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CORROSION PROCESSES AND FIELD PERFORMANCE OF EPOXY-COATED REINFORCING STEEL IN MARINE SUBSTRUCTURES

Alberto A. Sagüés
Department of Civil Engineering and Mechanics
University of South Florida
Tampa, Florida 33620

Rodney G. Powers and Richard Kessler
Materials Office
Florida Department of Transportation
2006 N.E. Waldo Rd.
Gainesville, Florida 32609

ABSTRACT

Severe corrosion of epoxy coated rebar in the substructure of marine bridges in the Florida Keys has prompted an investigation of the condition of other bridges in the State. Over thirty bridges were subject to field examination, which included determination of rebar condition, determination of extent of electric continuity between rebars, extraction of concrete cores, determination of chloride diffusivity, concrete resistivity measurements, and related electrochemical measurements. The results indicate that the time for development of external corrosion symptoms in the Florida Keys was dominated by the corrosion propagation stage, which in that case was comparable to that expected for plain rebar. Structures outside the Florida Keys were found to be generally corrosion-free. Extensive metal-coating disbondment was observed in virtually all structures whether or not significant chloride contamination existed at the rebar level. Chloride penetration was very slow in bridges with modern concrete formulations, suggesting that long corrosion-free service times are likely for those structures. It is expected that the corrosion-free service life in those structures will be primarily the result of concrete quality and thick cover, and not necessarily due to the use of epoxy-coated rebar.

INTRODUCTION

Epoxy-coated rebar (ECR) has been used in approximately 300 Florida bridges, principally in an attempt to control corrosion of the substructure in the splash-evaporation zone of marine bridges. Starting in 1986, severe corrosion incidents began to be observed in the substructure of major bridges along US 1 in the Florida Keys. The bridges affected were only a few years old, built generally between 1978 and 1983 [1,2].

Several investigations were conducted to assess the nature of the damage and the causes of the corrosion in the Florida Keys structures. It was determined that ECR corrosion could be aggravated by fabrication of the rebar [3], the presence of macroscopic breaks in the coating [4-6], and corrosion macrocells [7]. It was also found that extensive disbondment of the coating from the base metal could result from exposure to salt water [8], mild levels of cathodic polarization [7,8], and also under anodic conditions while corrosion is underway. It was determined that the disbondment could develop in the absence of chloride ions, and that sodium and possibly potassium ions were instrumental in the disbonding process [9]. Experiments also showed that disbondment could take place in chloride-free concrete under mildly cathodic polarization conditions such as those encountered by non-corroding rebar in the field [7].

Based on field observations and on the results of the investigations mentioned above, a development sequence was proposed to describe the corrosion process in ECR [8]. Figure 1 describes the salient elements of that sequence, as detailed below.

Pre-service history: ECR is produced according to the specifications existing at the time of the construction projects (Figure 1A). The bars contain a small number of initial coating imperfections, as permitted by the acceptance criteria. The bars are cut, shaped and then shipped and fabricated as required. Shipping introduces additional surface damage; fabrication creates disbondment by mechanical means (B). The bars are exposed to the construction yard environment for a time that may range from days to over a year. Salt water exposure at the yard creates additional disbondment; further deterioration might result from heating/cooling cycles, ultraviolet exposure and additional mechanical damage during handling (C). Rebar cage assembly procedures, positioning in concrete forms, as well as concrete pouring and vibration, create additional surface damage.

Service-in-concrete history: The ECR is exposed to a low-chloride concrete environment for a period that may range from several months to several years, depending on position with respect to the water level and other factors that affect the rate of chloride penetration. During that time the concrete pore solution interacts with the rebar coating, and penetrates between coating and metal in regions where disbondment had taken place during pre-service. Exposure to the low or moderate chloride content concrete aggravates coating delamination (D). Upon arrival of the chloride front corrosion begins at the exposed metal at imperfections, and in the crevices which exist below disbonded coating. Corrosion macrocells develop with cathodic regions in regions of good oxygen availability. The cathodes take place not only at exposed metal at imperfections but also to some extent into the surrounding disbonded crevices. Low concrete resistivity and a measure of electrical continuity of the rebar cage (at accidental contact points) promote macrocell action over significant distances, making for an unfavorable anode-to-cathode ratio. The resulting intense action at the anodic portion causes additional disbondment and corrosion at the crevices (E). Eventually, the corrosion morphology consists of extensive coating delamination, accumulation of corrosion products and low pH liquid below the coating, and metal consumption manifested by spots of severe pitting on a background of more general wastage. Externally observable corrosion develops then in a relatively short time, comparable to that experienced by plain rebar in a similar concrete environment.

