Epoxy-coated Reinforcement

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The Canadian Strategic Highway Research Program (C-SHRP) initiated a project in early 1990 that was aimed at determining the effectiveness and long-term performance of fusion-bonded epoxy coatings of steel reinforcement in preventing corrosion. This technical brief includes excerpts from the final report from that project, titled Effectiveness of Epoxy-coated Reinforcing Steel. Updates from the Ontario Ministry of Transportation on the current status of ECR and a Canadian exposure study are also included.

BACKGROUND

Corrosion of steel in concrete has evolved over the past two decades to become a serious and costly problem in highway structures in North America. Consequently, agencies across Canada and the United States have ongoing activities to reduce and eliminate such damage to structures. The use of fusion-bonded epoxy coating of steel reinforcement (ECR) was identified as an effective method of corrosion protection in the early 1970s. The primary function of an epoxy-coating is to act as a physical barrier to prevent corrosion-causing chloride ions and oxygen from reaching steel surfaces. The first use of ECR was in a Pennsylvania bridge deck in 1975. In Canada, primarily in Ontario, ECR has been used in bridge decks and substructures since 1979 and 1981, respectively. By the early 1980s ECR had become the preferred method of corrosion protection throughout most of North America. In recent years, instances of corrosion problems or premature failures in Florida, New York and Ontario have focused attention on the product and its quality.

The Strategic Highway Research Program (SHRP) was established by the United States Congress in 1987 as a five-year, $150 million research program to improve the performance and durability of highways and to make them safer for motorists and highway workers. As a follow-on program to SHRP, Congress established in the Intermodal Surface Transportation Efficiency Act of 1991 programs to implement SHRP products and to continue SHRP’s long-term pavement performance (LTTP) program. The Canadian Strategic Highway Research Program (C-SHRP) is directed at extracting the benefit of the US work for Canada.
C-SHRP STUDY OF ECR

Kenneth C. Clear, Inc. (KCC INC) was contracted by C-SHRP to study the effectiveness of epoxy-coated reinforcement. Three specific project objectives were identified and these were:

1. to determine whether fusion-bonded epoxy coatings are effective in providing long-term (50 years or more) corrosion protection to reinforcement,

2. to identify factors which have the greatest influence on the performance of epoxy-coated reinforcement, and

3. to prepare model specifications for epoxy-coated reinforcement.

Phase I of the project involved the definition of the state of knowledge, the status of usage of epoxy-coated rebars (ECR) in Canada, and a return to fundamentals involving definition of the characteristics and tests used in the pipeline, rebar and other fields to define quality and project future performance. An interim state of the art and fundamentals report was published by C-SHRP in August 1990. Phase II involved the acquisition and testing of epoxy-coated reinforcing bars from various coaters, jobsites and highway structures in the northern United States and Canada. Overall, bars from 12 coaters, seven jobsites and over 130 cores from existing structures were evaluated. Phase II also included six months of environmental exposure of ECRs in Toronto to simulate jobsite storage prior to concrete placement. More than 3,000 individual measurements were made on 317 epoxy-coated rebars, 173 cores and 93 ECR concrete specimens under laboratory and outdoor exposure. Extensive laboratory and field tests were conducted on the bars to characterize the properties of the concrete and core, the properties of the coated rebar (present condition), and to predict future performance. In the final report, published by C-SHRP in 1992, Clear reported a number of significant findings which are summarized in the following paragraphs.

**State of the art evaluations and field and laboratory testing suggested fusion-bonded epoxy coatings would not be effective in providing long-term (50 years or more) corrosion protection to reinforcement in salt-contaminated concrete.** Clear concluded the increase in life of epoxy-coated rebar structures over those constructed with uncoated rebar in northern US and Canadian environments (marine and de-icing salt) would range from three to six years in most instances, rather than the more than forty years previously estimated.

