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Beam Exposure Study of Epoxy-Coated Reinforcement

Etude de l'exposition des poutres avec des armatures enrobées d'époxy

Balkenbewitterungsstudie hinsichtlich epoxidbeschichteter Bewehrung

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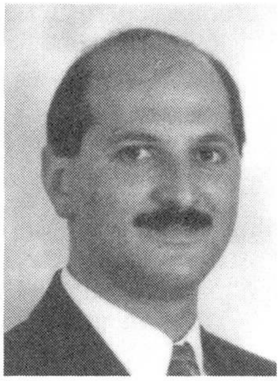

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SUMMARY

The performance of fusion-bonded epoxy-coated reinforcement under conditions which simulate a highly corrosive environment and under loading conditions producing concrete cracking was evaluated. Reinforcement details included longitudinal bars, stirrups, and splices. Coating condition was a variable to assess the effects of coating damage and patching on performance. The results indicated that corrosion initiation and progression was enhanced by concrete cracking and damage to coating. To enhance performance, coating damage and concrete cracking need to be reduced, and patching practice and coating adhesion to substrate need to be improved.

RÉSUMÉ

L'objet de l'étude est d'évaluer la performance des barres enrobées d'époxy dans un milieu corrosif et sous des charges produisant des fissures dans le béton. Les types des barres incluent les barres longitudinales, les étriers et les crochets. L'état de l'enrobage a été considéré comme une variable afin d'évaluer l'effet du dommage et des retouches subies. Les résultats ont montré que le début de la corrosion des barres et l'extension de la corrosion ont été provoqués par les fissures du béton et le dommage à l'enrobage. Afin de parvenir à une meilleure performance, il faut réduire les dégâts à l'enrobage et les fissures du béton, tout en améliorant les méthodes de retouche et d'adhésion de l'enrobage aux barres.

ZUSAMMENFASSUNG

Untersucht wurde das Verhalten aufgeschmolzener Epoxidbeschichtung von Bewehrungsstahl unter Bedingungen, die in hochkorrosiver Atmosphäre zur Beton-rissbildung infolge äusserer Belastung führen. Die Bewehrungsdetails umfassten Längs-eisen, Bügel und Stösse. Hauptparameter war der Zustand der Beschichtung, um die Auswirkung von Beschädigungen und Ausbesserungen zu bestimmen. Die Ergebnisse zeigen, dass Beginn und Fortschritt der Korrosion durch die Betonrissbildung und Schäden an der Beschichtung begünstigt wurden. Um die Leistungsfähigkeit der Beschichtung zu verbessern, müssen diese beiden Einflüsse reduziert und die Technik zur Ausbesserung von Beschichtungsschäden sowie die Haftung der Schicht am Untergrund verbessert werden.

1. INTRODUCTION

Concrete within the tidal zone in a marine environment undergoes cyclic wetting and drying and significant localized chloride accumulation. Surface cracking due to loading facilitates further chloride penetration which eventually precipitates corrosion of reinforcement. Although epoxy-coated steel is widely specified for new construction in corrosive environments and for replacing corroded steel in rehabilitated structures, the long-term performance of coated reinforcement has been questioned recently. Of concern are the effects of coating damage and debonding on corrosion resistance. In the following accelerated corrosion testing, the effectiveness of fusion-bonded epoxy-coated bars, with controlled levels of damage, was evaluated.

2. EXPERIMENTAL PROGRAM

2.1 Concrete and Epoxy-Coated Steel Details

Three similar concrete batches containing 222 kg/m^3 of ordinary portland cement and a maximum aggregate size of 20 mm were used to cast three groups of beams. The w/c ratio was about 0.62 producing concrete with high permeability and an average 28-day compressive strength of 26 MPa. The beams were 0.2x0.3 m in cross section and 3.0 m long. Clear concrete cover was 50 mm.

