

**CORROSION PERFORMANCE IN CONCRETE OF REINFORCING
STEEL WITH A PROTECTIVE INORGANIC COATING**

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ABSTRACT

A novel inorganic coating material, based on alkaline silicates, has been subjected to initial testing for evaluating the ability to provide corrosion protection for reinforcing steel in chloride-contaminated concrete. Reinforced concrete specimens were prepared with coated bars and exposed to simulated marine bridge substructure conditions. Measurements of electrode potential and corrosion macrocell currents were performed over nearly 300 days of exposure. The results show improved corrosion performance over uncoated bars.

Keywords: corrosion, reinforcing steel, inorganic coating, concrete, protection, testing, chlorides, fly ash.

INTRODUCTION

Reinforcing steel bars (rebars) in concrete tend to develop a passive surface because of the high pH of the solution normally present in the concrete pores. Carbonation of the concrete or chloride ingress (from seawater or highway deicing salts) to the rebar depth can result in passivity breakdown and subsequent severe corrosion. Reduction of oxygen permeating from the exterior provides an adequate source for the corresponding cathodic reaction. Because of the adverse impact of this form of deterioration on the national transportation infrastructure, considerable interest exists in using adequate means of protection [1]. In addition to using thicker and less permeable concrete cover and corrosion inhibiting admixtures, efforts have been directed to improving the corrosion resistance of the rebar itself. Because of the relatively low cost of plain

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carbon steel, rebar coating treatments (as opposed to alloying additions) have been employed in many applications. For example, epoxy-coated rebars are being extensively used in the United States for service where chloride contamination of the concrete is expected. The reported performance of epoxy-coated rebar has been satisfactory to date in numerous highway applications [2]. However, recent observations of undercoating corrosion of epoxy-coated rebars in severe marine environments have been reported [3], underscoring the importance of continuous development of effective rebar treatments for long term performance.

An alternative coating for corrosion protection of steel rebars has recently been developed and is currently undergoing testing. The coating consists of a proprietary mixture of inorganic alkali silicates and a cross-linking compound which are deposited on the surface of freshly sandblasted rebar. The bars are then heated to 400 °F for a short time and allowed to cool. The resulting coating is typically 0.1 mm thick, covering the entire bar surface. The bars can then be positioned in a form and the concrete is cast in place. The proprietary coating is produced and applied by PPG Industries, Inc., and covered by several U.S. patents.

Tests of steel coated by this procedure have been performed in aqueous solutions which simulated concrete pore solution chemistry. Cyclic polarization tests revealed a significant elevation of the pitting potential, indicating that the coating behaved as an effective anodic inhibitor [4]. This paper provides a brief summary of the results of initial tests of the corrosion behavior in concrete of rebars coated with this novel material.

EXPERIMENTAL PROCEDURE

The experiments were intended to examine the behavior of the coated material in conditions resembling the service encountered in marine bridge substructures, where severe chloride contamination and active macrocell action are expected.

Two types of test specimens (reinforced concrete cylinders and slabs) were constructed as shown in Figure 1. Both types of specimens were placed vertically in a test tank with a 5 % NaCl solution, so that the lower 7.5 cm of all specimens were submerged. This arrangement resulted in enhanced chloride accumulation (by capillary action and evaporation) in the concrete just above the water line, thus promoting corrosion initiation on the steel present in that zone. In addition, the concrete in the lower 15 cm of the reinforced concrete slabs contained NaCl, added at the time of casting, to obtain an initial chloride concentration of 20 pcy (12.5 Kg/m³). The exposure conditions were therefore intended to promote corrosion at the lower rebar segment in the slabs, while leaving the rest of the rebars in low-chloride concrete surroundings. The specimens were constructed using concrete with a water-to-cement ratio of 0.45 and coarse and fine aggregates commonly used in Florida substructure applications. The slabs used Type II cement only. The cylinders were made with three different concrete mix designs employing: Type I cement, Type II cement, and Type II cement with 20% type F fly ash replacement.

Each slab specimen contained 10 rebar segments in the chloride-free zone. All rebar segments within the slab were electrically connected. Switches between different levels allowed for the measurement of macrocell currents and independent polarization measurements. Activated titanium reference electrodes (calibrated periodically by means of an external calomel electrode) were embedded at three different levels. The slab configuration created the conditions for strong macrocell action (10 cathodes for one anode) after the lowest element achieved an actively

corroding condition.