An unexpected epoxy-coated rebar failure mechanism involving progressive loss of coating adhesion and underfilm corrosion was identified. This failure mechanism was active in northern and southern field structures and in very high quality coated rebars in laboratory and outdoor exposure specimens. In this mechanism, the epoxy film debonds and once significant chloride is present, becomes blistered, brittle and cracked. The debondment definitely occurs in concrete with significant chloride and may also occur in concrete which is essentially chloride-free. Hydrogen-evolving cathodes beneath the loosened epoxy film may also be involved.

At the time of the study, means of overcoming this unexpected failure mechanism had not been devised. Therefore, the study could not improve specifications to ensure long-term corrosion protection when only ECR and conventional concrete were used in severe chloride environments. Clear concluded then-present and proposed specifications, even if tightly enforced, would not provide assurance of long-term performance in salt-contaminated concrete. If they could be truly implemented in practice, modifications which would require close examination and patching of all visible bare areas, covered above ground bar storage prior to use, increased minimum coating thickness (to 180 micrometres), and increased severity of the bend test might increase the time to deterioration by another five years. This would bring the extended life to a total of about eight to eleven years more than that for an equal structure constructed with uncoated rebar. If longer low maintenance lives are desired, other protective systems would be required.

Macrocell action is another failure mechanism which occurs on epoxy-coated rebars with holidays (pinholes not visible to the un-
aided eye) and/or visible bare areas, and on bars which have already experienced significant underfilm corrosion resulting in the break-up of the epoxy film. Macrocell action may contribute to adhesion loss even when the total current magnitude and the overall current density, expressed on the basis of the total bar surface, is low. The corrosion current densities at coating breaks are quite high because the area of exposed steel includes the bare areas and pinholes.

Epoxy-coated rebars extracted from 19 field structures, varying in age from three to sixteen years, had numerous holidays and bare areas (averaging 66 per metre of bar) and showed varying degrees of corrosion damage, with concrete damage and/or significant corrosion on bars at cracks and in low cover areas with high chloride. About fifty percent of the epoxy-coated rebars removed from cores exhibited reduced and poor dry coating adhesion (although after up to sixteen years of service, many remain uncorroded because significant chloride had not yet reached the bar in uncracked areas). Many of the bars from field structures performed poorly in a seven day accelerated corrosion test used to project future performance in salty concrete. Instances of good performance of epoxy-coated rebars in salt-contaminated concrete were identified, although such was not the norm for those bridge structures and test specimens considered in the study.

Epoxy-coated rebars were obtained directly from US and Canadian coaters in 1988 and 1991, respectively. In most cases the bars met all requirements of then-present and proposed specifications for epoxy-coated reinforcing steel. However, in all cases, the tested bars showed loss of dry coating adhesion at intentional bare areas in chemical immersion tests of only forty-five days duration.

Straight epoxy-coated rebars were almost as susceptible to loss of adhesion and underfilm corrosion as bent bars, although the bent bars tended to have lesser initial adhesion, more coating cracks, more bare areas and lower AC resistance than their straight counterparts.

Pencil hardness measurements indicated there was not a wide variation in coating hardness, and the coatings exhibited the same pencil hardness when wet as when dry. This suggested the epoxy coating itself was relatively uniform and was not undergoing physical deterioration in service (except for the effects caused by steel corrosion). When this information was coupled with the variable and often poor dry knife adhesion test results, it became obvious the problem (loss of adhesion and underfilm corrosion) lay at the coating/steel interface.

The field bridge deck evaluations showed that improvements in concrete quality and deeper cover over the reinforcing steel (changes in design which coincided with the widespread use of epoxy-coated reinforcing steel) have both contributed significantly to the generally good performance of the structures (i.e. rebar level chlorides were often low in uncracked concrete after about ten to fifteen years of service). Clear suggested the generally good performance of many of the structures studied was due primarily to the deep concrete cover and better quality concrete used by highway agencies, rather than the epoxy-coated reinforcing steel. Concrete cracking was, of course, a weak point in these structures in that chloride ingress occurred more rapidly at these locations. However, on the basis of the field structures studied by KCC INC, ECR does not provide a long-term solution to the cracking problem.