U.S. grade 60 plant-coated and fabricated bars were used. Beam reinforcement consisted of two 19 mm coated bars at the tension side, one 10 mm coated stirrup at midspan, and two 10 mm uncoated bars at the compression side. Coating thickness measurements on the longitudinal bars and stirrups were within the acceptable range of 130-300 μm. A predetermined amount of damage in the form of small rectangles was introduced in the coating on some bars using a sharp blade. For the longitudinal reinforcement, damage was estimated (as % of surface area) and distributed along the middle 0.9 m of the bar. Damage spots were located between transverse lugs and at the lugs themselves. For the stirrups, damage was estimated for roughly half the length of the stirrup, and was distributed along the outer surfaces of the bends.

2.2 Test Variables and Conditions

Three groups with a total of 34 beams were included in the test. In the first group, the stirrups were isolated from the other bars to allow corrosion monitoring of the longitudinal tensile bars. In the second group, the tensile bars were isolated to allow corrosion monitoring of the stirrups. No isolation was used in the third group to allow corrosion monitoring of both longitudinal tensile bars (which included spliced bars in some cases) and stirrups. Table 1 summarizes the variables included in each beam group. The beams were positioned in such a manner that their own weight was causing bending about the weak axis. Loading as a test variable refers to imposed loads causing bending about strong axis. The three loading conditions selected for the test were as follows: Uncracked Unloaded: At rest condition (no cracks or imposed loads) during exposure; Cracked Unloaded: A load was applied to produce a crack of 0.3 mm width then the load was removed during exposure; Cracked Loaded: A load was applied to produce a crack of 0.3 mm width then the load was held during exposure.

Coating damage level up to or exceeding current specification limits may occur in field applications.[1] Recent discussions regarding modifying the specifications proposed limiting the total bar surface area covered by patching material to 3%. For this test, the bar surface conditions investigated were mainly: the as received condition (no visible damage); and 3% damage, exposed or repaired. Repairs were done according to the manufacturer's instructions using a liquid epoxy patching material and following recommended touch-up techniques.

2.3 Test Setup and Procedure

There were two replicate beams for each test condition. The two replicates were stressed back to back as in the model shown in Fig. 1.

The exposure conditions consisted of 3.5% NaCl solution flowing over the beam surfaces (within a defined exposure area) continuously for 3 days followed by air drying for 11 days. Periodic wetting and drying ensures continuous transport of corrosive substances to steel surfaces to promote corrosion. The cracked beams were subjected to cycles of loading and unloading twice during each exposure cycle: one time during wetting and the other during drying. Five load cycles were imposed each time up to a level producing the selected maximum crack width. Loading and unloading may promote physical damage to coating and to concrete at crack locations and increase exposure to corrosive substances.

Bar Condition (Damage Level and Condition, P=Patched)	Loading Condition		
	Uncracked Unloaded	Cracked Unloaded	Cracked Loaded
Group I Beams, Monitoring Longitudinal Bars			
As Received	B1, B2	B3, B4	B5, B6
3% Damaged	B7, B8	B9, B10	B11, B12
3% Damaged, P		B13, B14	
Group II Beams, Monitoring Stirrups			
As Received	B15, B16	B17, B18	B19, B20
As Received, P	B21, B22	B23, B24	B25, B26
3% Damaged, P		B27, B28	
Group III Beams, Monitoring Long. Bars and Stirrups			
Mixed Longitudinal Bars and Stirrups			
3% Damaged, P		B29, B30	
Mixed Splice Bars and Stirrups			
3% Damaged, P		B31, B32	B33, B34

Table 1 Summary of Beam Exposure Study Specimens

2.4 Corrosion Monitoring

The surfaces of beam specimens were visually inspected periodically for any signs of staining or crack development due to corrosion but none showed such activity during the 400-day observation period. For corrosion monitoring, half-cell potential measurements against a saturated calomel reference electrode (SCE) were made. The points of measurement were closely spaced along the concrete surfaces parallel to the coated bars. After 400 days of testing, half of the beams were demolished to relate measurements to actual bar condition. The test was continued with the remaining beams to provide more information in the future.