Specimens were built in duplicate using rebars of the following types:

- 1) black bar (as control)
- 2) inorganic coated bars as-received
- 3) inorganic coated bars with 1% surface damage
- 4) as in (3) plus 1 month exposure to 3.5% NaCl solution
- 5) epoxy-coated bars as-received
- 6) epoxy-coated bars with 1% surface damage

In addition to the above types, the slabs included:

- 7) inorganic bars with the lowest bar bent as a 7.5 cm hook.
- 8) as in (7) but with the hook patched after bending.

The patching procedure consisted of recovering the bent hook with the mixture and rebaking. The inorganic coating formulation was the same for all specimens, except for two slabs so identified in Figure 4.

The specimens have been exposed in the test tank for times ranging from a few months to one year. The initial results are summarized below.

RESULTS

Test Cylinders

The open-circuit potential of the test cylinders was monitored during the exposure period. The time to active corrosion T_a was defined as the number of days required to observe an open - circuit potential transition in the negative direction of enough magnitude to suggest that active corrosion spots had developed somewhere on the bar surface. The potential transitions were accompanied by considerable reduction in the magnitude of the electrochemical impedance at low frequency (to be reported elsewhere), consistent with the interpreted initiation of active corrosion. Figure 2 shows schematically the T_a value for all the cylinders included in the test. An upward arrow indicates that no transition had taken place during the reporting test period. Figure 3 displays the results of the potential transition observations in a time-cumulative manner, combining the results for all types of concrete and presence/absence of surface distress.

As shown in Figure 2, none of the inorganic-coated specimens tested in concrete with fly ash showed a potential transitions during the test period. Only two of the epoxy-coated specimens showed a transition during the test period. While the visualization in Figure 3 does not reflect a true random dispersion, the plot suggests that for the inorganic-coated material the T_a values were about double those of black bar, and that surface distress introduced no observable difference in corrosion initiation behavior. Insufficient data exists at this time on the specimens with epoxy-coated bars to assign a comparable factor for that material.

Test Slabs:

Figure 4 shows the macrocell current (duplicate specimens) measured between the anode and the combined cathodes, after 299 days of exposure. For this exposure period, the slabs with inorganic-coated rebar developed average currents that were 10 times to 300 times smaller than those of slabs with black bar. Shown in the same figure are currents for the precorroded specimens with inorganic coating, evaluated after 184 days of exposure. Compared with black bar at similar times of exposure, the prerusted inorganic coated bars developed currents that were 2 times to 100 times smaller.

The measurements permitted evaluating the cathodic behavior of the various test materials, by correlating the cathodic current and the potential at specific bar segments as shown elsewhere [5]. A comprehensive data summary at 299 days of exposure (184 days for the precorroded specimens) is shown in Figure 5. The results are presented in the form of an E-log I plot. Only about half of the specimens had developed sizable macrocell current patterns by the end of the reporting period. In those slabs the macrocell currents flowed in the usual direction (electrons from bottom to top, open symbols in Figure 5). The rest of the specimens had very small currents (typically less than 0.1 μA) and often of the opposite direction (crosses).

Polarization behavior can be gleaned by joining the data clusters for duplicate slabs (and/or different segments in the same slab) corroding at different regimes. For black bar and the inorganic-coated materials this results in apparent Tafel slopes on the order of 100 mV/decade. The results suggest that, for a given cathodic potential, the cathodic currents in the non-precorroded inorganic-coated bars were one to two orders of magnitude smaller than for black bar. The precorroded inorganic-coated bars show also a pronounced cathodic efficiency reduction, although not as much as in the case of the non-precorroded material. This may be the result of additional cathodic sites at preexisting corrosion products attached to the surface of the specimens during the preconditioning exposure. The slabs with 1% surface-damaged epoxy-coated rebar tended to show about one order of magnitude less cathodic current than the slabs with inorganic-coated bars without precorrosion. As-received epoxy-coated rebar resulted in the lowest cathodic currents.

DISCUSSION

The results to date indicate that the inorganic-coated rebars had considerably less tendency for corrosion in concrete than black bars. The presence of the coating resulted in longer times to active corrosion (as inferred from the potential transitions) than for black bar, suggesting that a higher concrete chloride content may effectively be required to initiate corrosion. After corrosion initiation the corrosion macrocell currents tended also to be significantly lower. Low cathodic efficiency seems to be an important factor in reducing corrosion currents. It is also possible that the size of the anodic regions is smaller than in the case of black bar, because of the speculated need for a greater chloride content to activate the coated material.

