EPOXY-COATED REINFORCING BARS — AN EFFECTIVE CORROSION-PROTECTION SYSTEM FOR REINFORCED CONCRETE STRUCTURES

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INTRODUCTION

Reinforced concrete is inherently a durable and near maintenance-free construction material under normal conditions. Harsh environmental conditions, such as exposure to deicing salts or seawater, however, can cause premature deterioration of the material. The expected service life of a reinforced concrete structure can be significantly reduced when chloride penetrates the concrete to the level of the steel reinforcement. When corrosion of the reinforcing steel is initiated, the products of corrosion expand and occupy a greater volume than the original steel and eventually cause cracking of the concrete. Once corrosion of the reinforcing steel has cracked the concrete, more chloride enters to attack the steel, and deterioration of the reinforced concrete component or structure proceeds at a faster pace. Premature deterioration of reinforced concrete structures due to corrosion of the reinforcing steel is of concern world-wide.

Epoxy-coated reinforcing bars have emerged as a viable and cost-effective corrosion-system for reinforced concrete structures. According to the original research, the epoxy coating is a physical barrier system that prevents moisture and chlorides from coming in contact with the bar (Ref. 1). Epoxy coating is also being regarded now as an electrochemical corrosion barrier which electrically isolates the bar by reducing the flow of corrosion current (Ref. 2).

In the USA, epoxy-coated reinforcing bars were used for the first time in highway bridge construction in 1973. During the intervening years, epoxy-coated bars have attained the status of being the preferred corrosion-protection system for bridge decks in a deicing salt environment. Epoxy-coated bars are also used in other components of reinforced concrete bridges, and in continuously reinforced concrete pavements. Other applications include parking garages, tunnels, wastewater treatment plants, and marine structures.

INDUSTRY PRACTICES AND MATERIAL SPECIFICATIONS

Coating Industry Practices

Steps in the basic procedure to epoxy coat reinforcing bars are abrasive blast cleaning of the bars to near-white metal; preheating of the cleaned bars to a temperature recommended by the manufacturer of the epoxy powder; application of the epoxy powder by the electrostatic spray method to the clean bars; and curing of the coating.

Two coating application processes are used in commercial practice. Presently, the most widely used process is to take stock length bars up to 60-feet (18-m) long, as received from a steel mill, and to epoxy coat several bars at the same time in a production-line operation. The epoxy-coated straight bars are then destined for fabrication or temporary storage. Fabrication consists of

cutting the coated bars to the lengths, or cutting and bending the coated bars to the configurations, required for the construction project. The cut ends, resulting from fabrication, should be coated with the patching material that is used for repairing damaged coating. Damaged coating on the bars, resulting from handling and fabrication, must be properly repaired prior to shipment of the coated bars to the jobsite.

In the second or alternate coating application process, the reinforcing bars, as received from a steel mill, are fabricated first and the epoxy coating is then applied to the fabricated bars. In this process, epoxy coating is also applied to the ends of the bars. Thus, there is no need to apply patching material to the ends. If any damage to the coating is incurred during handling of the coated bars at the epoxy coating plant, the damaged coating must be properly repaired prior to shipment of the coated bars to the jobsite.

ASTM Specifications

The two national consensus specifications for epoxy-coated reinforcing bars reflect the preceding coating application processes and industry practices. ASTM A775/A775M, which was issued in 1981, establishes the requirements for the epoxy coating of straight bars (Ref. 3). The second specification, designated as A934/A934M and adopted in 1995, prescribes the requirements for the epoxy coating of pre-fabricated bars (Ref. 4). Both specifications contain a common set of requirements for production-coated bars, including applicable acceptance tests therefor. These provisions include:

- Surface preparation of the bars before application of the coating.
- Recognition of, and permission to use, a pretreatment on the cleaned bars before application of the coating.
- Limits on the thickness of the coating; the permissible range of coating thickness after curing is 7 to 12 mils (175 to 300 μm).
- Continuity of coating; holidays* in the coating are limited to an average of one per foot (three per metre).
- Damaged coating is limited to one percent of the surface area in any one foot (0.3 metre) length of coated bar. A coated bar with damaged coating not exceeding the one percent limit is acceptable on the condition that all of the damaged coating is properly repaired prior to shipment to the jobsite. On the other hand, a coated bar with damaged coating exceeding the one percent limit is unacceptable even if the damaged coating were to be repaired.
- A mandatory annex which presents prequalification requirements in the form of testing criteria for chemical resistance of the coating, cathodic disbondment, salt spray resistance, chloride permeability, coating flexibility, relative bond strength in concrete, abrasion resistance, and impact.

Examples of differing requirements are: The ASTM A775/A775M specification prescribes a bend test to evaluate flexibility of the coating of production-coated bars. A section in ASTM A934/A934M requires cathodic disbondment testing of production-coated bars to evaluate coating adhesion.

* A holiday is defined as a discontinuity in a coating that is not discernible to a person with normal or corrected vision.

