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EVALUATION OF POINT ANODES FOR CORROSION PREVENTION IN REINFORCED CONCRETE

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ABSTRACT

The polarization performance of two types of commercial galvanic point anodes for protection of rebar around patch repairs is evaluated. Experiments include measurement of the polarization history of the anode under galvanostatic load simulating various aging regimes. Additionally, the anodes were evaluated in reinforced concrete slabs with residual chloride contamination and in field installations. Preliminary results indicate that only modest performance may be achieved with typical expected anode placement spacing in commonly encountered applications.

Key Words: anodes, zinc, cathodic protection, concrete, corrosion, reinforcing steel.

INTRODUCTION

Small anodes are being produced commercially or under development to be cast in patch repairs of concrete damaged by reinforcement corrosion. A phenomenon that affects the durability of such repairs is the “halo effect” wherein the steel within the new repaired area serves as a cathode generating accelerated corrosion of the steel in the original concrete surrounding the patch repair. The anodes are intended to prevent the initiation of corrosion on the rebar around the patch that was still passive, but in contact with concrete with moderate to high chloride content. These anodes usually consist of a zinc alloy piece with connecting wires that also serve to retain the anode in place and are embedded in a mortar disk.

The mortar has admixtures that promote high pH or otherwise activating the zinc. The mortar may contain also humectants to further promote activity of the zinc[1-4].

Embedded anodes of the type described above have been promoted by manufacturers for residential or parking building applications, and more recently there is increasing interest for highway applications. Of special interest in highway service is mitigation of corrosion in repaired bridge deck spalls, and patches in inland as well as in marine substructure components. The possibility of large scale applications in highway systems brings up several important performance and durability issues needing resolution. In the present investigation two types of anodes under production or development at the start of the project were evaluated to determine their effectiveness. The approach used was to establish the polarization characteristics of the anodes, and its dependence on relevant service variables (e.g. anode type and environment, including mortar type and humidity condition).

EXPERIMENTAL PROCEDURE

Laboratory, test yard and field experiments (referred in the following as Type A and Type B specimen tests, and Field installations respectively) were developed to assess the current/potential behavior of the anodes as a function of time and the combined anode-rebar performance. All potentials are reported in reference to the Copper/Copper Sulfate electrode (CSE).

Type A Specimen Tests (Humidity Chambers)

This experiment has been performed in chambers of relative humidity (R.H.) controlled at ~60% and 95% at room temperature. The basic test specimen is a prism 20 cm x 20 cm x 10 cm, with a sacrificial anode placed near the center and an embedded activated titanium rod (ATR) reference electrode placed against one of the external mortar faces of the anode[5]. Two embedding media were used: a specialty polymer modified cementitious repair mortar (proprietary mix) and an ordinary repair concrete (ORC). A summary of materials and test conditions is given in the Table 1. Two anode types were tested designated as follows:

C: Zinc alloy anode embedded in pellet of highly alkaline mortar. Anode model tested has a zinc alloy mass of ~ 30 g and mortar pellet external diameter ~70 mm and thickness ~30 mm.

W: Zinc alloy anode embedded in pellet of mortar with humectant and proprietary zinc activators. Anode mass and external dimensions comparable to that of C anode.

Type A specimens have been exposed for approximately 22 months. Measurements of the polarization history (instant-off potential) of the anode under galvanostatic load simulating various aging regimes were used to assess the polarization of the anode as function of service time.

Type B Specimen Tests (Test Yard Slabs)

Six reinforced concrete slabs with dimensions of 1.2 m length, 0.45 m wide and 0.15 m thick were constructed. Each slab contains 12 embedded segments (#7, 2.2 cm nominal diameter) of plain steel rebar placed ladder-wise at equal intervals, 10 cm apart, along each slab (Figure 1). The slabs were built using the same Ordinary Repair Concrete formulation as for the “ORC” test blocks, except that the shaded portion near the center contained admixed NaCl to obtain 10 pounds per cubic yard (pcy) (5.9 Kg/m^3) chloride ion simulating a conventional patch repair with chloride contaminated concrete adyacent. Four rebars located near the center of the slab were in contact with the chloride contaminated concrete that resulted in an active, net anode condition. The remaining rebars were passive. Each slab contained two anodes both of either Type C (triplicate slabs numbered 1, 3 and 5) or Type W (triplicate slabs 2, 4 and 6). All rebars were normally interconnected with switches that allowed measuring the macrocell current delivered/received by each bar segment, and performing depolarization tests. A copper/copper sulfate electrode (CSE) was used to measure the potential of each segment with respect to the concrete next to each rebar. Nominal concrete resistance between rebars (from which concrete resistivity was determined), current and potential (E_{IO}) as well as temperature measurements were performed periodically over 22 months.

The anode on the slab centerline (Main) was always connected to the rest of the rebar assembly. The other anode (Auxiliary) was reserved for special tests. Externally wired switches permitted performing instant-off potential measurements and measurements of current delivery to individual rebars. All rebars and the main anode were normally interconnected. The slabs were maintained outdoors under normal ambient exposure.

The slabs were cast on 11/23/04 and kept curing in the molds until 12/1/04 when the slabs were demolded and placed horizontally, elevated 1 ft above ground, in an outdoor test yard ~ 20 km inland from Tampa Bay in Florida. The main anode was kept provisionally wired to the four rebars in the Cl- rich zone while still curing in the forms and connected to the entire rebar assembly on 12/1/04 which was designated as the start of the exposure period (t=0). The total cathodic current delivered to those rebars for both anode types was substantial (~1 to 2 mA) during that early period. Despite that, cathodic prevention did not appear to have been achieved as this rebar group behaved as being in the active condition from the start. It is noted that in some of the slabs the concrete in the chloride-rich zone was poorly consolidated and exhibited honeycombing at places. The voids were repaired with grout soon after placement in the test yard.