Prerusting and fabrication of the inorganic-coated bars without subsequent repair tended to degrade performance. This observation underscores the importance of establishing practices and methods for preplacement protection and patching of the coating.

The cathodic performance observed in the slabs after nearly 300 days of exposure suggests that the coating retained protective properties (and is stable in concrete in that sense) during that exposure time. The presence of fly ash in the test cylinders did not appear to have adversely affected the coating performance; on the contrary, the inorganic-coated specimens in that concrete have retained passivity the longest. To date, there are no discernible trends in the performance of the coated materials when tested in concretes using Type I versus Type II cement.

During the time frame of the test epoxy-coated rebar showed generally longer times to nominally active behavior, and lower corrosion currents, than the inorganic-coated material tested in similar conditions. In examining the results, it should be kept in mind that the epoxy-coated bars were tested only in the as-received and 1% surface damage conditions, while the inorganic-coated bars were tested also in more severe conditions (bent, prerusted). Because the long term corrosion protection trends of coated products may differ widely from initial behavior [3], an assessment of the relative long-term performance of both materials cannot be made until an extended exposure period is examined.

There is latitude in the formulation of the material used for the inorganic coating. Alternative product formulations are currently being investigated for possible improvement of corrosion protection performance.

CONCLUSIONS

1. The inorganic-coated bars showed significantly improved corrosion performance in concrete when compared with black bar during the present test period.
2. The inorganic coating considerably reduced the extent of the cathodic reaction on steel in concrete when compared with black bar at the same potential.
3. Macrocell current reduction and cathodic efficiency reduction were still in effect after almost 300 days of service of the inorganic coating in concrete.
4. No indication of adverse effects on the coating performance were observed when using concrete with fly ash.
5. Prerusting and fabrication without repair tend to degrade the corrosion performance of the coating.
6. During this short test interval (1 year or less), epoxy-coated rebar showed lower corrosion currents and longer time-to-corrosion periods than the inorganic coating when tested under similar conditions (as-received and 1% surface damage). The relative performance of these coated materials should be evaluated over longer test periods, since different corrosion protection principles are involved.

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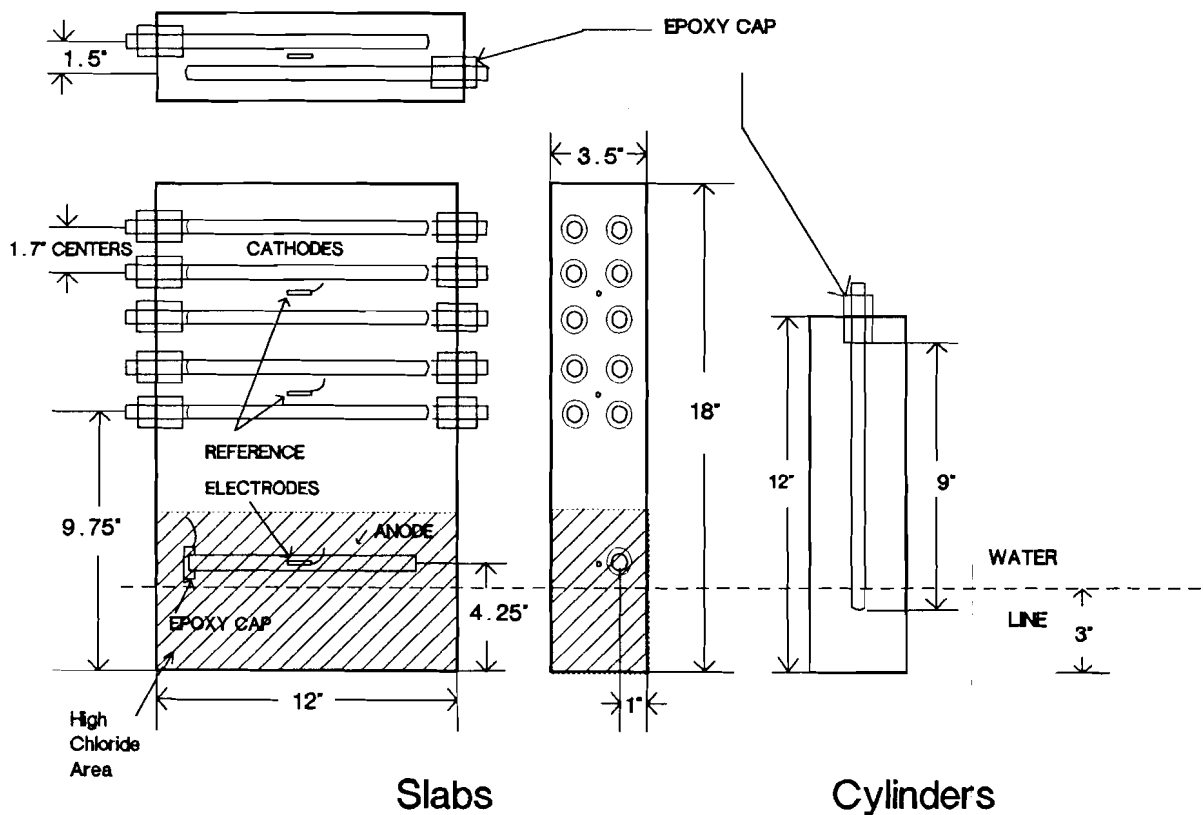