INITIATIVES TO ACHIEVE HIGHER-QUALITY EPOXY-COATED REINFORCING BARS

Following the introduction of epoxy-coated reinforcing bars as a protective system in bridge decks in the mid-1970's, the engineering community observed the apparent successful mitigation of the corrosion problem and the growing acceptance and specifying of epoxy-coated bars by State Departments of Transportation. Consultants and governmental agencies began to extend the usage of epoxy-coated bars to other types of reinforced concrete structures. A notable application on a large scale was in the construction of several bridges located in the Florida Keys. Significant premature corrosion of the epoxy-coated bars was detected in the substructures of several of the Keys bridges when the bridges had been in service for less than ten years. The portions of the substructures exhibiting the premature corrosion were located in a highly-corrosive environment — the splash zone with wetting and drying, and high water and air temperatures.

Several research studies and forensic evaluations were undertaken in response to the marginal performance of epoxy-coated bars in the Florida Keys bridges. Although those studies did not conclusively determine the cause of the problems in the substructures of the Keys bridges, the results of the studies and others have shown that performance is related to the quality of the coating. If there are numerous holidays in the coating and damage to the coating, the less effective the coating is in protecting against corrosion (Ref. 5).

Seizing upon the basic premise that "good performance in resisting corrosion is commensurate with the quality and integrity of the coating", considerable activity began, and it is ongoing, in three main areas:

- Improved quality control in the coating applicator plants and fabricator shops.
- More demanding requirements in the ASTM specifications for epoxy-coated bars.
- Emphasis on improving or upgrading construction practices at the jobsite.

Improving Quality Control

ASTM Specification A775/A775M prescribes acceptance tests and procedures with the objective of assuring production of a quality product. By following the prescriptive requirements in the specification, a satisfactory level of quality should be attained. Nonetheless, the reinforcing steel industry decided that a program should be instituted to improve the quality control in the epoxy coating applicator plants—a voluntary program comprising a means to measure or quantify an acceptable level of quality control. Thus, in 1991, the Concrete Reinforcing Steel Institute (CRSI) introduced its Voluntary Certification Program for Epoxy Coating Applicator Plants (Ref. 6). The program's objective is to assure a uniformly high level of excellence in plant facilities, production processes, and quality control. This industry-sponsored program sets forth stringent quality control procedures that in most cases, exceed the basic requirements of the ASTM A775/A775M specification.

CRSI's certification program has been well-received. Presently, over 30 applicator plants in North America are certified. Several State Departments of Transportation require their suppliers of epoxy-coated reinforcing bars to be certified under CRSI's program. Consulting engineering firms, who are highly knowledgeable about epoxy-coated bars, as well as with the epoxy coating industry and the certification program, contend that a significant increase in overall quality has occurred among the certified plants. Not to rest upon its laurels, the technical criteria of the program's manual are under continual review and revisions are adopted when deemed necessary to advance the level of quality and the industry.

More Demanding Requirements in ASTM Specifications

Revisions to ASTM A775/A775M

During the late 1980's in response to concerns about the Florida Keys bridges, a task group within the ASTM Subcommittee on Steel Reinforcement initiated a critical evaluation of the A775/A775M specification. The task group's goal was to develop proposed revisions to the specification which would translate into higher quality epoxy-coated bars. The task group's efforts focused on:

- Minimize the number of holidays in the coating.
- Reduce the limit on the number of permissible holidays.
- Require the repair of all damaged areas of coating which are incurred to the point of shipment of the coated bars to the jobsite.
- Reduce the limit on the total amount of damaged coating — all of which has to be repaired before the coated bars are shipped to the jobsite.
- Incorporate criteria in the specification to enhance adhesion of the coating to a bar.
- The frequency of conducting acceptance tests.

The task group proceeded to prepare specific revisions for the subcommittee's consideration and letter balloting. Considerable effort and time were expended to develop responsive and feasible revisions to the specification, and to secure their approval via letter balloting. The following revisions have been adopted in the A775/A775M specification during the period beginning with the 1989 edition and continuing through the current 1997 edition.

1. Coating Thickness — Raised the lower value of the permitted range of thickness to 7 mils (175 μm) from 5 mils (130 μm). Require 90% of all recorded thickness measurements to be 7 to 12 mils (175 to 300 μm). Measurements below 5 mils (125 μm) shall be considered cause for rejection of coated bars. Conduct thickness tests on a minimum of two bars of each size every four production hours.

2. Surface Preparation — Require average readings of 1.5 to 4.0 mils (40 to 100 μm) for the maximum roughness depth of the blast profile to assure a suitable anchor pattern. After abrasive blast cleaning, require the use of multidirectional high-pressure dry air knives to remove dust, grit and other foreign matter from the bar surface; prohibit the deposition of oil on the cleaned

bars by the air knives. Recognize and permit the use of a chemical wash or conversion of the steel surface of the bar to enhance adhesion; the pretreatment, if used, is applied after abrasive blast cleaning and prior to coating.

3. Coating Continuity — State in the specification that in-line holiday detection is recommended. The accuracy of the in-line system is to be verified by checking with a hand-held detector. Reduced the limit on the allowable number of holidays to an average of one per foot (three per metre) from two per foot (six per metre). Require conducting acceptance test on a minimum of two bars of each size every four production hours.