Measurements were performed for 16 months with all rebars connected to the main anode. After that, the four rebars in the chloride contaminated concrete were disconnected and only the passive rebars were kept connected to the anode assembly to evaluate the ability of the anodes to polarize an all-passive rebar assembly.

Field Installations

Suitable locations in Florida were selected for implementation of repairs fitted with embedded anodes. The performance of these anodes was monitored periodically.

Test anodes were installed in substructure components of Bridge Nos. 700028 and 700115 (s.r. 528 over the Banana River), Brevard County, Florida. Testing reported here is for the first 130 days of operation; further testing is in progress.

Three different types of sacrificial anodes have been installed in four spall repair areas at the experimental test locations shown in Table 2 (Figure 2). All reinforcing steel in each test area is electrically continuous and two ground connections have been installed in each test area. Two other locations are designated as controls, with no anodes installed. A polymer–modified silica fume-enhanced mortar was used as the patch repair material for all test areas. The same material was also used to repair all other spalls in bents 10 and 11 on both bridges.

Potentials were monitored periodically at positions 3, 6 and 12 inches (7.62, 15.24 and 30.48 cm) away from the patch perimeter. Anode currents were monitored as well. Depolarization tests (~22 hours) were conducted after 92 days of exposure.

RESULTS AND DISCUSSION

Anode Polarization

Humidity Chamber Tests: The potential E_{IO} of the anodes is reported in the instant-off condition (~ 1 sec after current interruption) either when measured directly in relation a CSE electrode placed on the block wall, or in relation to the internal activated Titanium rod calibrated against a CSE. Potentials are reported as function of time t, with t=0 chosen to correspond to the moment of energizing of the anodes, which was 48 days after casting for the 95% R.H. tests and 81 days after casting for the 60% R.H. tests. The average E_{IO} values of triplicate specimens were again averaged over the periods 0-200, 200-400, 400-600 days and the results are illustrated in Figure 3 for the high humidity condition. Any specimens for which the potential reached ~0V CSE (i.e., clearly incapable of protective action) at a given test time were disconnected and no longer used to calculate average potentials. This condition was reached in the high humidity chamber for only a few of the specimens, which were all in the 300 μA regime. In the low humidity chamber the condition was reached in more specimens and at lower current levels, effectively terminating the test early for those cases.

Both C and W anodes showed more negative open circuit potentials (OCP) in the proprietary mix medium than in the ordinary repair concrete, in both the high and low humidity chambers. For either medium, at high humidity, the C anodes had more negative OCP than the W anodes, but the OCP potentials of both anodes were comparable at low humidity. Despite their more negative OCP than the W anodes at high humidity, the C anodes at both humidity levels tended to polarize more, and faster with time, than the W anodes. Tests are still in progress and confirmation or variation of these trends upon longer exposure is pending. Absolute potential trends will be further examined toward improving accuracy by eliminating or correcting possible junction potential errors as indicated in the next section.

Yard Slab Tests: The current delivered by the anodes to the entire rebar assembly as function of exposure time is show in Figure 4. Initial currents were often large but after 16 months current from the C and W anodes had dropped to ~500 μA and 50 μA respectively. After the rebars in the chloride zone were disconnected (day 477), the decreasing trend was arrested or even reversed for both anodes. The current distribution patterns along the slab main direction showed that, before their disconnection, rebars in the chloride-contaminated zone were mostly net anodes, contributing usually a total anodic current comparable to or exceeding the current supplied by the point anode. During that period, the rebar potential distribution along the slab main direction showed clearly that the main polarizing sources of the rest of the system were the rebars in the chloride contaminated zone, which exhibited potentials typical of actively corroding steel. It is clear that steel in the chloride zone of the slabs had potentials more negative than the typical potential of the main anode, which in turn was more negative than that of the bars in the chloride-free concrete zones. After disconnection of the active rebars, the anodes were indeed the most negative elements in the system, and the only source of cathodic polarization of the remaining, passive, bars.

Four-hour depolarization test results are shown in Figures 5 and 6. These figures show the polarization achieved in rebar segments 1-5 (Figure 1), using the average values for rebar pairs 1-2, 2-3, 3-4 and 4-5, which are closest to the anode and all in the passive condition, averaging in turn results from the triplicate test slabs. For the period before disconnection of the active rebars, depolarization tends to be greater at the bars further removed from the anode (e.g. 1-2), but that is an effect of the presence of the active rebars on the overall macrocell relaxation during depolarization. After the active bars were permanently disconnected, the expected trend of less polarization further away from the anode was observed. The extent of depolarization after ~100 days was significantly greater for the C anodes than for the W anodes, consistent with the difference in overall current levels evident in Figure 4. However, during the period when all rebars where connected, not even the C anodes achieved depolarization levels reaching 100 mV.

After disconnection of the active rebars the maximum average depolarization increased to ~120 mV for the C anodes and slightly for the W anodes, reflecting the removal of the less polarizable, lower potential active steel.