Figure 1. Schematic specimen configuration.

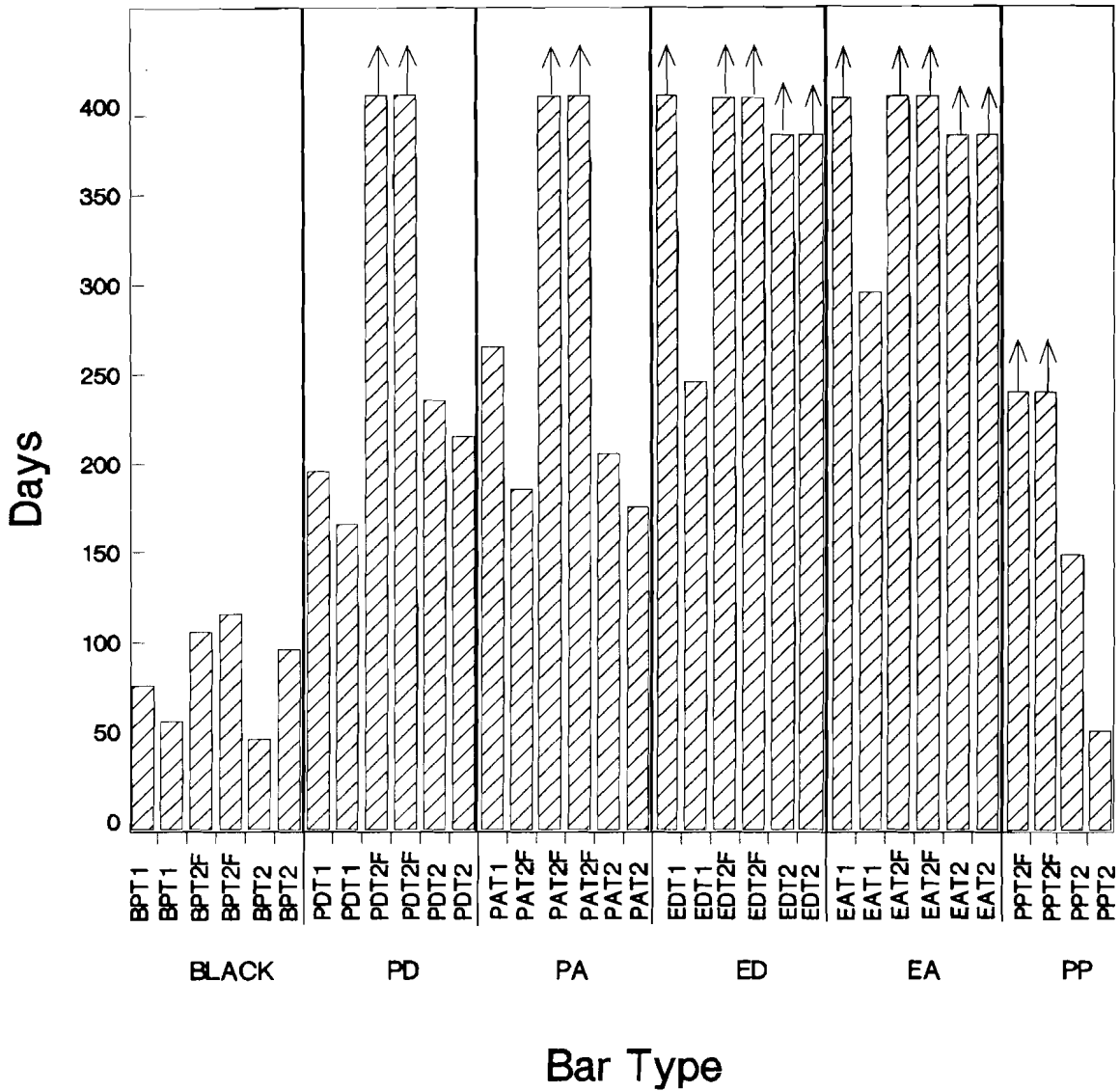


Figure 2. Time to active corrosion for cylindrical specimens.

Key:

Black: Black Bar

PD: Inorganic Coating, 1% surface damage.

PA: Inorganic Coating, as-received.

ED: Epoxy-coated, 1% surface damage.

EA: Epoxy-coated, as-received.