4. Coating Flexibility — Revised the requirements for conducting bend tests of coated bars; require a 180° bend except the bend angle for the large bars, bar sizes #14 and #18 (#43 and #57), is 90°; maximum time for completion of test is 15 seconds for bars to size #6 (#19), and 45 seconds for bar sizes #7 through #18 (#22 through #57). Previously, the bend angle was 120° and the test had to be completed within 90 seconds. Conduct a bend test on at least one bar of each size every four production hours.

5. Coating Adhesion — Evaluate production-coated bars by a cathodic disbondment test. The test is described in mandatory Annex A of the specification. Conduct test on at least one bar every eight production hours. Test data are to be furnished to purchaser upon request.

6. Permissible Amount of Damaged Coating and The Repair of Damaged Coating — All damaged coating incurred during handling and fabrication, to the point of shipment to the jobsite, must be repaired. Damaged coating on a bar is permitted to be repaired if the amount of damaged coating does not exceed one percent of the total surface area in each one foot (0.3 metre) length of the bar. The limit on the amount of repairable damaged coating does not include sheared or cut ends of bars that are required to be coated with patching material. Repaired areas of damaged coating shall have a minimum coating thickness of 7 mils (175 μm).

7. Storage — Require implementation of protective measures if coated bars are stored outdoors for more than two months before being shipped to the jobsite.

8. Three Major Revisions Have Been Adopted in Mandatory Annex A — The Annex Prescribes Requirements for The Coating Material (Prequalification)

a. Chemical Resistance — The requirements were revised to more accurately model the concrete environment to which epoxy-coated bars are exposed. Test requires immersion of coated bar specimens in distilled water, in a 3M aqueous solution of $CaCl_2$, in a 3M aqueous solution of NaOH, and in a solution saturated with $Ca(OH)_2$. Specimens are evaluated for blisters, softening, bond loss, if holidays developed, and the presence of undercutting.

b. Cathodic Disbondment — A coated bar specimen is immersed in 3% NaCl electrolyte solution; duration of test is 168 hours; average coating disbondment radius not to exceed 0.16 inches (4 mm).

c. Salt Spray Resistance — Evaluation of resistance of the coating in a hot, wet corrosive environment; salt spray 5% NaCl; duration of test is 800 ± 20 hours; average coating

disbondment radius not to exceed 0.12 inches (3 mm).

A non-mandatory Appendix has been added to the A775/A775M specification, titled Guidelines for Jobsite Practices. The appendix: (1) states the A775/A775M specification is a product specification and that it does not contain requirements for construction practices; (2) cites existence of the ACI 301 Standard Specifications for Structural Concrete (Ref. 7); (3) states that requirements for jobsite practices should be included in project specifications; and (4) states that in the absence of such requirements in project specifications, the guidelines delineated in the appendix are recommended.

Second ASTM Specification A934/A934M

In 1993, the task group initiated preparation of a second specification for epoxy-coated reinforcing bars. Development of the second specification occurred concurrently with the task of revising A775/A775M. This most recent specification, which received final approval in 1995 and is designated as A934/A934M, covers epoxy-coated prefabricated reinforcing bars. Under this specification, bars are fabricated prior to being epoxy-coated. Since the coated bars are not subject to bending, other types of epoxy coating materials can be used — harder and tougher but less flexible coating materials. Epoxy-coated prefabricated bars are intended for applications in the most-demanding corrosive environments. An examination of the contents of the specification reflects the intended applications of the coated bars. The specification includes requirements for:

- A cathodic disbondment test on production-coated bars to evaluate adhesion of the coating; a 24-hour test; for acceptance, the average coating disbondment radius cannot exceed 0.24 inches (6 mm).
- For prequalification of the coating material, a cathodic disbondment test with a duration of 168 hours; the average coating disbondment radius cannot exceed 0.08 inches (2 mm). A salt spray resistance test of 800 hours is also prescribed; the average coating disbondment radius cannot exceed 0.12 inches (3 mm).

Requirements in the A934/A934M specification at the onset also included: Recognition and permission to use pretreatment, limiting holidays to an average of one per foot (three per metre), and the same requirements for coating thickness, limits on and the repair of all damaged coating to the point of shipment, and so forth, as those adopted by the revisions in A775/A775M. The A934/A934M specification also includes two non-mandatory appendixes. One appendix is Guidelines for Jobsite Practices — similar to the guidelines in A775/A775M. The second appendix delineates procedures that should be included in a Coating Applicator's Quality Assurance Program for the coating application process and product testing.

Upgrading Construction Practices

The preceding efforts to improve quality control at the epoxy coating plant and to make the ASTM specifications more demanding have resulted in significant improvement in the overall quality of epoxy-coated reinforcing bars. Most observers agree, however, that the major challenge in improving overall quality of epoxy-coated bars is concerned with construction practices at the jobsite. Field investigations and experience indicate that most damage to the coating occurs in shipment to the jobsite and from construction practices at the jobsite. While the epoxy coating is relatively hard and it possesses abrasion resistance, more care must be exercised with epoxy-coated bars during construction operations as compared to the degree of care

exercised with uncoated reinforcing bars. Since practices at the jobsite are deemed to be such an important aspect of attaining overall quality of epoxy-coated bars, recommended construction practices are presented in Appendix A of this paper.