Performance Projections from Laboratory-Test Yard Data

Polarization regimes of anodes in controlled humidity chambers and in the test slabs are compared in Figure 7, illustrating the case of the C anodes. The potentials are shown time-averaged over the indicated periods. Greater ages are denoted by larger symbol size within each data sequence. The results comparisons apply primarily for the ORC medium since it was the only one used in the yard test slabs. Additionally, comparison were limited to the high humidity chamber tests since those resemble better the unsheltered yard exposure with periodic rain.

The approximate locus of the data for the anode in the slabs is circled. The data for early ages are found on the right side of the circled region and as the anodes aged the data moved leftward. As noted in Figure 7, after a relatively short initial period the potential of anodes in the slabs was in a relatively narrow band of values around ~ -350 mV. Under this nearly potentiostatic regime aging is expected to be manifested by a decrease in current, consistent with the observed trends. Conversely, aging in the galvanostatic regime used in the lab specimens was expected to manifest itself as an increase in potential in agreement with observed trends as well. Testing in both the humidity chambers and the yard slabs continues and long term trends are yet to be established [A].

Preliminary projections based on the available results are presented in Figure 8. In those figures cathodic current density data for long-term polarization behavior of passive rebar

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[A] It is noted that potential trends in the yard slabs include obscuring effects from surface carbonation or other surface chemistry changes of the concrete, which tends to introduce junction potential uncertainty. Those effects do not affect depolarization findings, which are based on short term potential changes. Correction terms for the absolute potential measurements are being developed using data from the internal reference electrodes and freshly exposed concrete surfaces; adjusted absolute potential trends will be reported in the future.

in concrete have been superimposed on the anodic performance curves for C anodes in the high humidity chamber. The shaded region denotes the approximate anode operating conditions after 22 months in the test slabs. The current density data have been converted into currents representing the polarization demand of steel surface areas of 1,000 cm^2 (~1 sq. ft.) and 5,000 cm^2 (~5 sq. ft.). The steel polarization data are from Reference 6 for passive steel embedded in concrete for periods of years. Considering typical steel densities in reinforced concrete and the expected “halo” region size around a patch, the assumed area values correspond respectively to tight (e.g. 0.30 m) and moderately relaxed (e.g. 0.70 m) inter-anode placement spacing. The intersections of the anode performance curves from the humidity chamber tests with the cathodic rebar demand indicates the expected operating point (best case, neglecting concrete resistance). For 22 months aged Type C anodes in ORC and 1,000 cm^2 of rebar surface area, that intersection occurs approximately at anode operating potentials in the order of -350 mV. The intersection roughly coincides with the operating region observed in the test slabs. The diagram projects that polarization of the larger rebar area (5,000 cm^2) would result in another ~100 mV increase in anode operating potential.

From the above case, it is noted that for ordinary repair concrete the projected level of polarization reached for the passive steel at the assumed steel densities is quite modest, and not clearly conductive to significant cathodic prevention effects[7]. The level of depolarization achieved in the test slabs after disconnection of the active rebars was not much above levels usually expected for cathodic protection, and in that case the area of steel polarized was quite small. Moreover, the decrease in performance with aging of both anodes (even in the C type) would further decrease expectations for adequate performance over long times if an appreciable steel area is to be polarized by a single anode. This analysis is preliminary and does not include possible junction potential corrections noted earlier; initial findings will be revisited as longer term data and improved potential measurements become available.

Field Installations

Potentials values at positions 3, 6 and 12 inches (7.62, 15.24 and 30.48 cm) away from the patch repair were averaged. Table 3 shows the Day 92 average potential and depolarization results at each of the test locations and controls. Only modest or very small protective polarizations were achieved in all cases. There was no significant difference in potentials between the anode and control sites.

Current delivered by the anodes decayed throughout the test period as shown in Figure 9. The results parallel those observed in the test yard slabs, with the C anodes retaining greater current delivery capacity longer that the W anodes, and with similar plateau current levels. This parallel is not surprising as the operating potential of the systems is similar in both cases. However, it is noted that the embedding medium in the field tests is a proprietary compound and the effect of medium in operating potential noted in the case of the laboratory humidity may need to be considered in future comparisons.

CONCLUSIONS

A laboratory approach to evaluate candidate anodes for patch repair applications was developed, and its feasibility demonstrated applying the experimental and analysis methods to actual commercially produced anode samples.

For both anode types, the results to date project that only modest anode operating potentials may be achieved with typical expected anode placement spacing in commonly encountered applications. That expectation is supported by the limited depolarization values observed in the test slabs before disconnection of the active rebar. After disconnection of the rebars in the chloride greater depolarization was recorded for the C anodes but the area of steel served was small.

Initial trends suggest that after 22 months aging under regular service conditions the anodes polarized significantly when delivering current. Thus, operating potentials necessary for effective protection/prevention action may not be achieved without using a high anode-to-steel placement density. Field Results were generally consistent with those from laboratory and yard tests. Decreased performance with aging was noted for both makes of anode, and it was particularly severe in one of them.

It is emphasized that these findings and preliminary and confirmation of trends is pending on continuing evaluation.