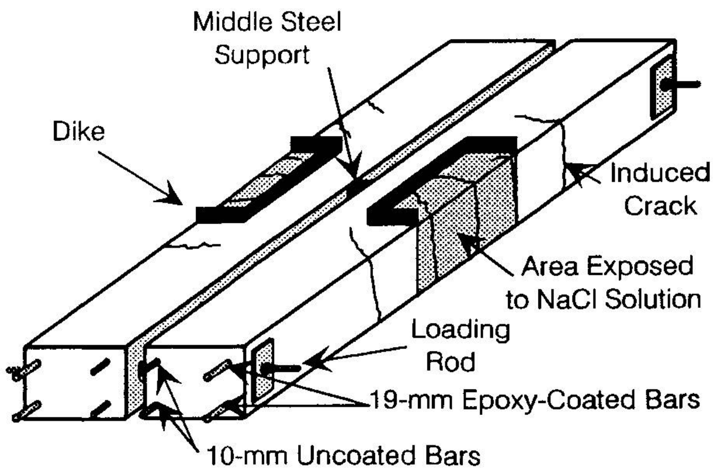

Fig. 1 Model of Beam Test Specimen

3. TEST RESULTS AND DISCUSSION

3.1 Half-Cell Potentials

Examples of average potentials measured on dry and wet regions along the beams versus time of exposure are shown in Fig. 2. Time-to-onset of suspected corrosion as indicated by potential drop varied among beams with different coating damage and loading conditions. In general, as received bars and stirrups delayed corrosion more than bars with 3% damage. Corrosion cells in cracked beams were suspected to form after the first salt application. Bars with patched damage showed comparable time-to-corrosion as bars with unrepaired damage suggesting that patching was not effective. In general, similar periods to suspected corrosion initiation were observed for bars in cracked loaded and unloaded beams. The similarity means that crack width did not affect the time to active conditions for corrosion.

At the beginning of the exposure test, half-cell potentials were not stable. The potentials measured on all uncracked beams were between approximately -50 and -200 mV SCE. This potential range reflects steel passivity. The initial potentials for all cracked beams, however, ranged between approximately -50 and -500 mV SCE. The cause of the different initial potential values may be attributed to early contact of steel with chlorides penetrating through the cracks.

After an initial or delayed potential drop, or fluctuation, the potential remained steady with time. The potential varied consistently within a narrow range of highly negative values which indicated that active conditions persisted for the remainder of the test. Corrosion progression in this situation was almost certain. Sufficient chloride ions were available to maintain activity. The final potentials for uncracked and cracked beams that exhibited an appreciable drop in potential reached about -400 and -650 mV SCE, respectively. The range of final potentials agrees very well with that presented by Wheat and Eliezer[2] for general corrosion due to loss of passivity which is -450 to -600 mV. Sagüés[3] also measured potentials in the range of -350 to -475 mV SCE after almost 300 days of exposure of uncracked columns containing coated bars.

Due to hydrolysis, the localized lower pH of solution within an active pit encourages further corrosion at the available potential level. This phenomenon explains why corrosion progression and pitting continued on some bars at a stable half-cell potential between -400 and -600 mV SCE.