In summary, the corrosion may be viewed as resulting from the presence of normal production imperfections which were then aggravated by fabrication, handling, and a severe construction yard environment. This is followed by placing the rebars in moist, warm, eventually high chloride-level substructure service which is conducive to severe corrosion, aggravated by extended macrocell formation.

Based on the results of the previous work, an investigation was conducted to evaluate the condition of bridges in other locations in the State, and to develop a prognosis for the future corrosion performance of those bridges. This paper describes highlights of the results of that investigation.

PROCEDURE

Approximately 30 bridges were identified for examination. The structures investigated included bridges not yet having reported as showing signs of developing corrosion (Table I) plus one bridge in the Florida Keys (Seven Mile) that had already experienced ECR corrosion . Four of the bridges were built with plain rebar and the remainder had ECR construction. All structures were located in locations that fell within the FDOT Extremely Corrosive category. The examination was limited to the substructure of the bridges, in the splash-evaporation zone (about 2 to 6 ft (0.6 to 1.8 m) above high tide). Typically two footers of each bridge were examined.

Field activities included visual examination, concrete resistivity profile determination, extraction of concrete cores with and without segments of rebar, determination of extent of coating-metal disbondment, measurement of extent of interconnection of exposed rebar segments, measurement of macrocell current that developed between segments, and related activities such as selected polarization resistance measurements and half cell potential determinations.

Laboratory tests of field specimens included evaluation of coating characteristics (thickness, coating breaks, additional disbondment tests), determination of chloride penetration profiles, and concrete resistivity measurements in dry and wet conditions.

RESULTS

Rebar continuity.

Figure 2 shows the degree of continuity, which was measured by the fraction of rebar segments showing direct electrical contact with other exposed segments in the same column in a cumulative graph.

Macrocell currents.

Macrocell current measurements were made by inserting an ammeter between non-interconnected exposed rebar segments located at different heights in the column being inspected. The current flowing after 10 minutes following interconnection was recorded. The results showed great variability (see Figure 3), but the lowest values (less than 1 uA) were recorded more frequently for the structures showing the smallest degrees of rebar continuity.

Coating adhesion.

Coating adhesion to the steel substrate was determined, in the field, immediately after extraction of each rebar sample by means of a knife test. Adhesive failure of the coating was obtained easily in virtually all the rebar segments extracted. Severe loss of adhesion was observed even for structures that were only six years old and also when the chloride content of the concrete was at initial very low background levels (0.1 to 0.3 pcy; 1 pcy = 0.6 Kg/m^3). Only one structure, three years old at the time of testing, exhibited coating-metal adhesion comparable to that of newly produced ECR.

Laboratory tests of coating adhesion were performed on selected specimens by means of a mechanical pulloff device. A contoured metal dolly (typically 5 to 6 mm diameter) was attached to the rebar coating surface with a cyanoacrylate adhesive. Coating around the perimeter of the dolly was removed with a dental drill. The pulloff force was measured and a pullout stress was computed in psi. Figure 4 shows that the pullout stress was significantly lower for the population of field specimens when compared with that of unexposed ECR controls. Pulloff in the controls resulted always from failure of the cyanoacrylate adhesive; pulloff in the field samples resulted primarily from failure of the epoxy-metal bond. The filled symbols correspond to full epoxy-metal failure; partially filled to fully open symbols indicate partial epoxy-metal failure with a surface fraction indicated by the extent of symbol filling.

The laboratory adhesion tests were performed after storage of the samples in a desiccator for periods ranging from several days to over one year. The results in Figure 4 indicate that the loss of adhesion between the coating and the metal was in most cases permanent. Knife tests with the long-dried specimens also showed widespread permanent loss of adhesion.

Corrosion.

Most extracted ECR specimens showed no conspicuous evidence of corrosion in progress, with the exception of specimens extracted from the Seven Mile bridge (which had shown earlier external signs of corrosion in its substructure). The steel surfaces revealed on all other rebars during the knife adhesion tests were generally bright, or only slightly darkened.

Other coating characteristics.

The condition of the coating backside was examined in detail for selected specimens that had shown pronounced knife test disbondment both in the field and in laboratory pulloff tests performed after extended desiccator storage. Specimens in the small group that actually showed corrosion products were excluded to avoid uncertainty in separating corrosion products from contamination initially present. Aside from contamination spots which affect only a small percentage of the coating surface (estimated to be between 1% and 10%), the coating backside was essentially clean. Qualitative examination of the surface relief did not reveal conspicuous deviation from normally blasted surfaces.