PP: Inorganic Coating, preexposed to NaCl solution.

T1: Type I cement.

T2: Type II cement.

T2F: Type II cement with fly ash.

(Duplicate tests except for PAT1 and PAT2F as shown)

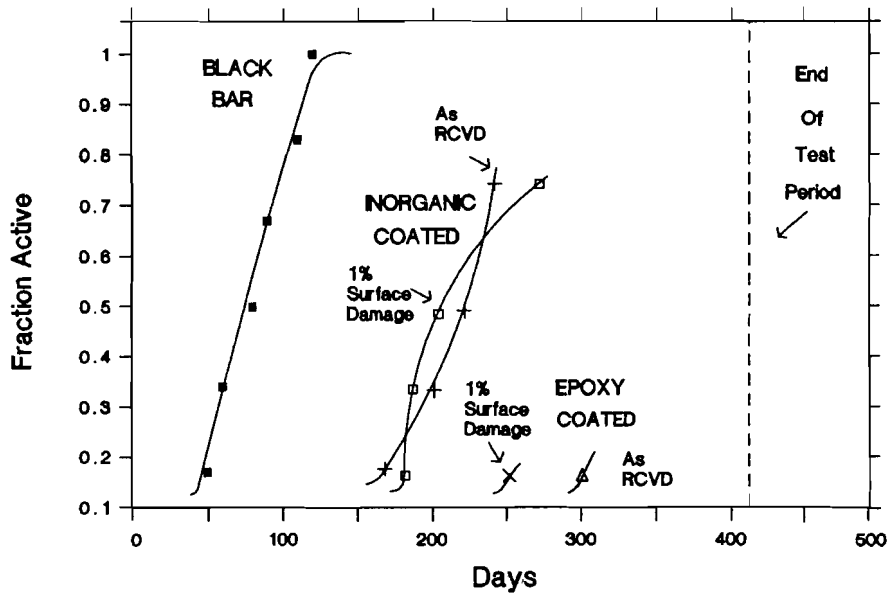


Figure 3. Cumulative sequence of time to corrosion indications. The preexposed specimens, which were started later (see Figure 1) are not included.