To be meaningful so that the desired end results are achieved, requirements for jobsite practices should be:

- Stated in mandatory language
- Reasonable
- Enforceable
- An integral part of the contract documents

The project specifications are the key element for controlling site practices. Consultants and agencies ought to ensure that their project specifications include appropriate clauses for epoxy-coated bars, and that the requirements are achievable and enforceable. In the USA, a national consensus standard specification covering all aspects of cast-in-place reinforced concrete structures, the ACI 301 Standard Specifications for Structural Concrete (Ref. 7), includes provisions for epoxy-coated reinforcing bars. The ACI 301 standard is widely used. Some agencies and consultants use the document in its entirety by reference for their construction projects. Other agencies and large consulting engineering firms use the ACI 301 standard as a resource document for developing the reinforced concrete section in their project specifications.

AREMA Requirements

Chapter 8 of the *AREMA Manual* (Ref. 8) requires epoxy-coated reinforcing bars to conform to ASTM A775/A775M or A934/A934M. The chapter contains provisions for construction practices: handling, storing, supporting, tying, and placing; limits on the amount of damaged coating, and repair of all damaged coating resulting from construction activities at the jobsite. Chapter 8 also includes the widely-accepted design requirements for determining the tension development length of epoxy-coated bars. Section 2.14e requires increasing the basic tension development length for epoxy-coated bars — a 50% increase when concrete cover is less than three bar diameters or clear spacing between bars is less than six bar diameters; and a 15% increase for other conditions of concrete cover and clear spacing.

Quality Concrete and Good Construction Practices

Emphasis in the preceding discussion of jobsite practices and the recommended construction practices in Appendix A are aimed at minimizing damaged coating. Minimizing damaged coating, and properly repairing coating that has sustained damage, should result in significantly increasing the long-term performance of epoxy-coated reinforcing bars in resisting corrosion. It should be realized, however, that the use of high quality epoxy-coated bars is but one element or

component, albeit a major part, of an overall strategy for the corrosion protection of reinforced concrete structures. A comprehensive strategy for effective corrosion protection should begin with quality concrete and require good concrete construction practices, including:

- Limit the amount of chloride being introduced into the concrete mix.
- Maintain a low water-cement ratio; cement in this context includes all cementitious materials, i.e., maintain a low water-cementitious materials ratio.
- Consider the use of high-range water-reducing admixtures.
- Provide and maintain adequate concrete cover to epoxy-coated reinforcing bars.
- Thoroughly consolidate concrete.
- Provide adequate curing.

PERFORMANCE OF EPOXY-COATED REINFORCING BARS IN CONCRETE STRUCTURES

Deicing Salt Environment

Overall, the track record of performance in resisting corrosion in deicing salt environments is very good. Several State Departments of Transportation have reported favorably on the excellent performance of epoxy-coated bars. The effectiveness and excellent performance of epoxy-coated bars in bridge decks over a 20-year period is documented in Reference 9, which reports on the first-known installations of epoxy-coated bars in 12 States. The 12 States are considered to be heavy users of epoxy-coated reinforcing bars – representing over 50% of the USA bridges using coated bars as the corrosion-protection system in bridge decks. States included in the report are Illinois, Indiana, Iowa, Kansas, Kentucky, Maryland, Michigan, Minnesota, Missouri, Nebraska, Ohio and Wisconsin. All of the condition reports are for structures built in the 1970's. Another documented example of excellent performance is the West Virginia DOT's report on their condition survey of the decks of several bridges (Ref. 10). The bridges were constructed in 1974-76. Little or no distress was observed in the decks reinforced with epoxy-coated bars. The West Virginia authorities commented in their inspection report: "It could be concluded from the data gathered in this investigation that the use of epoxy-coated reinforcement does result in a dramatic reduction of delamination in bridge decks and by inference an increase in the useful life expected of the deck."

Table 1 presents the latest available performance data for the first bridge decks in 14 States in which epoxy-coated bars were used. In the 1970's, many State DOT's specified epoxy-coated bars only in the top mat of reinforcement. Research has shown long-term performance is enhanced when all reinforcement is epoxy-coated. Current practice is to require both mats to be epoxy-coated.

Table 1 First Use of Epoxy-Coated Reinforcing Bars in Bridge Decks Deck Condition and Grading[1]

State DOT	Coated Bars in Top or in Top and Bottom Mats[2]	Bridge Opened	Initial Grade-Year	Latest Grade-Year	Deck Maintenance Caused by Rebar
Illinois	Top	1977	N/A	7-1997	0
Indiana	Top & Bottom	1976	7-1976	6-1997	0
Iowa	Top	1975	8-1975	7-1997	0
Kansas	Top	1977	8-1977	8-1997	0
Kentucky	Top	1975	7-1981*	7-1997	0
Maryland	Top & Bottom	1974	9-1974	7-1996	0
Michigan Michigan Michigan	Top & Bottom Top & Bottom Top & Bottom	1976 1976 1976	8-1980 8-1980 8-1980	7-1997 6-1996 7-1997	0 0 0
Minnesota	Top	1973	8-1973	7-1996	0
Missouri	Top	1974	9-1974	7-1996	0
Nebraska Nebraska	Top Top	1975 1976	9-1975 N/A	7-1997 8-1997	0 0
Ohio	Top	1974	8-1985*	7-1997	0
Pennsylvania[3]	Top	1973	6-1989*	5-1997	0
West Virginia	Top	1973	9-1973	6-1997	0
Wisconsin Wisconsin	Top Top	1975 1976	9-1975 9-1976	7-1996 8-1996	0 0

1. Data compiled in January 1998.
2. "Mat" refers to the layers of reinforcing bars; "Top" for the orthogonal grid of bars near top surface of deck and "Bottom" for the grid near bottom surface of deck.
3. Acknowledged as the first use of epoxy-coated reinforcing bars in a bridge deck.