Coating thickness of the extracted samples was generally within values specified at the time of construction. Only 3% of the samples showed average coating thicknesses of less than 0.005 in (0.125 mm). About 5% of the samples had average coating thickness exceeding 0.020 in (0.5 mm).

The fraction of the rebar surface composed of bare metal spots (macroscopic coating breaks) in the extracted specimens was estimated visually. The results are statistically represented as a cumulative graph in Figure 5. The median extent of macroscopic coating breaks affected about 0.4% of the specimen surface. During the examinations it was attempted to disregard damage clearly produced during rebar extraction. However, that procedure is to some extent subjective and it is possible that the extent of exposed metal determined on the extracted specimens exceeded the amount of surface damage actually present at the time of concreting. There was no clear correlation between bridge characteristics (date of construction, type of structure, location) and the extent of macroscopic coating breaks.

Chloride penetration in concrete

Concrete chloride content (acid soluble) profiles (as a function of distance from the concrete surface) were determined for cores extracted from the examined structures. Estimates of the effective chloride diffusion coefficient and effective chloride surface concentration were made by fitting the results with predications based on an ideal Fick's second law diffusion mechanism. Effective surface concentrations in the splash-evaporation zone of structures in marine environments were on the order of 20 pcy (12 kg/m^3). The distribution of values of D obtained is shown in Figure 6 (two other bridges in the Florida Keys, Niles Channel and Long Key, which had shown ECR corrosion, were added to this listing). The results illustrate the large variability of conditions existing in the substructure of Florida bridges. Structures in the Florida Keys, which experienced severe ECR corrosion, showed D values typically in the upper end of the distribution (0.5 to 2 in^2/y ; 1 in^2/y = 20.4 10^{-8} cm^2/s).

Concrete resistivity and permeability considerations

The resistivity of concrete was measured in the field with a 4-point Wenner array probe with a point-to-point spacing of 5 cm. Resistivity of the field extracted cores was also measured in the laboratory in the dry and 100% relative humidity conditions. Minimum field concrete resistivities measured in individual bridge columns ranged from 2.5 kohm-cm to nearly 100 kohm-cm. The 100% RH laboratory measurements in cores gave results roughly equal to the minimum field resistivities measured in the columns from which the cores were extracted.

The 100% RH resistivity measurements showed a general inverse correlation with the chloride diffusivities reported above. This was to be expected, as both parameters are indirect indicators of the overall concrete permeability [10,11]. The overall log-averaged correspondence observed in this investigation (roughly 10 kohm-cm resistivity for 0.1 in^2/yr ($2\ 10^{-8} cm^2/s$) diffusivity) approximates well the result of independent empirical laboratory correlations [10] and theoretical predictions [11].

Bridges built with concrete containing fly ash (as determined by observation of paramagnetic behavior) tended to have the lowest chloride diffusivities/highest resistivities. The Sunshine Skyway bridge, built recently (1986) with a modern concrete mix design which included incorporation of fly ash , high cement content and a low water to cement ratio, was among that group. Bridges in the Florida Keys built in the late 1970's-early 80's using traditional concrete formulations, were at the other end of the diffusivity/resistivity ranking.

DISCUSSION

Present condition of ECR structures in Florida

The investigation revealed no incidents of severe corrosion of ECR in Florida bridges beyond those in the Florida Keys documented in the Introduction. The most significant finding of ECR deterioration in the study was the observation of coating-metal disbondment at almost all the structures examined. As indicated in the Introduction, coating disbondment can be considered as a key step in the corrosion development. The ECR in all these structures appears to be already susceptible to the development of severe crevice corrosion at that time in the future when the chloride concentration at the rebar level reaches the value for corrosion initiation.

The measurements of the extent of electrical continuity of rebar assemblies (Figure 2), of a finite amount of coating breaks, and of the levels of macrocell current attainable (Figure 3) suggest that other conditions for aggravation of the corrosion process (as discussed in the Introduction) are also in place in several of the ECR structures examined.

Prognosis of future performance.

It is of special interest to develop a prognosis of future corrosion performance for the structures using ECR presently in Florida. The observations to date provide valuable clues for that prognosis.

It will be assumed that a two-step mechanism of corrosion exists [12]. In the first step (initiation), the chloride ion concentration at the surface of the ECR is below the critical threshold for appearance of active corrosion of the steel. The concentration, however, is increasing constantly because of chloride transport through the concrete cover. The initiation period ends when the chloride concentration at the rebar surface reaches the critical threshold value. During the propagation period corrosion products accumulate. The propagation period ends with the development of concrete cover spalls or concrete cracks.