ACKNOWLEDGEMENTS

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TABLE 1
Materials and test conditions - Type A specimen Tests

Anodes evaluated	C and W
Embedding media	Proprietary mix (abbreviated EC) Ordinary Repair Concrete (abbreviated ORC) EC: 2l water + 50 lb bag (22.68 Kg) polymer modified repair mortar + 15 lb (6.8 Kg) 3/8" Aggregates ORC: 0.41 w/c, 658 pcy (390.38 Kg/cm^3),Type II cement, 3/8" Aggregates
Test environments	95% R.H.(Chamber 1) and 60% R.H. (Chamber 2) – target values
Galvanostatic regime	0, 30, 100 and 300 μA anodic current
Replication	Triplicate
Total test blocks	96
Blocks cast date	10/29/04
Energizing Date	12/16/04 Chamber 1, 1/18/05 Chamber 2

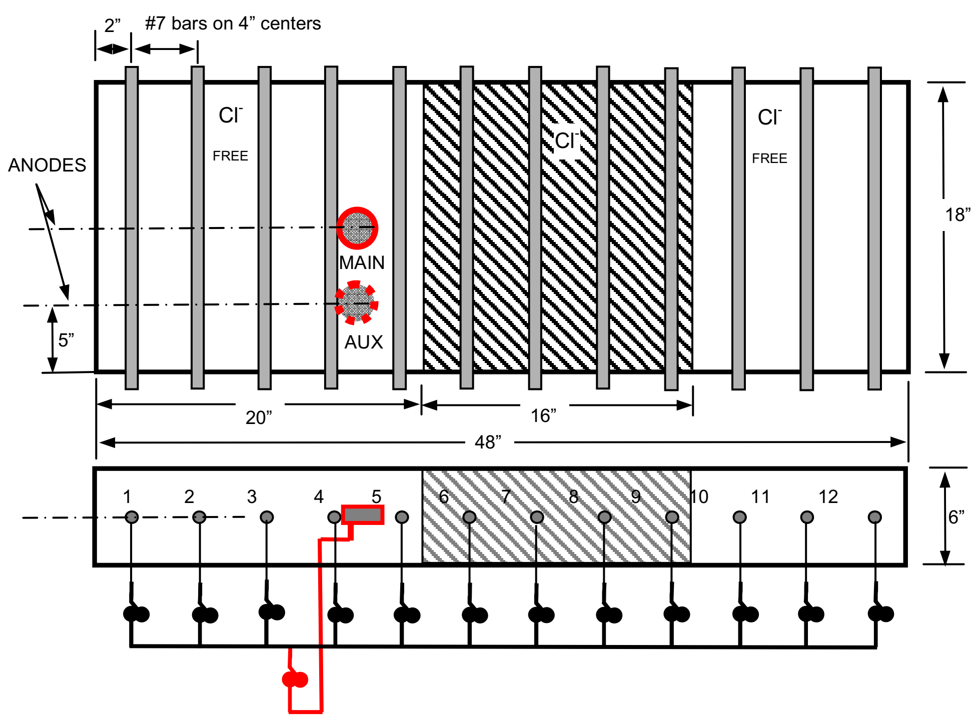

FIGURE 1 - Test Slab Configuration. 1" = 2.54 cm

TABLE 2
Test area locations and material installation information.
(Location 2 is not listed as it involves a type of anode not covered in this investigation)

Location	Bridge No.	Bent	Component	Anode Type	Date Anodes Installed	Date Patch Material Placed	Approx. Patch Area, s.f.
1	700028	10	Strut (E Face & NE Corner)	W	10/7/05	10/7/05	12.6
3	700115	10	Column (N Face & NW Corner)	C	9/13/05	9/14/05	17.5
4	700115	10	Column (W Face & SW Corner)	W	8/24/05	8/24/05	11.6
5	700115	11	Strut (W Face & Top Corner)	C	8/4/05	8/4/05	11.8
6	700028	10	Strut (W Face)	N/A (control area)	N/A	8/18/05	5.9
7	700115	10	Strut (W Face)	N/A (control area)	N/A	8/23/05	9.3