N/A = not available * Initial grade unknown
FHWA Grade 0 to 9.9 Grade of 9 = new condition Grade of 8, 7, 6 and 5 = very good to satisfactory

Reference 11 summarizes the evaluations of 92 bridge decks, two bridge barrier rails, and a noise barrier rail – located in 11 States and three Canadian provinces. Information presented in the report is supportive of the use of epoxy-coated reinforcing bars as a corrosion-protection system. The authors' conclusions include: The overall condition of the bridge decks was considered to be good; no evidence of any significant premature concrete deterioration that could be attributed to corrosion of epoxy-coated bars; and the use of adequate good quality concrete cover, adequate inspection, finishing and curing of the concrete, and the proper manufacturing and handling of epoxy-coated bars complements the use of epoxy-coated bars in providing effective corrosion protection for concrete bridge decks. Epoxy-coated reinforcing bars provided effective corrosion protection for up to 20 years of service.

Reference 12 presents information on the performance of epoxy-coated bars in deicing salt environments which has been reported by three other States: New York, Pennsylvania and Virginia. Performance was described as satisfactory.

An evaluation of three bridge decks in Virginia, conducted in 1996, has been reported (Ref. 13). The bridges had been in service for 17 years. Epoxy-coated bars comprised the top mat of reinforcement in the decks. Uncoated bars were used for the bottom mat of reinforcement. Examination of the coated bars showed significant loss of coating adhesion and corrosion is occurring under the epoxy coating.

Thus, the published data show that the overall performance of epoxy-coated reinforcing bars in a deicing salt environment is certainly admirable and adds to the body of technical information and confidence in the material. And that epoxy-coated bars are mitigating the premature deterioration of bridge decks for which the coated bars were originally intended. At this time, however, published data are lacking regarding the performance of epoxy-coated bars in other corrosive environments. The relatively few evaluations of the performance of epoxy-coated bars in non-deicing salt environments, which have been reported in the technical literature, are summarized in the following discussion.

Bridges in Marine Environments

Reference 14 includes an excellent summary of field performance of epoxy-coated reinforcing bars in actual structures. The summary, which covers findings in reports through mid-1995, essentially confirms the overall good performance of epoxy-coated bars in deicing salt environments as stated earlier in this paper. Reference 14 also reports on the performance of epoxy-coated bars in a 9-year old coastal bridge in the State of Georgia which was subjected to seawater tidal and splash. Evidence of inadequate concrete consolidation was observed along with severe corrosion of the epoxy-coated bars. The evaluators of the structure questioned the added corrosion protection of epoxy coating and recommended that epoxy-coated bars should not be used in a continually wet marine substructure. Information on the performance of epoxy-coated bars in three coastal bridges in North Carolina is also reported. Examination of the substructures of the approximately 8-year old bridges in North Carolina revealed no significant corrosion of the epoxy-coated bars. The investigators of the substructures concluded that epoxy coating was providing adequate corrosion protection. In the part of their paper, update on field performance, the authors report on investigations of some 26 bridges in Florida outside the Keys.

The bridges were located within the Florida DOT's areas which are designated as Extremely Corrosive Category. The structures were found to be generally corrosion-free, which the authors attribute to the quality of the concrete and thick concrete cover over the reinforcing bars, and not necessarily to the usage of epoxy-coated bars.

U.S. Navy Exposure Tests

The results of a research project by the U.S. Naval Facilities Engineering Service Center (NFESC) have been reported (Ref. 15). In this study, concrete specimens, reinforced with epoxy-coated bars or zinc-coated (galvanized) bars, were evaluated after seven years exposure in three different marine environments. The specimens were placed in nylon nets and suspended from piers into the marine intertidal zone at three locations: at Bermuda; at Key West, Florida; and at Port Hueneme, California. The epoxy-coated bars performed very well. Comments in the report's conclusions include: Epoxy-coated rebar and zinc-coated (galvanized) rebar can extend the life expectancy of reinforced concrete structures in the marine environment. The degree of life extension offered is a function of the quality of the concrete and quality of the epoxy coating. Many factors affect both issues and one must impose rigorous standards to assure optimum performance. Results from NFESC field experiments using relatively porous concrete show that near perfect epoxy coatings or hot-dipped galvanizing can eliminate surface spalls for at least seven years. Reference 16 provides further information on the NFESC's exposure program at Key West, Florida. Rankings of the performance of the specimens in the exposure study were: Damage-free epoxy-coated bars performed best, followed by galvanized rebar, uncoated rebar with calcium nitrite admixture, uncoated rebar, and finally uncoated rebar with calcium nitrite pretreatment.