The length of the initiation period was evaluated by making the simplifying assumptions that chloride ions move only by diffusion, and that the concentration of chloride ions at the concrete surface reaches a constant value shortly after the substructure member is placed in service. The one-dimensional solution to the diffusion equation was used to calculate the time needed for chloride buildup at the rebar surface to reach an assumed critical threshold value. A nominal length for the propagation period was assumed for all cases.

Figure 7 exemplifies the results of applying these assumptions for systems with a concrete cover of 4" (10 cm) (typical of guidelines for design of new marine substructure), and a surface chloride concentration of 20 pcy (12 kg/m^3) (representative of values observed in the splash-evaporation zone of Florida substructures). Three possible values for the corrosion threshold (1.2, 2.4 and 3.6 pcy; 1 pcy =0.6 kg/cm^2), a range of diffusion coefficients bracketing those observed in the present survey, and a nominal propagation time of 3.5 years were used. Similar calculations were performed for other rebar cover and surface concentration combinations.

The results of the simplified calculations predicted a time for spall/visible corrosion of about 4 to 8 years for structures with D near 1 in^2/year (20.4 10^{-8} cm^2/s) and covers in the 2 to 4 in (5 to 10 cm) range (as those in the Florida Keys). The actual times for corrosion in those structures were of the same order as the calculated values, which was partly the reason for selecting the assumed set of parameters. The calculated times for corrosion initiation in those conditions of fast chloride transport are very short. For a finite length of the propagation period, the initiation time becomes a less important contribution to the time to spall as more rapid chloride transport is assumed. Because of that, as shown in Figure 7 the time to spall becomes also less sensitive to the value of the critical chloride threshold when chloride penetration is fast.

The observed chloride diffusivities, coupled with the model predictions, suggest that propagation times for the corrosion in the Florida Keys cases were on the order of the 3.5 years assumed in the model. This propagation time is similar to that assumed for plain rebar bridge deck structures as a reasonable mean based on field observations [13]. As shown in Ref. [7], macrocell effects alone could account for corrosion rates in the surface-damaged ECR propagation period of up to 0.3 uA/yr, which in turn could be expected to cause spalls after about 10 to 15 years. If local cell action currents are added to the macrocell action, shorter propagation times (such as those assumed above) could be reasonably expected. Short propagation times, comparable to those of plain bars, have also been proposed based on the results from other investigators [14].

Because of the rapid chloride penetration, the field experience in the Florida keys cannot shed light on the value of the critical chloride threshold for corrosion of ECR. Results from the other structures examined are not very helpful as chloride buildup is still small; both the other ECR and plain rebar structures show generally no corrosion. There is laboratory indication that for surface-damaged rebar the time for initiation is comparable to that of plain steel [3]. Short-term (30 day) experiments with ECR in simulated concrete pore solutions (SPS) did not show corrosion of surface-damaged ECR under likely polarization conditions when chloride contents were low (comparable to about 1/10 of the threshold value for plain bar). However, recent investigations with plexiglass-steel crevice specimens in SPS with chlorides [15] have shown a marked decrease in the apparent pitting initiation potential when compared to that of freely exposed surfaces. That observation suggests that the threshold for long-disbonded ECR might actually be lower than for plain steel. The calculations presented above were limited only to the case of the commonly accepted minimum threshold values for plain steel (1.2 pcy, 0.7 kg/m^3), and two cases that represent somewhat higher resistance to corrosion initiation.

The prognosis for many of the other structures examined in this study appears to be much better than for those experiencing damage in the Florida Keys. The projected improvement due to concrete modifications alone in the more modern structures is dramatic. The length of the propagation period in these new structures, presumably built with ECR that was more carefully handled and produced by more experienced coaters, might be longer than in the case of the Florida Keys bridges. However, the improvement in concrete impermeability could easily obscure even a tenfold increase in the length of the propagation period, making the application of ECR only a marginal improvement. If there were an actual reduction in the critical chloride threshold of ECR compared with black bar, the overall effect over the long term could even be negative. In conditions where chloride penetration takes places in short times, the initiation period is fast and the presence of ECR could have been expected to significantly increase durability, by lengthening the propagation phase. Unfortunately, the experience in the Florida Keys did not support that expectation. Present attempts to improve the performance of produced and in-place ECR might result eventually in distinctly better durability in similarly harsh conditions. Possible performance improvements need to be verified with long term, actual experience in the field.

CONCLUSIONS

1. Severe corrosion of ECR was found in the substructure of five major bridges in the Florida Keys. Twenty other structures examined in salt water environments in the State showed no indication of ECR corrosion at present.