**UPDATES**

**Controversy Surrounding ECR**

Other investigations of epoxy-coated reinforcement and its corrosion performance have been undertaken by different researchers and different sponsors. In some cases, good performance was achieved. As a result, some controversy surrounds ECR and its ability to extend the service life of steel-reinforced concrete structures.

An independent review of Clear's report was commissioned by C-SHRP in 1992. Professor Dr.-Ing. P. Schiessl studied the reports written by Clear for C-SHRP. He prepared a critical review of the reports based on his knowledge and experience. The review supported Clear's major conclusions. Schiessl asserted that the corrosion mechanism is similar to known mechanisms at polymer
coated steel surfaces exposed to outdoor environments. The mechanism is initiated when chloride levels at the reinforcing steel surface reach critical values and corrosion occurs at bare areas. Once a bare area is covered by corrosion products, a "self polarization" of the bare area will occur which induces opposite polarization in adjacent areas covered by the coating. The polymer coatings are permeable to moisture and oxygen, and therefore a cathodic reaction may take place under the coating, causing cathodic disbondment of the coating. Adhesion may also be lost by hydroxyl ions undercutting the coating around the defect. Schiessl suggested that even if there are no local defects in the coating, the permeation of water, oxygen and chloride ions through the film may result in very low rates of corrosion that, nonetheless, cause adhesion loss and, eventually, blistering. As corrosion propagates, the initially cathodic areas may become anodic as water and chlorides penetrate below the film. The increased anodic area causes further disbonding at increasing rates. The deterioration of the coating and the loss of its protective ability begins slowly and accelerates with time. The rate of degradation of the coating also increases rapidly with increasing water content of the concrete. Water is absorbed by the film, which not only softens it but increases its permeability. Diffusion of substances through the coating, or alternate wetting and drying also lead to embrittlement of the film.

Presentations made at the Transportation Research Board in Washington D.C. in January 1993 reflected the diversity of viewpoints about ECR. Nonetheless, it became clear from the presentations that the three most important properties influencing the corrosion performance of epoxy-coated reinforcing steel are

1. the maintenance of a high resistance coating,
2. the number of defects in the coating, and
3. the adhesion of the coating to the bar.

Ontario Field Performance Study

In addition to contributing samples of defective bars to the C-SHRP study by KCC INC, the Ontario Ministry of Transportation (MTO) undertook, in 1992, an extensive study of field performance of ECR. By undertaking the independent study, MTO sought to verify Clear's findings. Dr. David Manning of the MTO has reported on the status of ECR in Ontario in Corrosion Performance of Epoxy-Coated Reinforcing Steel: North American Experience. Excerpts from the paper are provided below.

The investigation included 12 bridges built in Ontario between 1978 and 1992. Only one structure had a number of small spalls in a barrier wall while the remainder appeared to be in good condition. However, the results showed that the coated bars were losing adhesion in the concrete, independent of whether corrosive conditions existed around the reinforcement. This provided the first confirmation of loss of adhesion of ECR under normal service conditions and the implications of this finding are serious. Most bars contain minor defects and, if there is sufficient salt to initiate corrosion, the corrosion will not be limited to the defects but will spread underneath the coating. In such situations the extension of service life, compared with black steel, would be short and repairs would be difficult.

C-SHRP Exposure Study

Following the study by MTO, C-SHRP undertook an exposure study to quantitatively assess the effect of storage conditions on the condition of epoxy-coated reinforcing bars. Three exposure sites were identified where specimens were placed on an outdoor exposure plot and left undisturbed in a secure location. A site in Alberta was selected to represent a dry, cold environment with large temperature fluctuations and high ultraviolet radiation. In New Brunswick, a site representing a marine environment was selected. A humid, temperate environment was represented by a site in Ontario. The specimens were 15M bars, each 1 m long with six 4 mm drilled holes. Three of the holes and the ends were patched. Two different coatings (3M Scotchkote 213 and Akzo) were tested. The bars coated with the Akzo coating also had a zinc chromate primer which was developed to counteract adhesion problems.
After one month, corrosion was observed in unpatched holes. The bars coated with the primer and Akzo coating showed no underfilm corrosion. The bars coated with Scotchkote had underfilm corrosion causing disbonding by six months.

