EPOXY-COATED REBARS IN EUROPE: RESEARCH PROJECTS, REQUIREMENTS AND USE

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The first European pilot construction projects with epoxy-coated reinforcing steel have been completed, some fifteen years after the first applications in North America. Epoxy-coated rebars were used for the first time on a large scale in Denmark, 1990, as part of the Storebaelt Tunnel project and on some other projects in Switzerland, Germany and Great Britain. Initial tests in Germany in 1983 identified the conditions under which epoxy-coated rebars (ECR) should be used. These test results were used as the basis for a German guideline on the use of epoxy-coated rebars. The requirements in these guidelines are similar to those in the ASTM A 775 Standard, but are generally more stringent. Limited preliminary tests investigating the behavior of damaged epoxy-coated rebars in different chemical environments with cathodic and anodic polarization indicate the need to examine the causes of unexpected material performance problems such as disbonding and under-rusting. Additional tests are needed to obtain a more accurate view of the mechanisms involved and their correlation with decisive influencing parameters in the long-term performance of ECR in aggressive environments.

INTRODUCTION

In 1983 the first test in Europe to examine the suitability of reinforcing steel coatings as a corrosion protective measure were initiated at the Institute for Reinforcing Steel and Reinforced Concrete Structures (IBS) in Munich, Germany. Some 40 different coatings were examined using standard test methods employed in Europe and the North America in the pipe-coating and rebar coating field. The fusion-bonded epoxy-coatings achieved the best performance with respect to corrosion protection of rebars.

In the early 1980's tests with epoxy-coated and PVC-coated rebars were performed at the University of Stuttgart. In the mid-1980's, tests with different powders were started at the Institut für Bauforschung (Building Research Institute - IBAC) of the RWTH Aachen. These tests were conducted in cooperation with powder coating manufacturers to provide coated reinforcing steels with improved quality characteristics for the German market.

In 1987 an independent German expert group was formed at the Institut für Bautechnik in Berlin (Institute for Building Technology (IFBT) -- the national authority responsible for approval of building materials not covered by national standards) to develop technical guidelines for the production and use of epoxy-coated rebars (ECR). The technical guidelines developed by this expert group are based on a review of the literature in Europe and North America, and rebar testing. The basic finding of this group was that the requirements for ECR should be the highest possible. Their test results showed that high powder quality and adhesion of the coating film to the steel surface were the most important parameters for corrosion protection. Adhesion is dependent primarily on the cleanness of the steel surface, i.e., effectiveness of the blasting procedure. Based on these tests, three epoxy resins and one PVC-system have been certified by the IFBT. In Germany, two coating companies that produce welded wire meshes and steel bars have IFBT certification. The PVC-system was never produced and marketed.

Similar studies were begun in the 1980's in other European countries, including Great Britain, the Netherlands and Norway. Coating plants for rebars have been constructed in Norway, Great Britain and Switzerland.

In the late 1980's discussions between Swiss, Dutch and German experts were initiated to harmonize guidelines and standards for ECR. The Swiss and German guidelines have been published and are very similar. The Dutch guidelines have just recently been published. All of the guidelines are similar to those in ASTM A 775 Standard with generally stricter requirements.

REQUIREMENTS FOR COATED REBARS AND COMPARISON OF GUIDELINES

The design engineer should use the same design and dimensioning characteristics for coated reinforcing steels as for uncoated steels. The organic coating should provide permanent protection against corrosion for the

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reinforcement. Table I compares the requirements imposed for ECR in various international guidelines or standards (*1*). The German and Swiss guidelines have been harmonized as a result of close cooperation between the two countries, and thus, the German requirements represent both in Table I.

The quality of adhesion of the coating to the steel surface is one of the dominating parameters with respect to the effectiveness of epoxy-coated rebars, and is dependent primarily on the cleanness of the steel surface (i.e., effectiveness of the grit blasting procedure). The roughness of the steel surface after blasting is another factor. Investigations have shown that the hot water test, immersion of coated rebars in 90°C (194°F) demineralized water, is an excellent test for quality of adhesion and to a certain extent the permeability of the coating film. This test is accepted in Germany and Switzerland as a quality criterion in the pipe coating business, and is one of the main quality control tests in the German guideline. Recent studies indicate that permeability is also an important property in long-term corrosion protection. Besides the hot water test, the cathodic disbonding test has been used to evaluate the quality of adhesion and the quality of application at the coating plant. This test is required in European guidelines/standards. The ASTM standards do not have a selective adhesion test requirement.