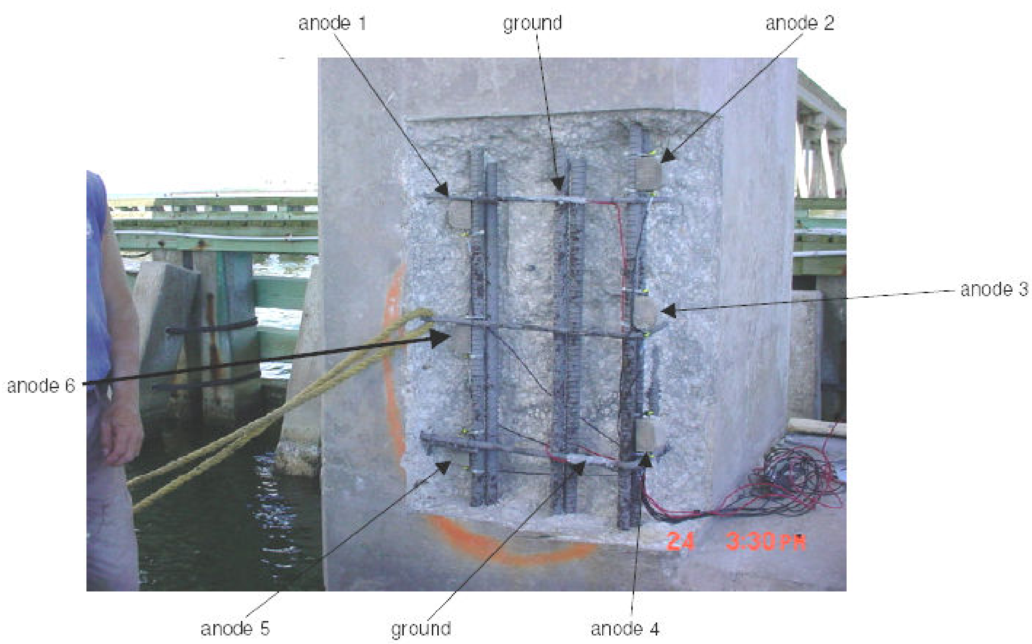

FIGURE 2 - Field Test Location No.4

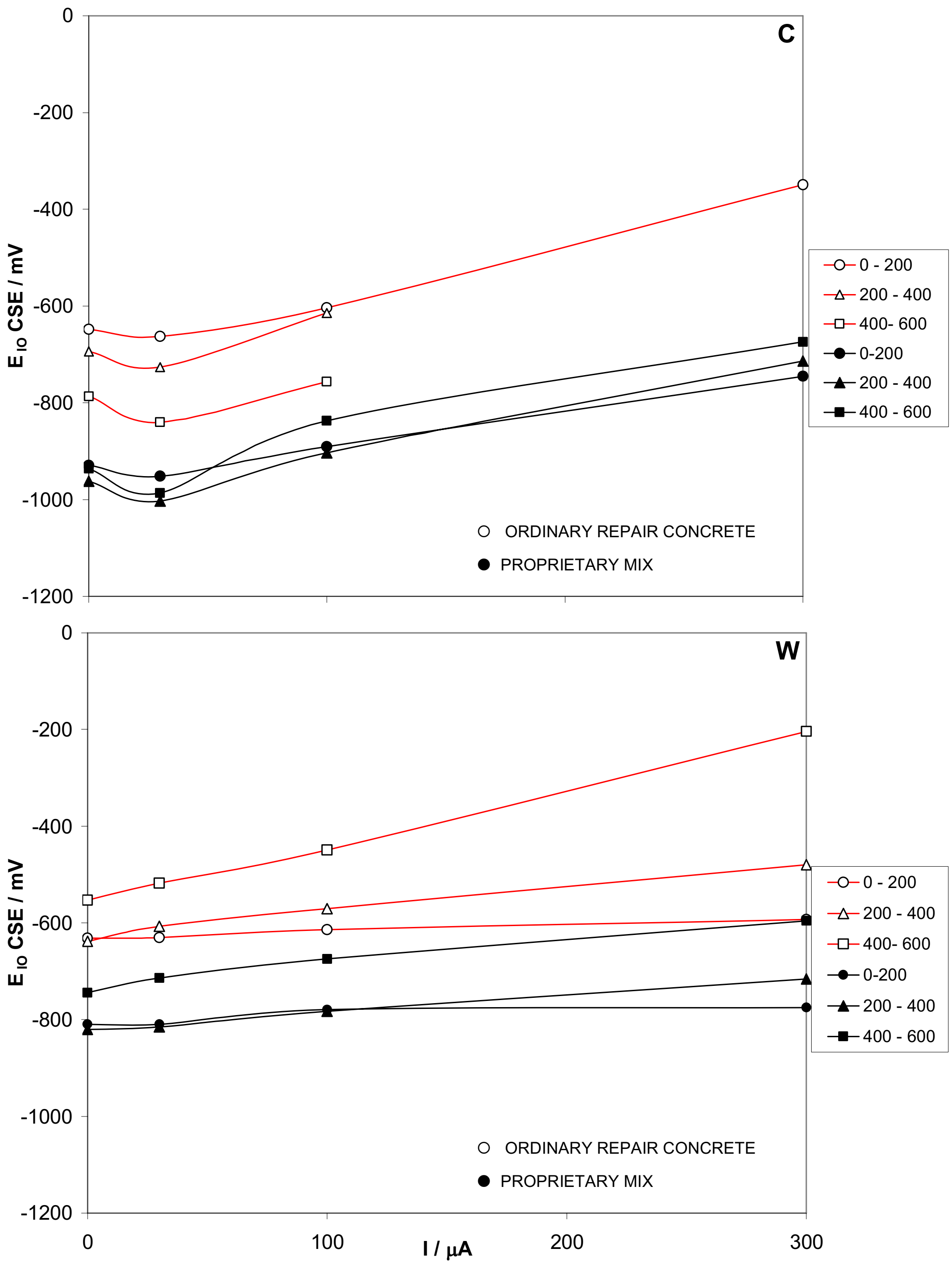

FIGURE 3 - E_{IO}-I evolution, W and C anodes, 95% RH.
Averages for time periods shown in days since energizing