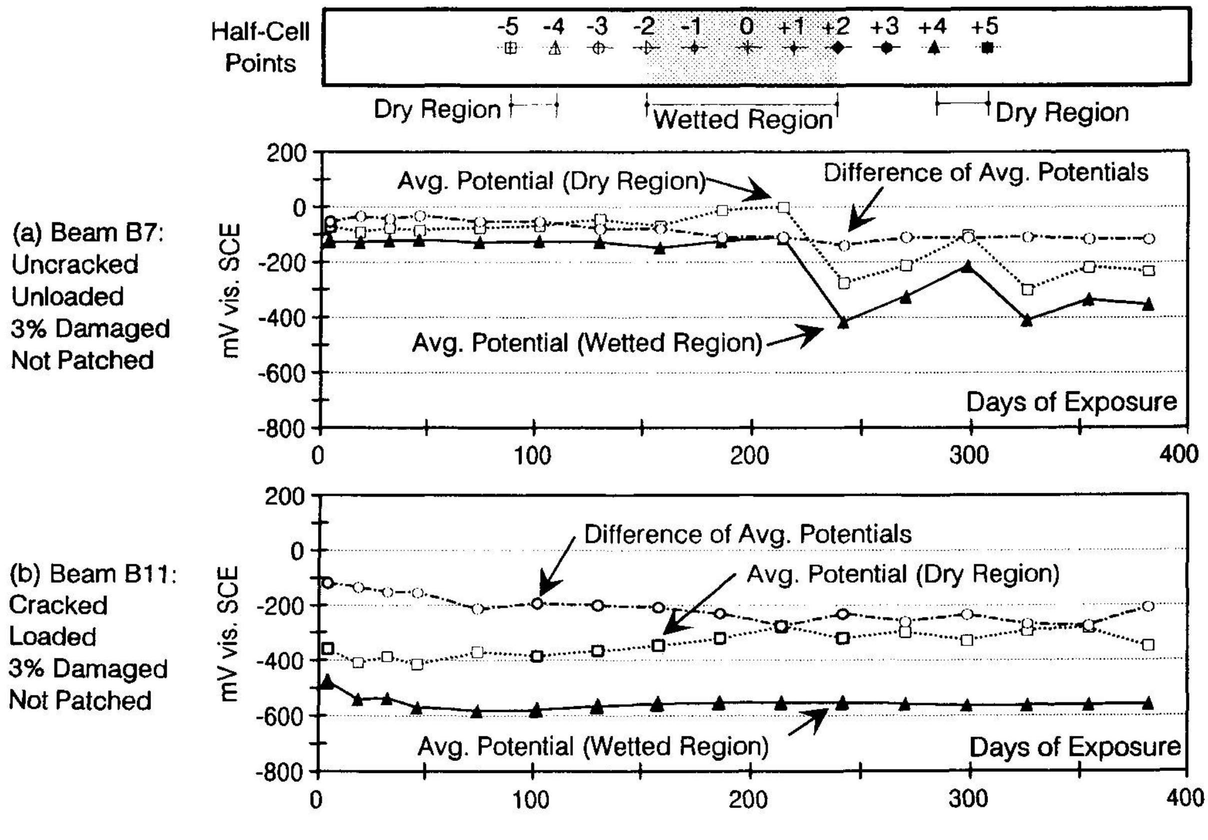

Fig. 2 Average Potentials of "Dry" and "Wet" Regions

Based on the discussion above and observations of actual bar condition, electrical half-cell potential values correlated well with the state of corrosion of coated steel. Figure 3 summarizes the relation between the ranges of measured potentials and corrosion state. Although the extent of corrosion spreading on the bar surface did not correlate with steel potential, the corroded area tended to increase as corrosion severity increased.

Previous studies have indicated that the electrical potential of an anode cannot be used to indicate rate of corrosion. Elsener and Bohni[4] found that the local potential gradient was a better way to identify the type of corrosion and to locate corroding sites. Large differences of potentials along a concrete member may be used as indicators of macrocell formations. The closely-spaced potential measurement points along the beam surfaces allowed the identification of predominantly anodic and cathodic sites. Potential differences were studied between adjacent and far points (about 0.6 m apart). The state of corrosion was consistently related to these differences as follows:

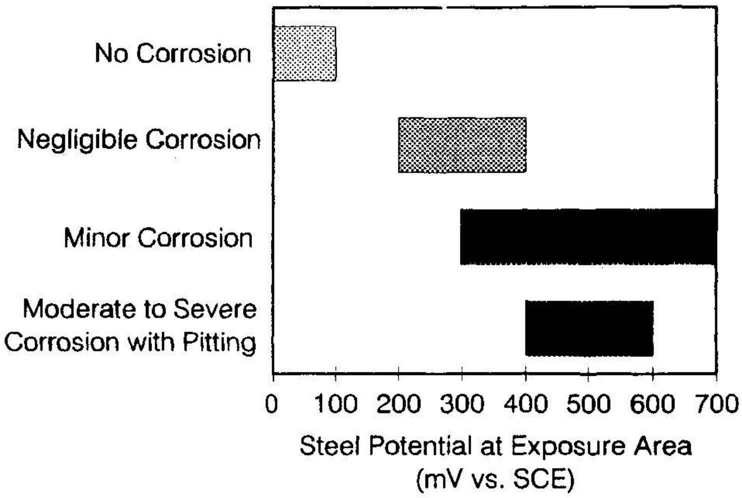

Fig. 3 Relation Between Corrosion Activity and Steel Potential

- No corrosion was associated with potential gradients < 150 mV.
- General corrosion (negligible-moderate) was associated with potential gradients > 150 mV.
- Pitting corrosion in presence of chlorides was associated with potential gradients > 200 mV.

3.2 Condition of Coated Reinforcing Steel

Based on visible surface corrosion of steel, coated bars and stirrups exhibited more corrosion in cracked beams than uncracked beams. In general, corrosion was not much different on bars and stirrups in cracked loaded and unloaded beams. Thus, whether cracks were wide or narrow had less impact on corrosion performance than whether concrete was cracked or not. The severe corrosion testing conditions for both coated bars and stirrups resulted in significant loss of coating adhesion to steel. Coating debonding occurred around all corroded sites and damaged spots. The straight portions of stirrups initially had stronger coating adhesion than the bent portions. However, all portions exhibited significant debonding after one year of exposure, particularly in cracked beams. Significant pitting was only observed on damaged longitudinal bars in cracked loaded beams. In addition, blisters formed mainly on the bottom sides of bars (in casting position) facing air voids in concrete.

The undamaged epoxy-coated bars and stirrups in uncracked beams retained their original appearance with negligible or no corrosion or blistering despite the high chloride content (about 5-6 kg/m^3). For these bars, there was no or very limited loss in coating adhesion to substrate steel. These results indicate that originally intact epoxy coating can provide adequate protection to reinforcing steel from chloride-induced corrosion. Corrosion was also apparent on repaired areas and cut bar ends indicating that patching was not effective.

For longitudinal bars, undercutting was confined to some mill marks and exposed steel areas in uncracked beams. Undercutting increased slightly in cracked beams and spread around the crack locations and areas of no previous damage. For stirrups, undercutting increased noticeably in cracked beams and mostly covered the bends and hook ends. It is believed that exposure to excessive amounts of chlorides for extended periods and macrocell formation on the stirrups eventually led to corrosion initiation and breakdown of coating.

4. CONCLUSIONS

- Cracking of concrete surfaces promoted corrosion of epoxy-coated steel. The impact of crack width on corrosion initiation and later progression was not significant.

- Systematic periodical measurement of half-cell potentials at the end of wet periods was valuable in predicting the corrosion state of embedded epoxy-coated bars. Corrosion was negligible when potentials remained below -400 mV SCE without significant potential gradients along the monitored bar. Pitting corrosion was always associated with potentials in the range of -400 to -600 mV SCE and steep potential gradients in excess of 200 mV.

- Severity of corrosion on epoxy-coated bars was related to both coating damage level and loading condition. As received bars and stirrups in uncracked members performed well, whereas those with damaged coating in cracked beams showed the worst performance. Patching of damaged coating and cut bar ends reduced the severity of corrosion, but did not provide full protection.

- The quality of concrete at the bar interface affected the location where corrosion initiated and progressed. There was a tendency for the epoxy coating to develop blisters and to break down at voids in contact with bar surface.

- To improve the effectiveness of coated steel, damage to coating needs to be reduced, patching requirements need to be modified, concrete quality needs to be improved, coating adhesion to steel needs to be enhanced, and treatment of cracked concrete surfaces needs to be considered.

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