Requirements on other points shown in Table I, such as bendability, corrosion resistance, maximum permissible defect size and freedom from holidays are very stringent in the German guideline. The German regulations are also strict in terms of conditions of use, such as minimum spandrel diameter and permissible defects. The German and Swiss guidelines recommend exclusive use of coated reinforcement in any single structural component. Where coated and uncoated reinforcement are combined, suitable binder wires and spacers must be employed to exclude any electrically conductive contact. The Swiss guideline prescribes electrical resistance measurements between coated and uncoated bars where mixed reinforcing systems are used.

In Germany, an association for coated reinforcing steels has been founded with the objectives of assuring a quality standard that exceeds the requirements of the guidelines, and initiating research projects to extend scientific knowledge in coated reinforcing steels.

EXPERIENCE IN USE

European experience in the use of ECR in construction projects is limited. Some projects are presented below.

Spiez Bridge, Switzerland. This is the first civil engineering structure in Switzerland to incorporate epoxy-coated reinforcing steel in the barrier walls of the four-section bridge 57 m (187 ft) long by 11.8 m (38.7 ft) wide. The exposed bridge is subjected to extensive weathering and road salt. The project was completed in 1988 with close collaboration between the Bundesamt für Straßenbau (Federal Highway Construction Authority), the Institut für Baustoffe, Werkstoffchemie and Korrosion (Institute for Building Materials, Materials Chemistry and Corrosion) of the ETH Zürich, and a coating company. The objective of the project was to acquire experience in the handling and installation of epoxy-coated reinforcing steels and to test the long-term behavior of the coating and the rebars. For comparison, half of each of the two barrier walls was constructed with coated and half with uncoated reinforcement. Inspection areas, 0.5 to 5 cm^2 (0.1 to 0.8 in^2), were constructed at two different heights from the road deck on selected coated steel elements to allow monitoring of corrosion behavior. One half of the inspection area steel is insulated, and the other half is connected externally to the uncoated reinforcement of the road deck. This permits periodic measurement of the corrosion potential, the electrical resistance and the macro-element current. Up to now (October 1992), all coated-rebars are in the passive state, as is the uncoated reinforcement.

Cooling Towers for a Cell Re-cooling Plant in Ludwigshafen, Germany. The first large-scale use of epoxy-coated reinforcing steels in Germany was in the cooling towers of a cell re-cooling plant for the chemical industry. Roughly 18 t (20 tons) of coated reinforcing steel were used for the site-mixed concrete cover of the re-cooling works and the prefabricated shell elements of the diffusors. Since neither a national standard nor a suitability test was available for the epoxy resin powder, individual certification by the supervising authority IFBT, was necessary. Studies on the suitability of the powder for the specific application were conducted at the IBAC.

Reinforced Concrete Elements of the Storebaelt Tunnel, Denmark. The most extensive European pilot project for ECR is the 7.3 km (4.5 mi) railway tunnel beneath the Great Belt forming part of the rail connection between the Danish Islands of Funen and Zealand. The reinforcing steel for the concrete segments, approx-