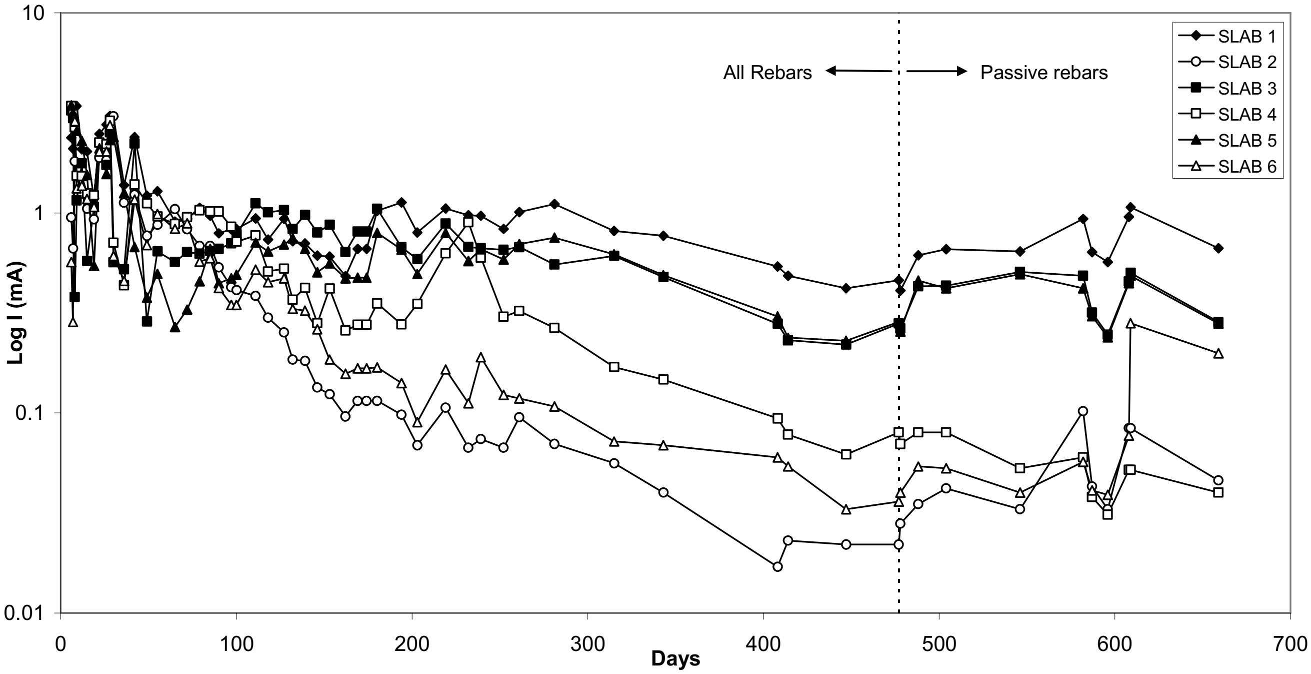

FIGURE 4 - Main anode current in test slabs as function of exposure time.
Slabs 1, 3, 5: C anode. Slabs 2, 4, 6: W anode

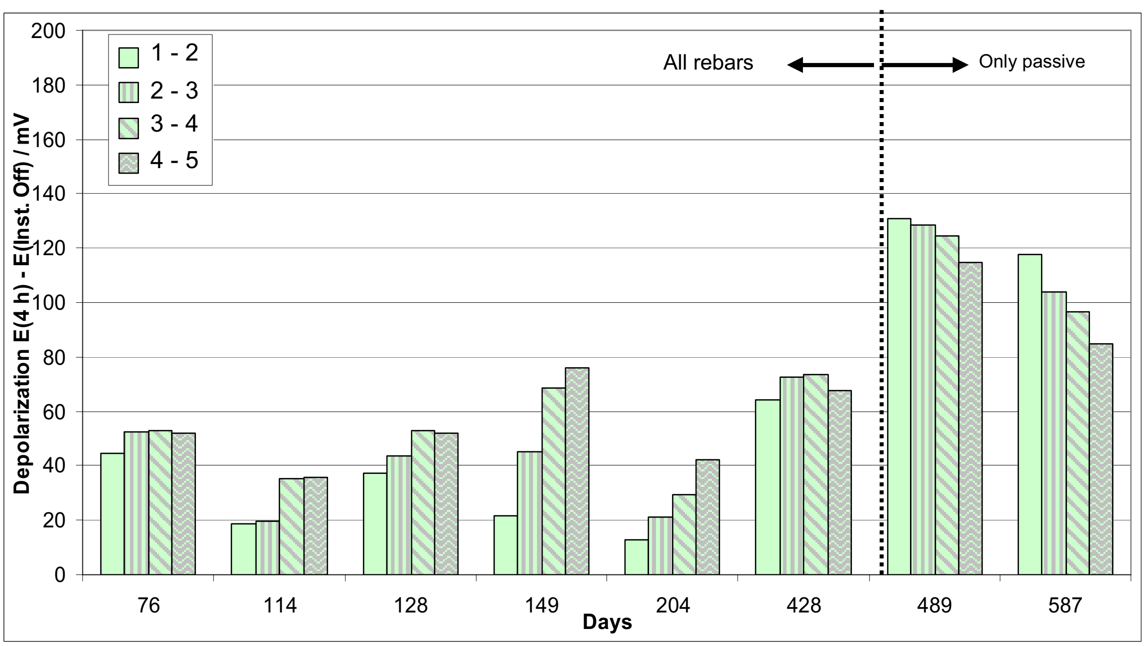

FIGURE 5 - Four-hour rebar depolarization test. C anodes.
Average results of triplicate slabs.