2. Epoxy coating disbondment from the steel substrate, confirmed by instrumented laboratory tests, was observed in virtually all of the structures examined. The disbondment was present even in the absence of chloride ion contamination, and it was observed in specimens that were desiccator dried over long periods of time.

3. Coating disbondment was not associated with conspicuous undercoating contamination.

4. The coating thickness and total extent of coating breaks were generally within production and use guidelines in effect at the time of construction.

5. ECR rebar assemblies showed a median value of 30% electrical continuity. Significant amounts of electric macrocell currents were recorded upon interconnection of separate elements.

6. The structures showing corrosion tended to exhibit much higher chloride diffusivities and lower concrete resistivities than those constructed with modern concrete formulations.

7. Based on analysis of the results with initiation-propagation corrosion model, the time-to-spall in the Florida Keys structures was dominated by the propagation stage. This in turn suggests that the corrosion propagation times were comparable to those normally experienced by plain rebar.

8. Corrosion-related durability of the remaining structures built with modern concrete formulations and thick cover is expected to be dominated primarily by the characteristics of the concrete.

9. The important question of the effect of coating disbondment on the chloride concentration threshold for corrosion initiation is not resolved. A reduction in the threshold value could seriously reduce the long-term corrosion protection performance of the coating.

10. Demonstrated corrosion protection performance in actual field structures is essential to verify the success of present attempts to improve the characteristics of ECR.

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TABLE 1
Epoxy Coated Rebar Investigation
List of Bridges and Locations

Bridge name	County	Location
Green	Manatee	Bus. US 41 over Manatee River
I-75 SB	Manatee	I-75 Southbound over Manatee River
I-75 NB	Manatee	I-75 Northbound over Manatee River
Halifax	Volusia	SR 40 over halifax River
Indian River 1	Brevard	US 192, Melbourne Causeway (Channel)
Indian River 2	Brevard	US 192, Melbourne Causeway (Channel
New River	Broward	SR 811 over New River, Ft. Lauderdale
Vaca Cut 2	Monroe	US 1 over Vaca Cut, Marathon
Vaca Cut 1	Monroe	US 1 over Vaca Cut, Marathon
Alafia River 1	Hillsborough	I-75 over Alafia River
Alafia River 2	Hillsborough	I-75 over Alafia River
Snake Creek	Monroe	US 1 over Snake Creek, Florida Keys
ICWW-A	Broward	SR 838 over Intracoastal Waterway
ICWW-B	Broward	SR 838 over Intracoastal Waterway
Matanzas	Lee	SR 865 over Mantanzas Pass, Ft. Myers
Perdido	Escambia	US 98 over Perdido Bay
Choctawatchee	Okaloosa	SR 30 over East Pass, Destin
Peace River 1	Charlotte	US 41 Northbound over Peace River
Peace River 2	Charlotte	I-75 over Peace River
Peace River 3	Charlotte	I-75 over Peace River
Apalachicola	Franklin	US 98 over Apalachicola River
ICWW-2	Dade	SR 852 over Intracoastal Waterway
ICWW-3	Dade	SR 852 over Intracoastal Waterway
New Pass	Sarasota	SR 789 over New Pass, Longboat Key
ICWW-4	Palm Beach	SR 786 over Intracoastal Waterway
Hobe Sound	Martin	SR 707 over Hobe Sound
Miami River 1	Dade	Miami Ave. over Miami River
Miami River 2	Dade	Miami Ave. over Miami River
Skyway	Pinellas	I-275 over Tampa Bay