Exposure Tests in Japan

A paper, which was published in 1994, reports on exposure tests of precracked reinforced concrete specimens in a marine environment in Japan (Ref. 17). The epoxy-coated bars performed very well. After five years of exposure, the authors stated: ". . . When epoxy-coated reinforcing bars were used, almost no corrosion or longitudinal cracks were found. This indicates that epoxy-coated bars were cost-effective in preventing corrosion . . ." After ten years of exposure, there was evidence of corrosion in some of the epoxy-coated bars that the authors attributed to: "....inadequate hardening of the coating, bluing of the reinforcing bar, and partial lack of coating thickness, all of which reflected inadequate manufacturing technology for epoxy-coated reinforcing bars at the early stages of that industry in Japan." They reported the bars were coated in 1980, and that the problems with coating technology have now been solved.

Exposure Tests in Saudi Arabia

Reference 18 reports on the performance of epoxy-coated bars, galvanized bars, stainless-clad bars, and uncoated bars which were embedded in concrete with three different chloride contents. The test specimens were exposed outdoors for seven years on a site at the King Fahd University of Petroleum and Minerals in Dhahran. The epoxy-coated bars, which were coated in accordance with ASTM A775/A775M-81, performed well in the test specimens with concrete chloride contents of 2.4 and 4.8 kg/m^3. In the concrete specimens with the highest chloride content (19.2 kg/m^3), the epoxy-coated bars exhibited significant corrosion which was advancing under the

epoxy coating. Only the stainless-clad bars performed well in the concrete specimens with the highest chloride content. The stainless-clad bars did not exhibit any sign of corrosion after seven years.

Exposure Tests in United Arab Emirates

Reference 19 is an interim report on a long-term research study in the UAE. A part of the study involves reinforced concrete specimens which are exposed to aggressive environmental conditions at a site adjacent to Dubai Creek. The specimens were placed at the exposure site in December 1991. The specimens are situated above ground, below ground, and in the tidal zone. Another part of the study in concerned with evaluating the effectiveness of two rebar coating systems. The research work is scheduled to continue through 1998. Included among several general conclusions in Reference 19, the researchers state that after the concrete specimens had been exposed for three years, the epoxy-coated bars in concrete with a water-cement ratio of 0.44 did not exhibit any symptoms of corrosion. The researchers emphasize that their general conclusions after three years of exposure should be regarded as tentative. The exposed specimens were not in a state of stress (structurally) and that the observed trends to date may change with time.

Study at University of New Brunswick

An experimental study is underway that uses an accelerated testing apparatus to subject test specimens to simulated sea water (Ref. 20). The researchers contend that one year of accelerated testing by the apparatus is equivalent to approximately 8 to 10 years of natural marine exposure at Treat Island, Maine. (The Treat Island site is an especially severe environment — freezing and thawing plus a large tidal range.) Test specimens in the program represent a variety of concrete mixtures, including high-performance concrete incorporating silica fume, prefabricated and post-fabricated epoxy-coated bars, and other corrosion-resisting materials. Some specimens were fabricated with a preformed crack. Results to date indicate epoxy-coated bars are performing very well.

CLOSING COMMENTS

Protecting reinforcing steel from corrosion in concrete structures is indeed a dynamic technology. In the USA during the 1960's, the dilemma of premature deterioration of reinforced concrete bridge decks in the deicing salt environment served as the attention-getter to a widespread and costly problem. It is interesting to observe that the corrosion of steel reinforcement in somewhat lower-technology structural systems, viz., bridge decks, has lead to high-technology means and methods of mitigating the problem. In the USA, individuals and agencies who have the authority to establish policy and provide funding were able to easily relate to the decay of a somewhat simple structural system and its importance to the nation's infrastructure. And research and development projects, like the landmark NBS work on epoxy-coated reinforcing bars (Ref. 1), became a reality.

Technical authorities are now advancing the goal of a service life of 75 years or more for bridges. In various fields of technology and construction materials, the term "high-performance" is becoming increasingly popular, e.g., "high-performance concrete". Corrosion experts are also

speaking of redundant corrosion-protection systems to achieve satisfactory long-term performance. Using epoxy-coated reinforcing bars in combination with another material or system would be an example of a redundant corrosion-protection system.

Research on epoxy-coated bars is ongoing. Several projects are currently underway — laboratory studies, field exposure tests, and evaluation of actual structures. A major laboratory project completed in 1998 was a 5-year study funded by the U.S. Federal Highway Administration. Several types of bars and coatings were evaluated. Some 24 types of bars including inorganic-clad, ceramic-clad, copper-clad, stainless steel, zinc-coated (galvanized), and so forth, were part of the initial testing. Initially 33 different organic-coated bars were evaluated. After initial testing to select the most-promising candidates from the vast array of materials, the researchers proceeded to the phase of the program which involved in-place concrete accelerated corrosion testing. The epoxy-coated bars, which were tested in the two-year in-concrete phase, included three nonflexible and three flexible epoxy coatings. The report for the project, which was published in December 1999 (Ref. 21), is supportive of epoxy-coated bars. It includes a statement: The research supports the continued use of epoxy-coated reinforcing bars as a corrosion-protection system.