TABLE I COMPARISON OF REQUIREMENTS FOR EPOXY-COATED REBAR IN DIFFERENT STANDARDS/GUIDELINES

REQUIREMENT	GERMAN GUIDELINE IFBT -RULE 05.90	ASTM A 775/90	BRITISH STANDARD 09.90
POWDER IDENTIFICATION	• DSC, TGA, IR	-	-
DIFFUSION*	• H_20-Diffusion • H_20-Absorption	• Chloride • Diffusion	- -
CHEMICAL RESISTANCE	• 10% NaOH • Bars Embedded in Concrete • Outdoor Exposure (Free)	• Distilled Water** • 3 M $CaCl_2$** • 3 M $Ca(0H)_2$**	• 3 M $CaCl_2$** • 3 M NaOH** • 3 M $Ca(0H)_2$**
ADHESION QUALITY	• Hot-Water Test • MIBK Test • Cathodic Disbonding	- - -	• Cut Test** - • Cathodic Disbonding
COATING THICKNESS	• 130 to 300 μm	• 130 to 300 μm	• 200 ± 50 μm
BENDABILITY d_{br} = mandrel diameter d_s = steel diameter	• Testing $d_{br} = 4\ d_s$, ($d_s < 20$ mm) $d_{br} = 6\ d_s$, ($d_s \geq 20$ mm) Additional Bending After 6 Months Outdoor Exposure • Application $d_{br} = 6\ d_s$, ($d_s < 20$ mm) $d_{br} = 8\ d_s$, ($d_s \geq 20$ mm) Note: T = +5°C	• Testing and Application $d_{br} = 8\ d_s$, ($d_s < 43$ mm) $d_{br} = 10\ d_s$, ($d_s > 43$ mm) Note: T = 20 to 30°C	• Testing and Application $d_{br} = 6\ d_s$ Note: T ≤ 15°C
HOLIDAY TEST	• Zero (0) Holidays: Acceptance Test for Powder and Coating Firms. • Maximum 6 Holidays/m: Run Production	Maximum 6 Holidays/m	Maximum 5 Holidays/m
DAMAGE	• < 25 mm^2 • < 0.5% : Manufacturer • < 1.0% : Building Site	< 60 mm^2 < 2%	< 10 mm^2/m and maximum 4 pieces/m
CORROSION TEST	• Salt-Spray Test • Cathodic Disbonding	• Current Test	• Salt-Spray test • Cathodic Disbonding
MECHANICAL DEFECTS	• Impact Test** • Free-Fall Test	• Impact Test**	• Impact Test**
BOND	• Pull-Out Test (Short and Long Time)	-	-
COATING TESTS	- -	• Vickers Hardness** • Abrasion Test**	• Vickers Hardness** • Abrasion Test**

* Tests on resin films.
** Tests on epoxy-coated steel plates.

imately 65,000 segments equal to 22,000 t (24,000 tons) of reinforcing steel, was coated on site in a coating plant using the fluidized bed dipping process. Following blasting and preheating, the welded reinforcing cages 4.20 x 1.65 x 0.40 m (13.78 x 5.41 x 1.31 ft) were coated with epoxy resin in a dip tank and passed through a cooling section. The cycle time for this fully-automated coating plant, including continuous quality control on coating thickness, freedom from holidays and curing was 3 to 4 minutes. The on-site production process minimized later bending, and hence, weakening of the coating film. The coated reinforcement is part of a multi-barrier protective system. Besides excellent concrete quality, alternative cathodic protection systems have been provided if the protective coating should prove insufficient.

Schießbergstraße Bridge in Leverkusen, Germany. This bridge, 53 m (174 ft) long by 9 m (30 ft) wide, was completed at the end of 1990 and is second largest in Germany. The cell cooling tower project is the largest. The coated reinforcing steel, 8 t (9 short tons), is located in the pier caps. One side was constructed with hot-coated reinforcing steel bars that were bent after coating and the other with cold-coated welded wire mesh bent before coating. Inspection areas were provided for observation of corrosion behavior. The corrosion behavior of any macro-element can be measured continuously via electrically conductive connections with uncoated reinforcing steels.

Epoxy-resin coated reinforcements have also been used on other European construction projects in Switzerland (sewage treatment plants & bridge extensions), the Netherlands (part of a port structure in Rotterdam) and in England (salt storage silo, bridges sea walls).

RESULTS OF RECENT LIMITED TESTING

Factors that may initiate and propagate corrosion of straight epoxy-coated rebars include the chemical environment of the rebar, e.g., before and after embedding in concrete, and damage to the coating. As damage is generally unavoidable during production and handling, it is accepted in the American and European standards for ECR. Electrochemical effects, such as cathodic disbondment, is very important in these circumstances.

To investigate the behavior of damaged epoxy-coated rebars under different chemical environments, limited tests were conducted at the IBAC in which epoxy-coated rebars were exposed to various liquid chemicals. Epoxy-coated rebars from a coater operating under ASTM requirements (Coater A) and a coater operating under the German guidelines (Coater B) were used. The test solutions chosen were:

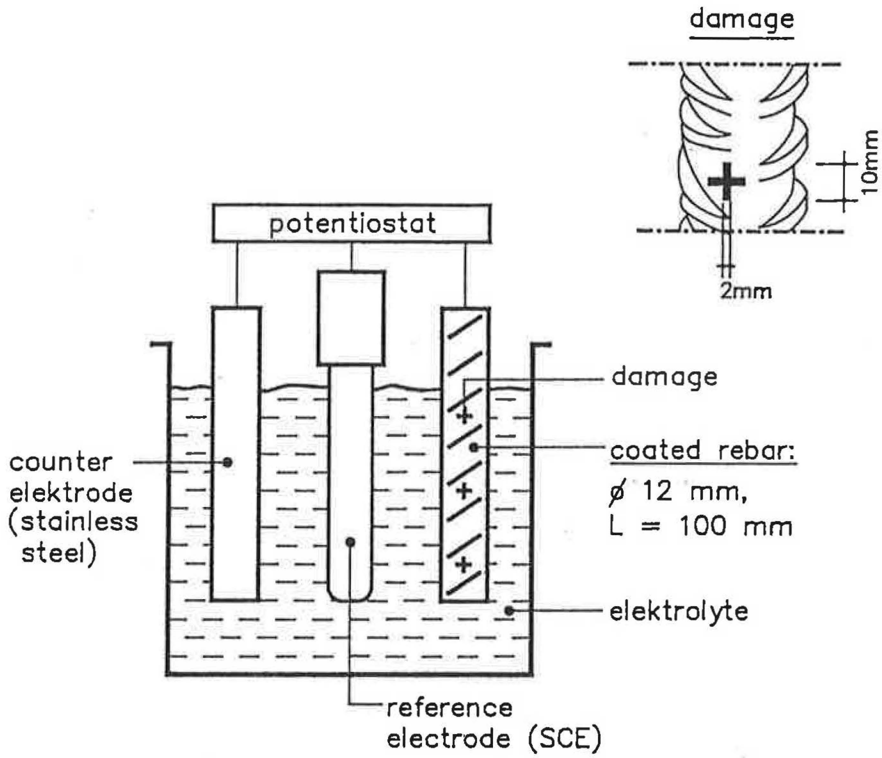
- NaCl,
- simulated pore water of concrete with KOH + NaOH, and
- a mixed solution of KOH + NaOH and NaCl.

The intent was to evaluate the respective effects of storing unbedded coated rebars in a marine environment (NaCl-solution), a chloride-free environment (KOH+NaOH-solution) and a chloride-containing concrete (KOH + NaOH + NaCl-solution). In addition to freely corroding conditions, open circuit (OC) potential, the rebars were tested under potentio-static control ranging from -1800 mV (cathodic polarization) to +100 mV (anodic polarization). A stainless steel counter electrode was used, see Figure 1. Three cuts, nominally 2 by 10 mm (0.1 by 0.4 in), were made in the coating of each bar with a knife. After exposure for 30 days, the specimens were dried and the area of coating that could be easily removed by sliding a knife was determined. Figures 2 to 4 show the amount of disbondment expressed as a fraction of the total surface of the bar in contact with the liquid.

Exposure to 3.5% NaCl-solution caused corrosion under anodic polarization at +100 mV in the coated bars from both producers, see Figure 2. The bar from Coater A showed pitting corrosion with metal loss in the form of circular craters in the steel. By comparison the bar from Coater B showed less corrosion pits, but a greater amount of coating disbondment immediately surrounding the pits. The bar from Coater A suffered disbondment at -1000 mV (cathodic polarization) while no disbondment was observed on the other bar.

Epoxy-coated bars exposed to an alkalinic solution of KOH + NaOH (pH=13.5) suffered considerable disbondment under cathodic polarization, see Figure 3. At -1800 mV the coating of the bar from Coater A could be removed completely, while the bar from Coater B showed a disbondment of 50%. Neither bars showed signs of corrosion under anodic polarization and OC potential.

Exposure to the mixed solution of KOH + NaOH and NaCl caused disbondment under cathodic and corrosion under anodic polarization in both bars. There was more disbondment and pitting corrosion on the bars from Coater A than on the other bars, see Figure 4.



Series	Polarisation	Potential (mV) (SCE)	Electrolyte
1	anodic open circuit cathodic	+ 100 − ~600 − 1000	3,5%NaCl
2	anodic open circuit cathodic cathodic	+ 100 − ~100 − 1000 − 1800	0,3nKOH+0,05nNaOH
3	anodic open circuit cathodic	+ 100 − ~500 − 1000	0,3nKOH+0,05nNaOH+3,5%NaCl

Figure 1 Test set-up (schematic) and test parameters.