No corrosion was evident in the patched holes on the bars coated with Scotchkote. The patches on the bars coated with Akzo were improperly cured and some corrosion was evident after six months.

Minor rust stains which increased with time were apparent around the end patches, regardless of coating type.

Once the data from the study have been fully analyzed, a final report for the work will be made available.

**Status of ECR in Ontario**

In cooperation between the MTO and the epoxy-coating industry, a number of actions have been undertaken to resolve the deficiencies in bond. Effective July 1993, the Ontario coating industry voluntarily agreed to supply rebars with improved adhesion produced using new technology which incorporates a primer between the epoxy coating and the steel bar. MTO agreed to place additional requirements for bond in the specifications and to work with industry to develop test procedures and acceptance criteria. Three test procedures were investigated to measure adhesion, a hot water soak, cathodic disbondment, and exposure to a salt spray. The hot water regime was found to be very discriminating in identifying bars with poor adhesion of the coating but there was poor correlation in knife adhesion ratings from different operators in round-robin testing. As a result, only the requirements for cathodic disbondment and salt spray testing were introduced into the specifications in 1994.

In Ontario, the following guidelines aimed at reducing the number of defects in ECR were implemented prior to the 1993 construction season.

- Unprotected storage shall not exceed 30 days, and the total on-site storage time shall not exceed 120 days.
- Bars with damage greater than 1% of their surface areas in any one metre length shall be rejected (not repaired).
- Any coating damage detected on bars which are accepted (i.e. with damage less than 1% of surface area) must be repaired.
- Resilient-head vibrators shall be used for placing concrete in bridge decks, barrier walls and end dams.

The requirement for resilient-head vibrators arose from a laboratory investigation in which concrete was placed in a form and compacted using a steel vibrator or a resilient vibrator following standard field procedures. The investigation was undertaken following a study in the United Kingdom which reported that about 80% of the defects measured on a coated bar occurred during compaction of the concrete. If a steel vibrator
were held against a bar, the coating could be removed from all the deformations. The resilient vibrator, in the worst case, could be made to penetrate the coating, but in normal use the coating was scuffed but not broken.

Improvements, such as those described above, made in the last two years have reduced the number of breaks in epoxy coatings and improved adhesion to the steel bar. Better techniques for ensuring the cleanliness and anchor pattern of the bar, and process changes such as the use of primers or inflexible coatings applied after bar fabrication, resulted in significantly improved adhesion when measured by accelerated laboratory tests. However, none of these tests have been correlated with field performance and the effect of the changes on long-term corrosion protection cannot be quantified. The relationship between corrosion performance and defects is well established, but the minimum number and size of defects which can be permitted without significantly compromising long term performance has not been established. In Ontario, the conclusion has been drawn that the necessary and sufficient conditions for the effective long term performance of epoxy-coated reinforcement exposed to environments containing salts have not been determined. Epoxy-coated reinforcement continues to be used in Ontario, although the policy is under review.
For full details of this research see:

Effectiveness of Epoxy-coated Reinforcing Steel - Interim Report
Kenneth C. Clear, Kenneth C. Clear, Inc.,
Boston, VA
Canadian Strategic Highway Research Program
Transportation Association of Canada
Ottawa, ON 1990

Effectiveness of Epoxy-coated Reinforcing Steel - Final Report
Kenneth C. Clear, Kenneth C. Clear, Inc.,
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Canadian Strategic Highway Research Program
Transportation Association of Canada
Ottawa, ON 1992

Corrosion Performance of Epoxy-Coated Reinforcing Steel: North American Experience
David G. Manning, to be published in “Construction and Building Materials”
Elsevier Science Limited, United Kingdom