Another aspect of the quest for extended service life of civil engineering structures is concerned with the concept of life-cycle costs. Corrosion-protection systems which have a projected long service life but may be perceived as being too expensive in terms of initial costs could fare favorably in a life-cycle cost analysis. For example, the initial cost of redundant systems might be viewed as being more favorable when such costs are amortized over a longer service life.

Thus, it is an exciting and challenging time to be a participant in the process of mitigating the corrosion problem. The many challenges involve technology in the broadest sense. Materials science, engineering, and construction are all a part of the overall solution. Economics or cost-effectiveness are also vitally important.

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APPENDIX A — RECOMMENDED CONSTRUCTION PRACTICES

The majority of the following recommendations can be characterized as common-sense. These recommended practices are relatively simple, but effective ways to minimize coating damage and extend the corrosion protection benefit of epoxy-coated reinforcing bars.

Preconstruction Meeting

When a construction project involves the use of epoxy-coated bars, a preconstruction meeting or conference would be an ideal time to initiate the steps for achieving quality at the jobsite. Effective communication at that time should minimize future problems and disputes among the various parties. Applicable provisions in the project specifications should be reviewed. The Owner's representative should clearly communicate the intent to enforce those provisions. All parties connected with the epoxy-coated bars should participate in the meeting. The roles and

responsibilities of the parties should be established or clarified. Specific construction practices and inspection procedures should be reviewed. Anticipated delivery schedules of epoxy-coated bars and proposed storage sites should also be outlined.

Delivery of Coated Bars

Upon receipt of epoxy-coated bars at the jobsite, the quantities of bars should be carefully checked against the bill of materials. Repair (touch-up) kits and instructions for their use may accompany the delivery of coated bars. During the unloading operation, the coated bars should be inspected for coating damage incurred in shipment. If shortages or damaged bars are found, the carrier should be notified. Bars with extensive damaged coating which cannot be repaired at the jobsite should be rejected and will require re-shipment of replacement coated bars. Coated bars with damage, within the limits established in the project specifications, should be repaired.

Handling

During the unloading of epoxy-coated reinforcing bars from a truck, care must be exercised to minimize scraping of the bundles or bar-to-bar abrasion from sags in the bundles. Bundles of coated bars should not be skidded from the truck bed over timbers or rails to the ground as is usually done with bundles of uncoated bars when power hoisting equipment is not available. Power hoisting equipment should be used for unloading and handling the bundles of coated bars. If hoisting equipment is unavailable, smaller units or individual coated bars should be carefully off-loaded by hand. Equipment for handling the bars should have protected contact areas. Nylon slings or padded wire rope slings should be used. Bundles of coated bars should be lifted at multiple pick-up points. Hoisting with a spreader beam or similar device is an effective method of preventing sags in bundles of coated bars. Coated bars or bundles of coated bars should not be dropped or dragged.

Storage

Reinforcing bars, and in particular epoxy-coated bars, should be stored as close as possible to the area on the structure where they will be placed to keep handling operations to a minimum. Deliveries of coated bars to the jobsite should be scheduled and coordinated with placing the bars in the structure to avoid any need for long-term storage at the jobsite. Storage of epoxy-coated reinforcing bars at the jobsite, such as from one construction season to the next, is not recommended. If circumstances or other conditions make it absolutely necessary to store epoxy-coated bars outdoors for an extended period of time, the bars should be protected from sunlight and salt spray, and sheltered from the weather. Current practice is to implement protective measures when storage of coated bars at the jobsite is expected to exceed two months. Shorter periods should be considered when coated bars are expected to be stored in severe corrosive environments. The following storage practices are recommended to minimize the amount of damaged coating:

- Store coated bars above the ground on protective timbers; space the supports sufficiently close to prevent sags in the bundles.
- If a relatively large quantity of coated bars has to be stored in a small area, bundles of straight bars should be stacked with adequate blocking placed between the layers of bundles.

- Cover the bars or bundles of coated bars with opaque polyethylene sheeting or other suitable protective material. For stacked bundles, drape the protective covering over the sides of the bundles around the perimeter of the stack. Secure the covering adequately, and make provisions for adequate air circulation around the bars to minimize condensation under the covering.

Since there are various possible shapes and dimensions of bent bars, some of the preceding recommended practices, such as stacking of bundles, may not be directly applicable nor practical for the storage of bent bars.

Identification

To maintain and assure identification of the stored bars, non-metallic tags on the bundles of coated bars should be protected, or consideration should be given to attaching additional back-up galvanized metal tags on all bundles of bars.

Placing

In general, placing of epoxy-coated reinforcing bars is done similarly as for uncoated bars. The key exception is that coated bars require more careful handling and placing. The same hoisting and handling methods and precautions, which were discussed for unloading coated bars from a truck, should be used and followed during all placing operations. After bundles of epoxy-coated bars have been broken, dragging one bar over another, or over any abrasive surface should be avoided. Using common-sense precautions should minimize coating damage during placing operations.