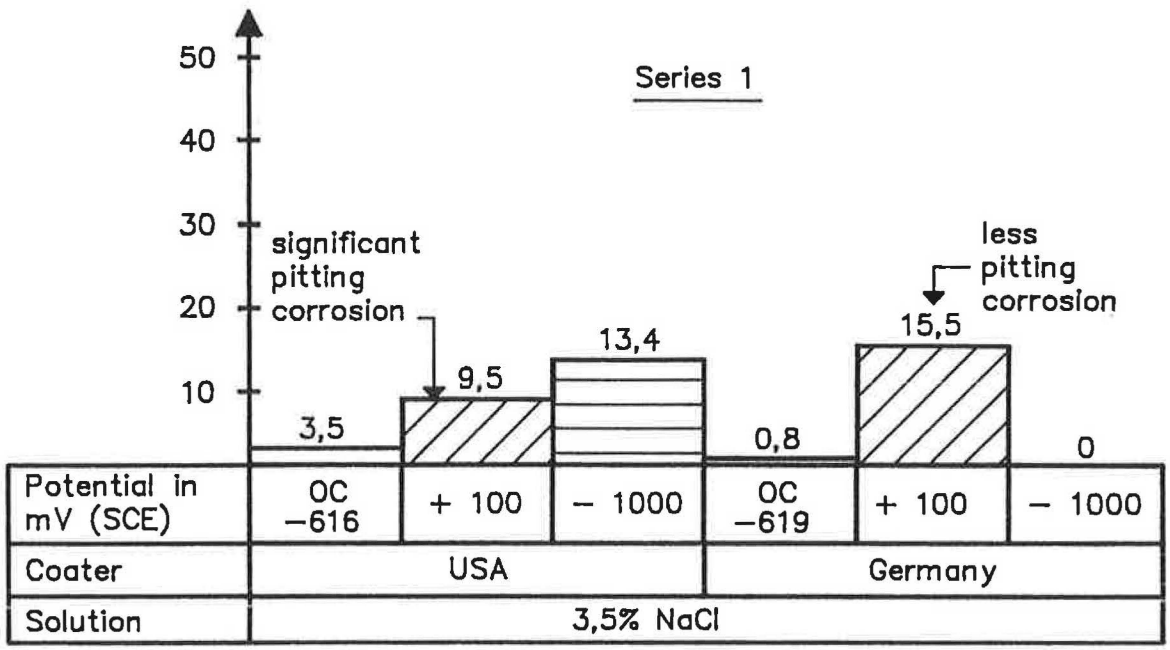


Figure 2 Disbondment (%) of coating after 30 days exposure in NaCl solution at different potentials.