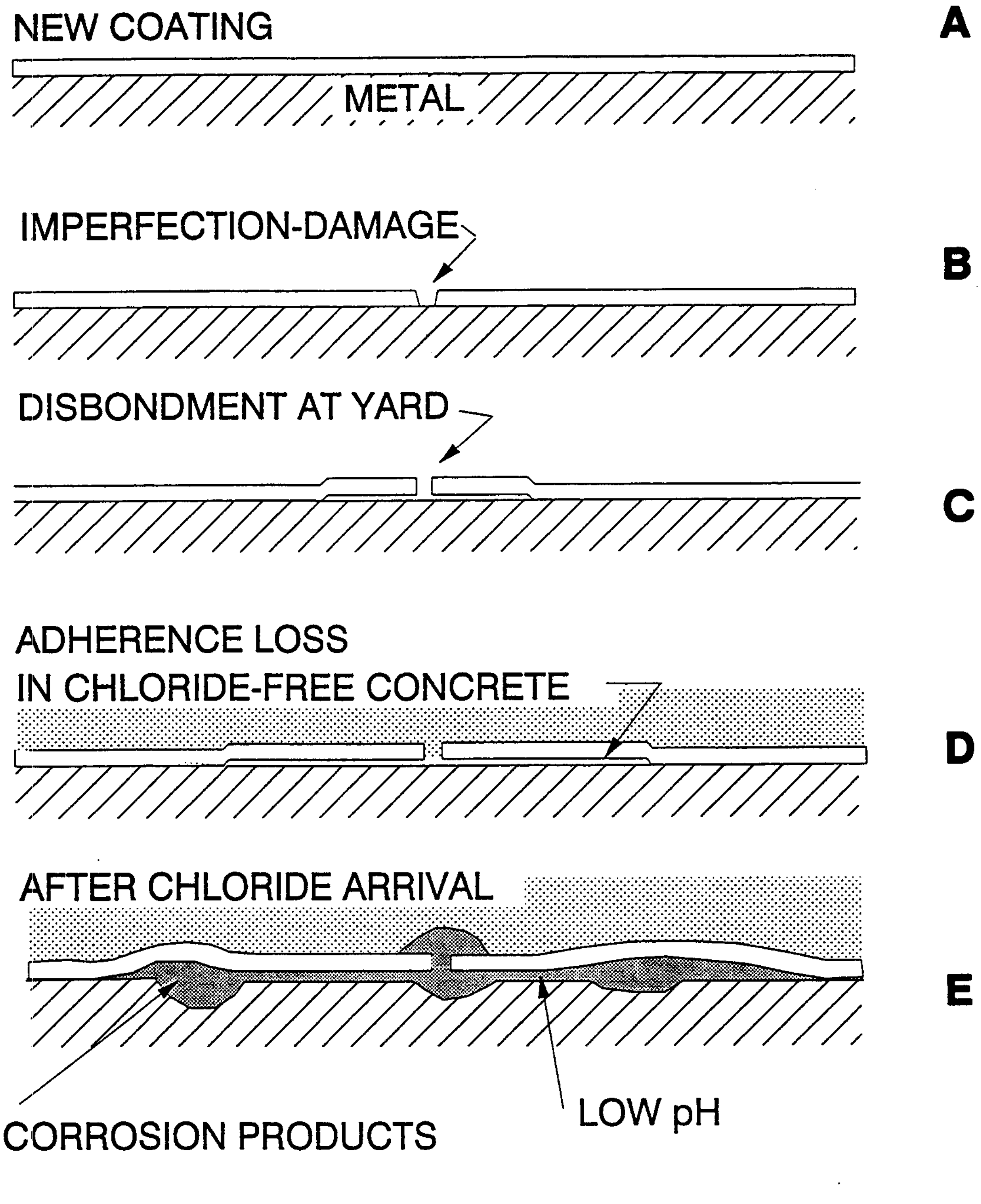

Figure 1. Stages in the development of corrosion of epoxy-coated rebar in concrete.

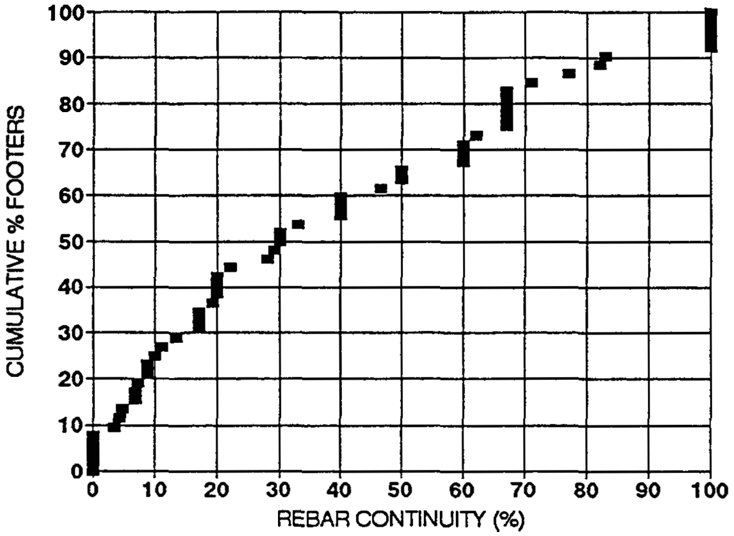

Figure 2. Cumulative plot of the percentage of bridge footers examined which have up to the degree of rebar electrical continuity indicated in the horizontal axis. The median degree of continuity was 30%.

