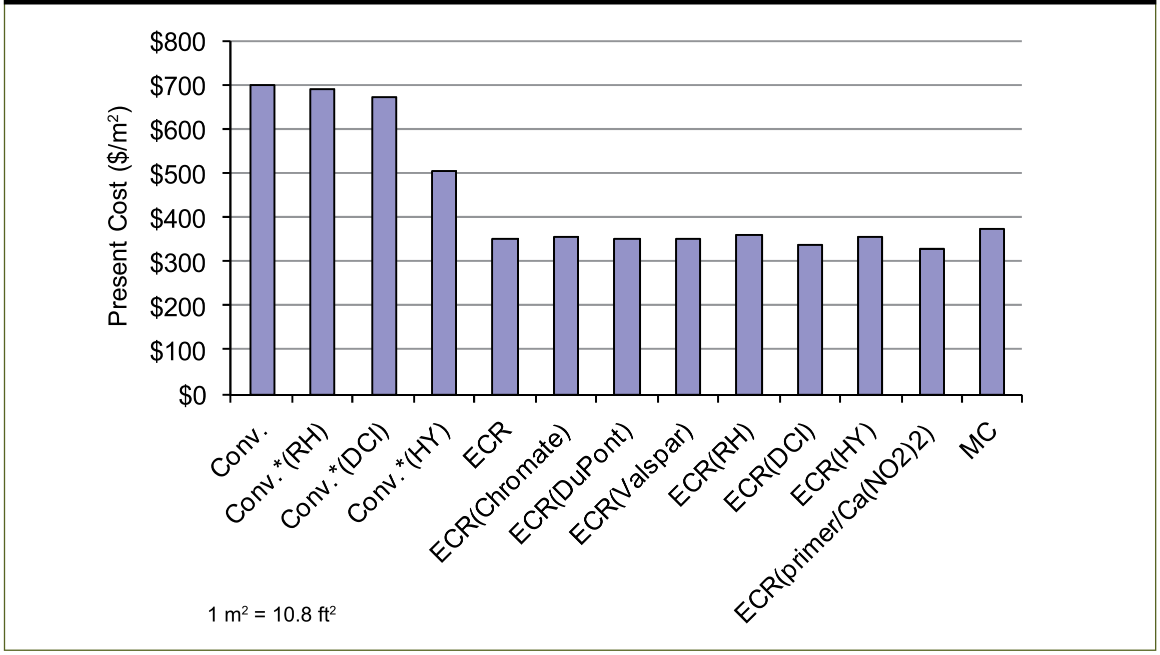


Figure 2. Present cost for initial construction and repair over 75 years.



that are several times greater and corrode at rates that are typically two orders of magnitude below those exhibited by conventional reinforcement.

- Limited additional protection and extension of time to first repair are achieved using bars with a primer coating containing microencapsulated calcium nitrite underneath a conventional epoxy coating, multiple-coated bars with a 2-mil (50-μm) coating of 98 percent zinc and 2 percent aluminum underneath a conventional epoxy coating, and concrete containing the corrosion inhibitors DCI and HY. The differences in costs over a 75-year design life are relatively small for coated bars. Concrete containing HY may exhibit lower compressive strength and reduced resistance to surface scaling compared to concretes with other inhibitors or without an inhibitor unless modified, such as through an increase in cement content. As a result, additional research is required to establish criteria that will preclude a loss of durability when HY is used.

- Conventional reinforcement in concrete containing a corrosion inhibitor has a longer service life and is more cost effective than conventional reinforcement in concrete without a corrosion inhibitor but has a shorter service life and is less cost effective than any of the coated-bar systems evaluated.

- Cracks in concrete directly over and parallel to the reinforcement, such as those found in bridge decks, result in earlier corrosion initiation and higher corrosion rates than obtained with intact concrete for all systems.

- Epoxies that provide initially high adhesion to the underlying steel provide no advantage in terms of improved corrosion performance or improved adhesion when used in concrete.

- Using concrete with a reduced water-cement ratio lowers the corrosion rate for both conventional reinforcement and ECR under all conditions in intact concrete but provides only limited corrosion protection when cracks allow direct access of chlorides to reinforcing bars.

- Corrosion inhibitors consistently provide improved corrosion protection when used in conjunction with conventional reinforcement and ECR in intact concrete but do so to a lesser degree in cracked concrete.

- Corrosion inhibitors have a greater relative effect on uncoated than on coated reinforcement.
- Reinforcement with multiple coatings consisting of 98 percent zinc, 2 percent aluminum, and conventional epoxy exhibits high corrosion rates in cases where the concrete is often wet but exhibits corrosion rates similar to those exhibited by conventional ECR under conditions similar to those in bridge decks. The metallic coating corrodes in preference to the underlying steel, providing some additional protection.
- All coated bars that were evaluated exhibited corrosion losses at openings through the coating. A reduction in adhesion between an epoxy coating and the reinforcing steel occurs after a period of exposure to corrosive conditions. This reduction increases with increasing chloride content in the concrete and in the presence of cracks and decreases with the use of corrosion inhibitors, the use of multiple-coated reinforcement, and the use of electrical isolation of the epoxy-coated bars from each other. Corrosion products form under the coating where adhesion has been reduced.
- For periods up to 5 years under exposure conditions representative of those in bridge decks, the reduction in adhesion between an epoxy coating and the reinforcing steel did not affect the rate at which coated bars corrode.

References

1. ASTM A775/A775M-04a (2004). "Standard Specification for Epoxy-Coated Steel Reinforcing Bars," ASTM International, West Conshohocken, PA.
2. McDonald, D.B., Pfeifer, D.W., and Sherman, M.R. (1998). *Corrosion Evaluation of Epoxy-Coated, Metallic Clad, and Solid Metallic Reinforcing Bars in Concrete*, Report No. FHWA-RD-98-153, Federal Highway Administration, Washington, DC.

Researchers—This study was performed by the University of Kansas Center for Research, Inc., 2385 Irving Hill Road, Lawrence, KS, 66045-7563, (785) 864-3441.

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