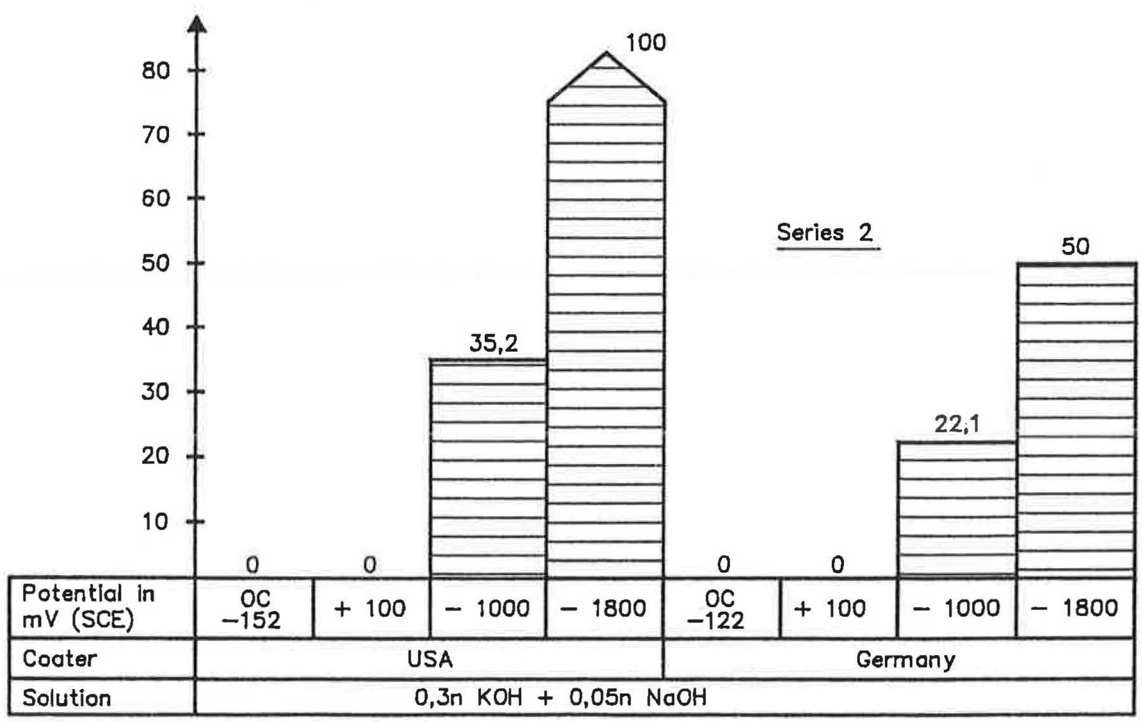


Figure 3 Disbondment (%) of coating after 30 days exposure in KOH + NaOH solution at different potentials.

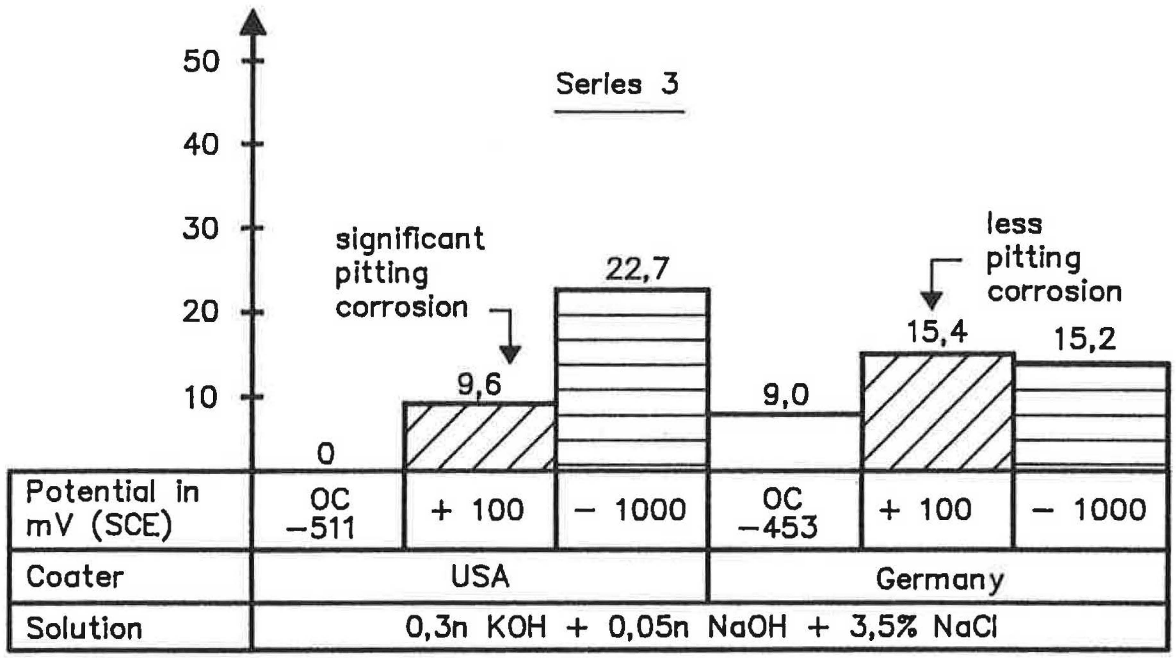


Figure 4 Disbondment (%) of coating after 30 days exposure in KOH + NaOH + NaCl solution at different potentials.

CONCLUSION

The preliminary investigation presented here, based on a single bar, represents an initial attempt to examine the causes of unexpected material performance problems such as disbonding and under-rusting. Additional tests based on a representative sample of test specimens are needed to obtain a more accurate view of the mechanisms involved and their correlation with decisive influencing parameters. Nevertheless, the laboratory experiments suggest that particular attention needs to be paid to the long-term performance of ECR in aggressive environments.

REFERENCE

1. P. Schiessl and C. Reuter, "Coated Reinforcing Steels," Corrosion 91, *1991 NACE Conference*, Paper No. 556.