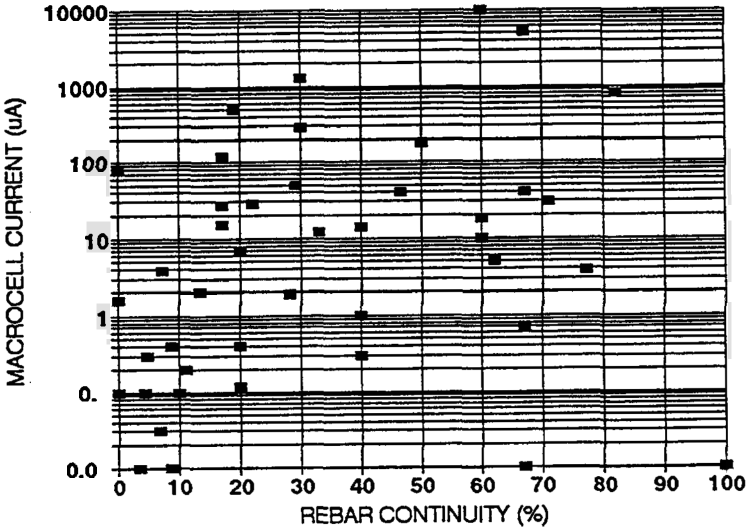

Figure 3. Distribution of macrocell currents as a function of degree of rebar continuity.

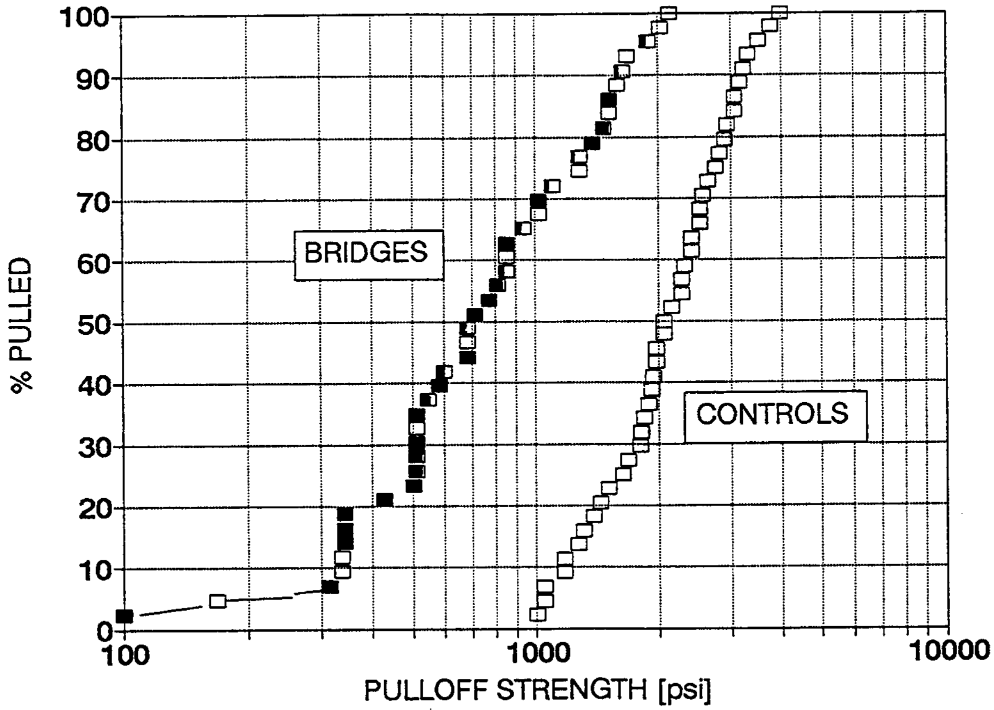

Figure 4. Cumulative percentage of bridge rebar specimens tested versus the pulloff strength. The controls were unexposed rebars. The extent of darkening of each symbol indicates which fraction of the pulloff spot had experienced separation between the epoxy and the rebar metal. None of the control specimens experienced failure of the epoxy-rebar metal bond.