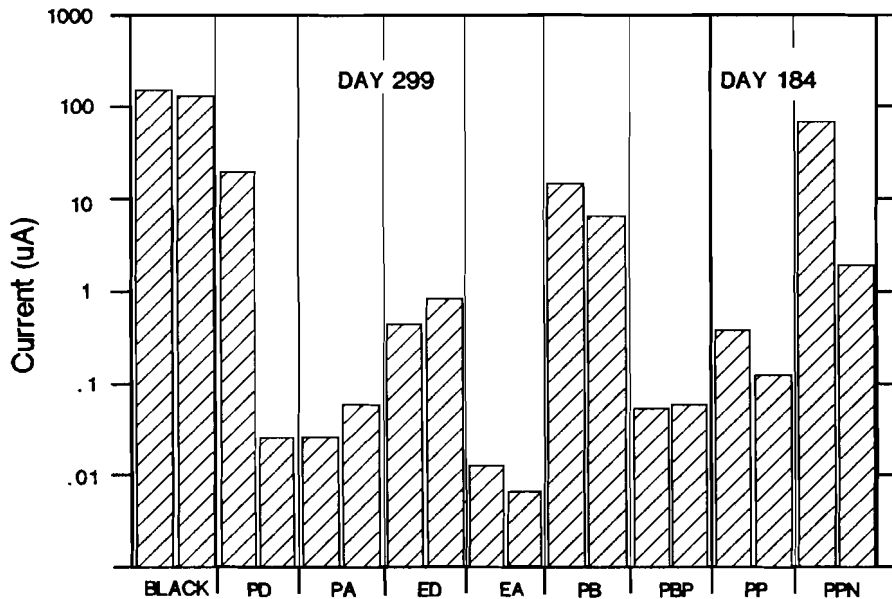


Figure 4. Macrocell current measured after the indicated number of days of exposure for test slabs (results showing duplicate specimens). Key is as in Figure 2 plus PP, PPN: inorganic-coated specimens (two different formulations) that were 1% surface-damaged and prerusted prior to casting in concrete; PB: inorganic-coated, bent; PBP: inorganic-coated, bent and patched.

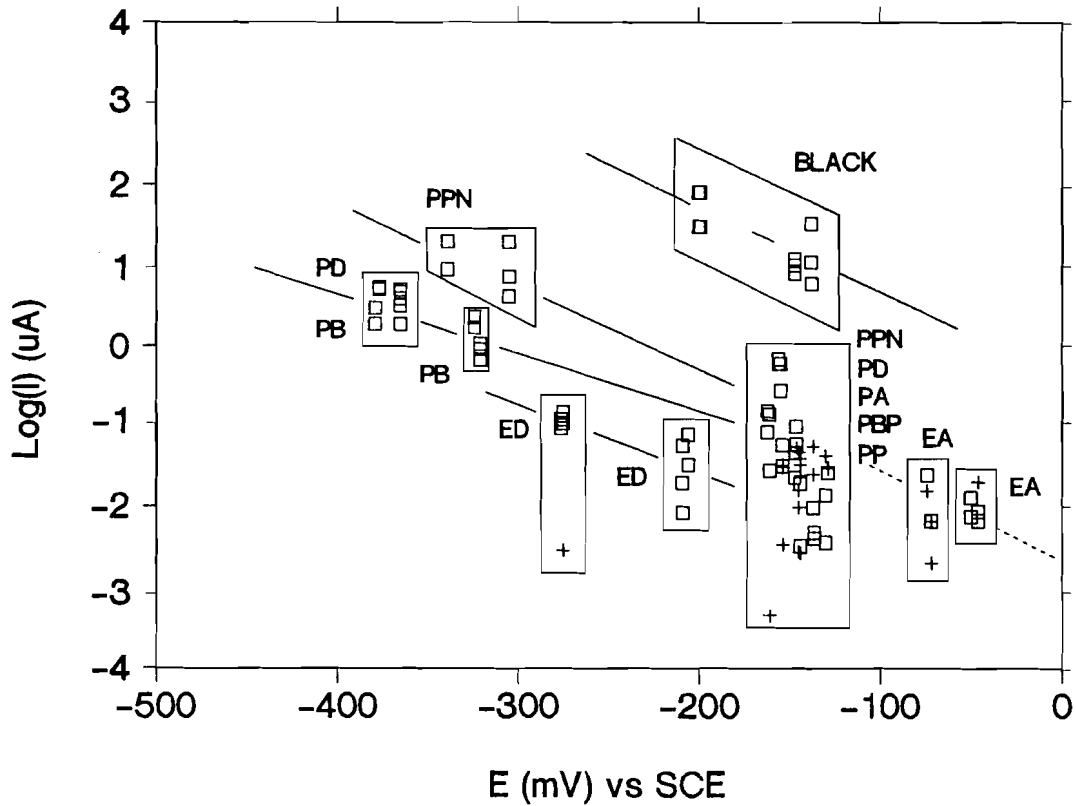


Figure 5. Logarithm of current measured at various levels of the test slabs, as a function of the potential of each cathodic element. Key is as in Figures 2 and 4. The lines join data clusters of cathodic current from specimen pairs corroding under different conditions, thus providing an approximate indication of cathodic polarization behavior. Bar types PA, PBP and PP did not develop enough activity to establish a trend; the line for EA type is tentative. Crosses represent current in the opposite direction (usually in specimens where a macrocell pattern had not fully developed). Measurements taken after 299 days of exposure, except for PP and PPN which had accumulated only 184 days.