Bar Supports and Spacers

Non-corrosive bar supports and spacers should be used for epoxy-coated reinforcing bars. The requirements for these materials should be included in the project specifications. The purpose of the special types of bar supports and spacers is to: (1) minimize damage to the coating on the bars during field placing of the coated bars; (2) avoid establishing electrical contact between coated bars; and (3) not to introduce a potential source of corrosion at and in close proximity to the point of contact of the bar supports with the coated rebars. Usually wire bar supports and spacers or portions of them will be coated with epoxy or vinyl (plastic) material. Bar supports and spacers on the jobsite might be made of non-metallic material. Recommendations for bar supports and spacers for supporting epoxy-coated reinforcing bars are:

- Wire bar supports and spacers should be coated with non-conductive material such as epoxy or plastic, which is compatible with concrete, or
- Bar supports and spacers should be made of dielectric material. If precast concrete blocks with embedded tie wires or precast concrete doweled blocks are used, the wires or dowels should be epoxy-coated or plastic-coated; or,
- Reinforcing bars that are used as support bars should be epoxy-coated.

Additional information on bar supports and spacers, and industry practices are presented in Reference 22.

Tie Wire

Coated tie wire should be used for fastening and assembling coated bars. The reason for using coated tie wire is to minimize cutting into the bar coating, and to avoid electrically tying the bars together. Tie wire is typically black-annealed wire. The coating material on the wire is usually plastic or epoxy. Suitable coated tie wire is commercially available.

Splices

Splices of epoxy-coated bars are essentially the same as those for uncoated bars. The design drawings and project specifications should contain any special requirements.

Lap Splices

Epoxy-coated bars have less bond strength in concrete than uncoated bars. Thus, tension lap splice lengths probably will be longer than those for comparable size uncoated bars.

Mechanical Splices

The project specifications should require that after installation of the mechanical splices, all parts of the splices including steel sleeves, bolts and nuts must be coated with the same patching material which is used for the repair of damaged coating on the bars; and coating damage on the bars in the vicinity of the splices must be repaired. For well-planned and coordinated projects, which require numerous mechanical splices, consideration should be given to epoxy coat the mechanical splice hardware at a coating applicator plant --- epoxy-coated similarly as the reinforcing bars.

Welded Splices

Some agencies discourage or even prohibit the welding of epoxy-coated bars because considerable damage to the coating in the vicinity of welded splices most likely will occur. Welding of epoxy-coated bars is addressed in the ANSI/AWS D1.4 Welding Code (Ref. 23) and in Reference 7. Suitable ventilation should be provided when welding coated bars.

Field Cutting

Field cutting of reinforcing bars, whether uncoated or coated, should be done only if permitted by the Architect-Engineer*. The project specifications should address field cutting, and in the case of epoxy-coated bars, the project specifications should require coating of the cut ends with the same material that is used for the repair of damaged coating. Coating damage and field touch-up can be reduced by saw cutting. Flame-cutting of epoxy-coated bars should be prohibited.

Field Bending or Straightening

The project specifications should also contain any special requirements for field bending or straightening of epoxy-coated bars which are partially embedded in hardened concrete. The project specifications should require repair of damaged coating after the bending or straightening has been completed. If the Architect-Engineer approves the use of heat for the field bending or straightening, suitable ventilation should be provided.

* In this context, field cutting is the unplanned cutting of bars when corrective action must be taken so that placing operations can continue. Corrective actions might require cutting bars to avoid obstructions, adjusting overlength bars for fit, and so forth.

Other Precautions

After the epoxy-coated bars are placed, walking on the bars by workers should be held to a minimum. Workers should be careful not to drop large hand tools or other heavy construction materials on the coated bars in place. Care should be exercised so that concrete conveying and placement equipment does not damage the coated bars. Runways for concrete buggies and hoses for pumping concrete should be set up, supported and moved carefully to minimize damage to the coating and not displace the bars out of their intended position.

Repair of Damaged Coating

Damaged coating must be repaired. The patching or touch-up material should be applied in strict accordance with the instructions furnished by the manufacturer of the patching material. Generally, surface preparation consists of thorough manual cleaning of damaged spots and complete removal of rust. Cleaning is usually done with a wire brush and emery paper. Care should be exercised during the preparation of the surface so that the bare areas are not made larger than necessary to accomplish the repair of the damaged spots. The patching material should be allowed to cure, according to the manufacturer's instructions, before concrete is placed over the bars.

Current practice is to require the repair of all damaged coating. Proper repair of damaged coating can be a tedious, time-consuming, and expensive operation. It is more productive and cost-effective to exercise care during the construction operations at the jobsite rather than having to repair extensive coating damage. If the amount of damaged coating exceeds the limits established by the project specifications, the bars will be subject to rejection and will have to be replaced. Replacement or additional coated bars may not be readily available, and could cause delays in the construction schedule.

Placing and Consolidating Concrete

Epoxy coating is also susceptible to damage from concreting operations. A study by the British Research Establishment was undertaken to assess damage caused by placing and consolidating (vibrating) concrete (Ref. 24). The troublesome aspect of damaged coating from such sources is that the damaged bars cannot be inspected nor repaired. It would be prudent to equip all immersion-type vibrators used on a project with non-metallic heads.