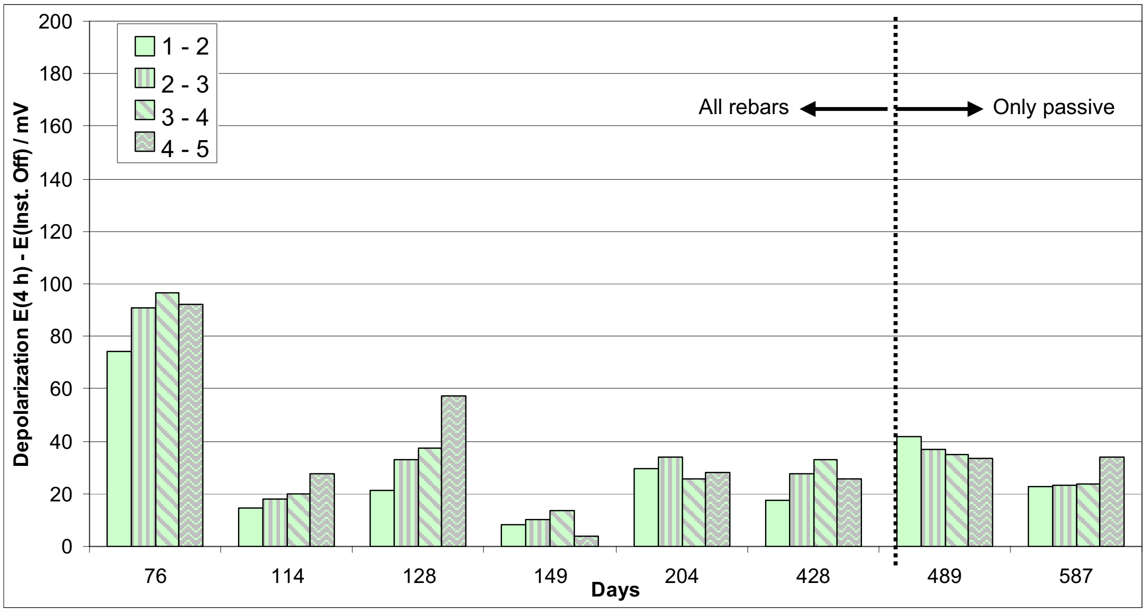

FIGURE 6 - Four-hour rebar depolarization test. W anodes.
Average results of triplicate slabs.

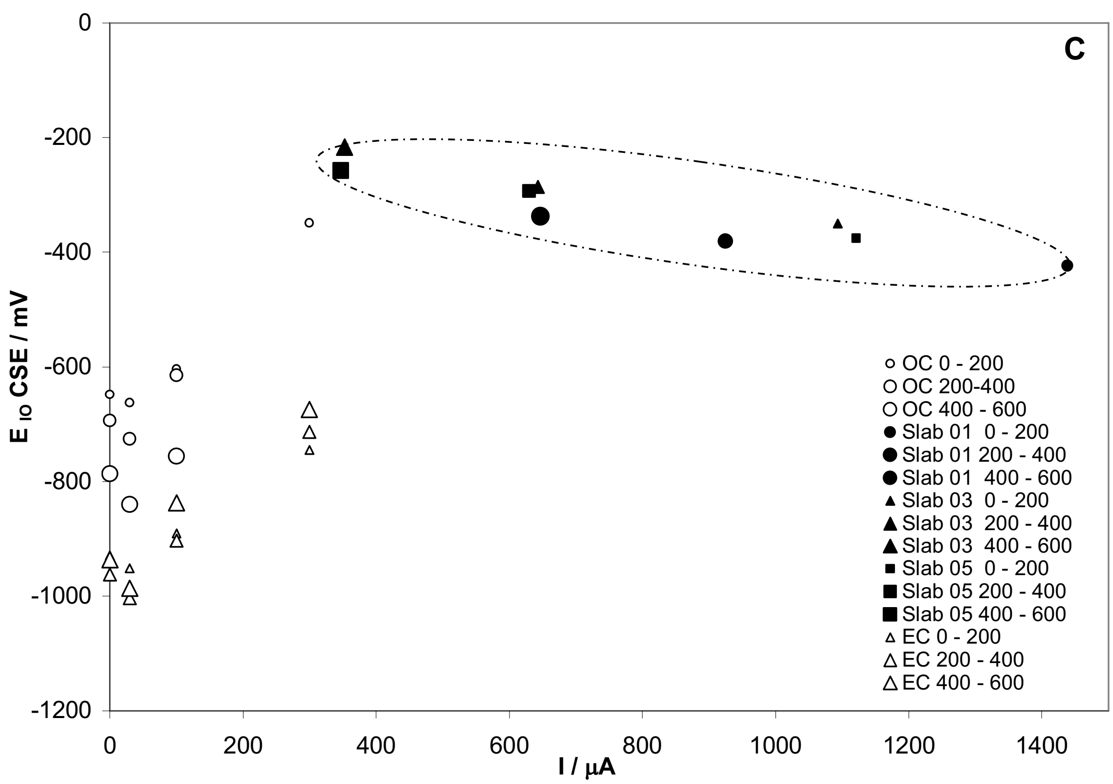

FIGURE 7 - Composite diagram showing polarization behavior of “C” anodes in the 95% R.H. test chamber and anodes in the yard slabs. Averages for time periods shown in days since energizing