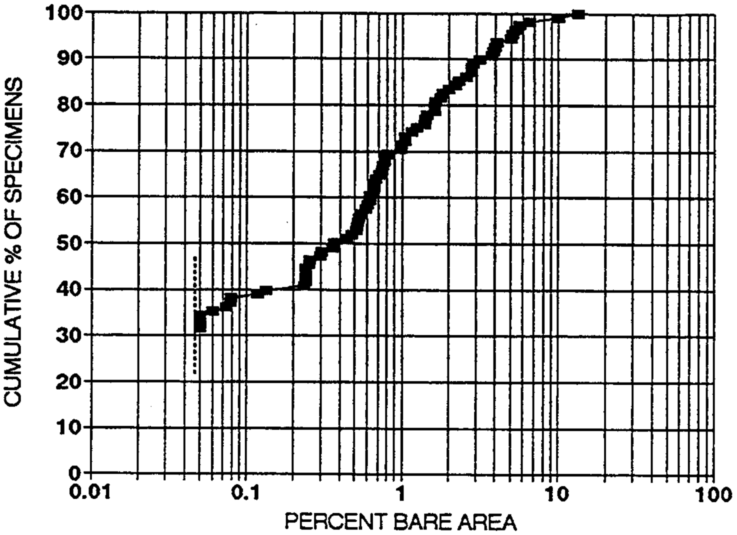

Figure 5. Cumulative percentage of bridge rebar specimens versus the percentage of the specimen area showing macroscopic coating breaks. The median percentage of bare area was 0.4%. The dashed line shows the lower visual detection limit.

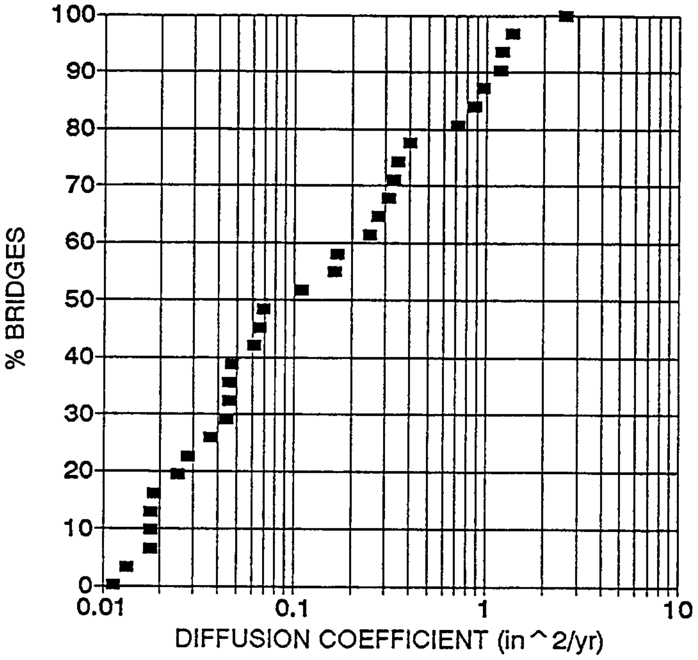

Figure 6. Cumulative percentage of bridges versus effective chloride diffusion coefficient measured from extracted cores (1 in^2/y = 20.4 10^{-8} cm^2/s).

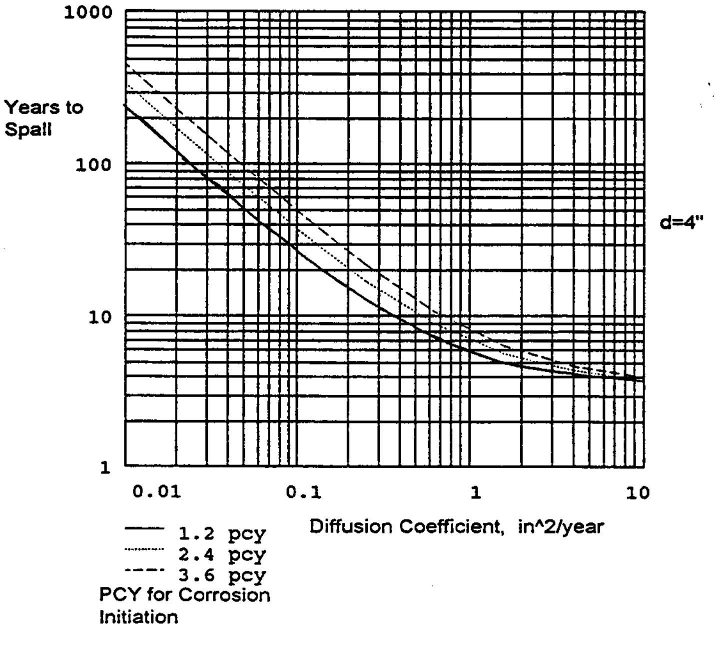

Figure 7. Projections of the time to development of a corrosion spall based on the simplified model. A nominal value of 20 pcy was assumed for the surface chloride concentration. This particular diagram is calculated for a concrete cover of 4" and a nominal propagation period of 3.5 years (1 pcy = 0.6 kg/m$^{3)}$.