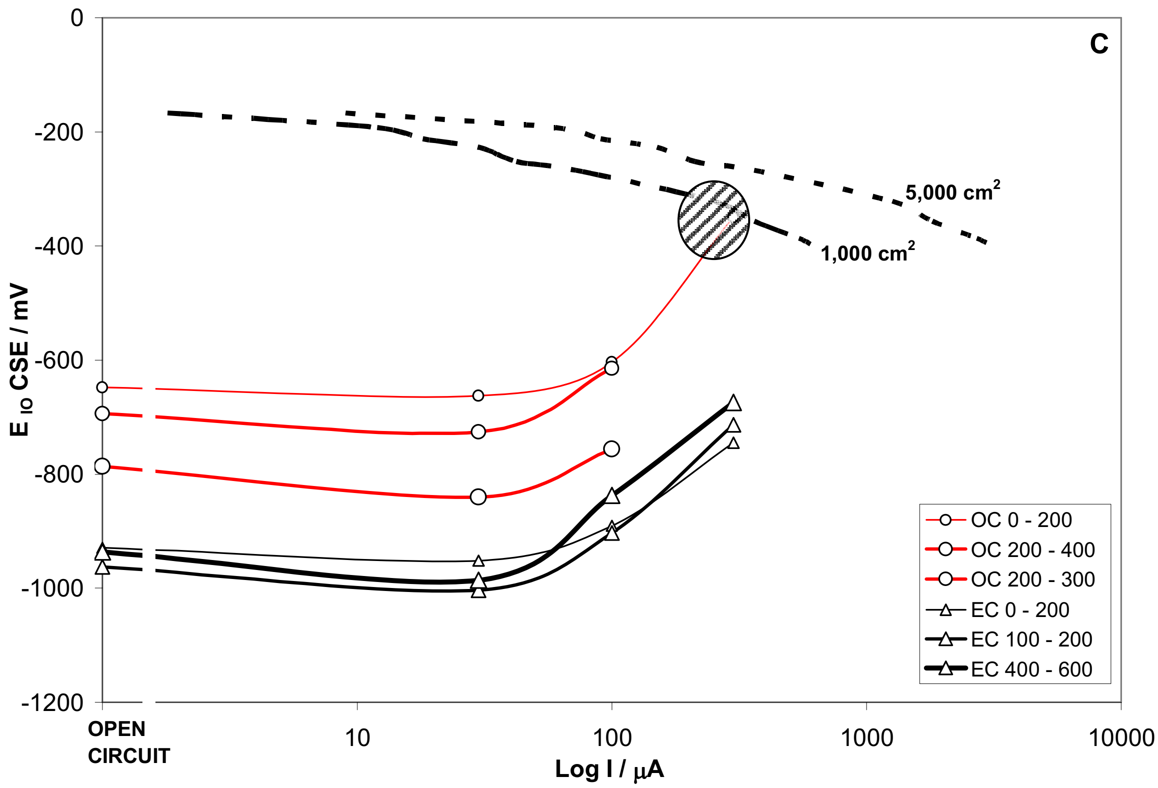

FIGURE 8 - Composite diagram showing polarization behavior of “W” and “C” anodes in the 95% R.H. test chamber and cathodic polarization behavior of passive rebar. Averages for time periods shown in days since energizing

TABLE 3
Field Potentials and Depolarization Test Results for Exposure Day 92
Average of all Anodes at Each Field Location

Location	Potential(*)	Distance From Perimeter (cm)		
		7.62	15.24	30.48
1 (W)	DP (mV)	-367	-354	-337
	P-DP (mV)	-5	1	-5
3 (C)	DP (mV)	-349	-349	-337
	P-DP (mV)	38	27	17
4 (W)	DP (mV)	-411	-402	-364
	P-DP (mV)	-10	-2	-9
5 (C)	DP (mV)	-454	-462	-456
	P-DP (mV)	19	11	11
6 (CTRL)	P (mV)	-418	-419	-429
7(CTRL)	P (mV)	-459	-458	-468

(*) DP: Depolarized potential ~22 h after anodes disconnection.
P-DP: Potential before start of depolarization test, minus depolarized potential.
A positive number indicates protective action.
P: Potential of steel in control areas.

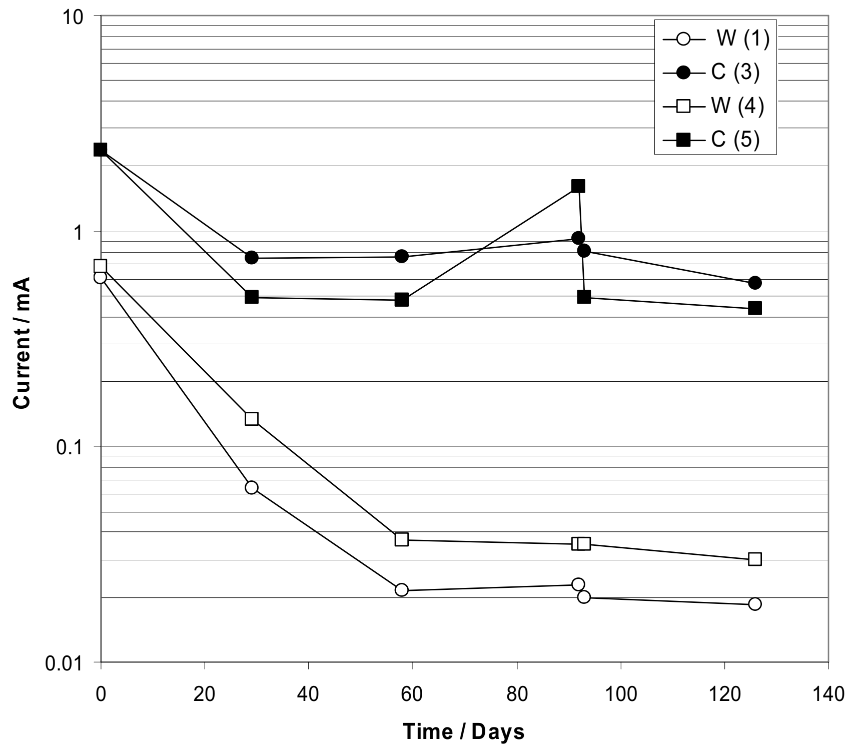

FIGURE 9. Average current output of field-installed anodes as function of time. The number after each anode type denotes location per Table 1.