

Cathodic Prevention for Reinforcing Steel in Cracked Concrete of Chloride Contaminated Structures

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ABSTRACT

Steel in concrete in marine service corrodes actively when chloride ion concentration exceeds a critical threshold level, C_T , causing passive film breakdown. There is interest in alternative or supplemental corrosion management approaches to extend structural life. One such approach is Cathodic Prevention (CPrev), based on the increase of C_T when steel is polarized in the cathodic direction while still in the passive condition. This work seeks to determine the effectiveness of cathodic prevention on cracked concrete in a marine environment. Experiments use reinforced concrete blocks with controlled-width cracks placed along the length of a central reinforcing steel bar, with initial cyclic exposure to a 5% NaCl solution. Crack widths ranging from 0.01 in to 0.04 in and polarization levels ranging from -330 mV to -540 mV (SCE) were evaluated over 1 year. Results suggest that CPrev with moderate cathodic polarization levels may be of limited benefit in the presence of the lengthwise cracks. Polarization at potentials ≥ -430 mV SCE was insufficient to prevent corrosion initiation in cracks of any of the tested sizes. Polarization at the stronger -540 mV SCE regime resulted in no corrosion initiation events for any crack size during the one-year test interval.

Key Words: cathodic prevention, cracked concrete, chlorides, polarization, corrosion.

INTRODUCTION

A major factor in limiting the service life of many reinforced steel bridges in marine service is the corrosion of the embedded steel.^{1,2} The resulting expansive corrosion products cause deterioration in the form of spalling and cracks on the concrete cover, with attendant costly

repairs. There is strong motivation to develop alternative corrosion management approaches to extend the life of existing structures while minimizing adverse impact. One technology that holds considerable promise to that end is Cathodic Prevention (CPrev).^{3,4,5} Unlike conventional Cathodic Protection (CP), which is normally applied after a structure has already suffered significant corrosion, CPrev is implemented before the initiation of corrosion to avoid or greatly delay its onset. CPrev may also prevent the onset of corrosion in areas around patch repairs in existing structures.^{6,7} Steel in concrete in salt water corrodes because chloride ions penetrating from the outside toward the steel eventually build up there to a critical threshold level, C_T , that causes breakdown of the protective passive film on the steel surface. CPrev is based on the observation that the value of C_T increases if the steel is polarized in the cathodic direction while still in the passive condition. Thus, the steel passive film does not experience breakdown until the chloride concentration exceeds that increased threshold, with consequent extension of the period before corrosion takes place. The beneficial effect is stronger the greater the applied polarization, conceivably to the extent that corrosion initiation is effectively prevented for the foreseeable future. As an added advantage, because no corrosion has yet occurred CPrev needs to polarize only the cathodic reaction, as opposed to conventional CP where both the anodic and cathodic reactions need to be polarized.⁸ Thus, CPrev may require significantly lower impressed current density than conventional CP with consequent lesser requirements for anode performance and rectifier current capability, thus reducing both initial and operating costs. However, CPrev is not yet as widely used as CP and merits further investigation, in particular to establish feasibility in cases of local concrete deficiencies such as cracks.

Previous research has established some of the characteristics of chloride induced corrosion in the presence of cracks.^{9,10,11,12} There chloride ingress can be significantly enhanced because chloride ions can penetrate the concrete cover directly and rapidly reach the steel reinforcement, faster than in sound concrete, and creating greater demands in a corrosion control system.⁹ In this paper the findings from an ongoing investigation to determine the effectiveness of cathodic prevention on cracked concrete exposed to a marine environment are presented. Findings of a one year test are presented in the following sections.

EXPERIMENTAL PROCEDURE

A total of 30 concrete prisms were constructed with dimensions 16 in (40.6 cm) long, 14 in (35.6 cm) wide and 5 in (12.7 cm) thick, with three embedded reinforcement bars # 4 (diameter ~ 12.7 mm) of 18 in (45.7 cm) length spaced 4.5 in (11.4 cm) as shown in Figure 1, and with a concrete cover of 3.5 in (8.9 cm). The concrete used was a class IV concrete mix, made with 590 pcy (350 kg/m³) ordinary Portland cement with 20% fly ash cement replacement, w/c = 0.39 and limestone coarse aggregate #67 gradation. Two activated titanium mesh strips ½ in (12.7 mm) width were cast within 1.5 in (3.8 cm) from the top of the concrete prism to serve as anodes. An activated titanium electrode rod 1.5 in (3.8 cm) long was embedded horizontally ~ 2.5 in (6.4 cm) from the center bar to serve as a reference electrode (calibrated periodically against an external saturated calomel electrode (SCE)) for polarization control purposes. Plexiglas exposure ponds: 10 in (25.4 cm) long, 11 in (27.9 cm) wide, were fabricated and attached to the concrete surface on the crack side of the specimens.

The cracked concrete conditions were addressed to simulate situations with cracks running alongside to the rebar length (worst case). The cracks were created by 3-point bending and

short stainless steel shims were introduced at the external opening prior to springback to achieve the desired surface width. The cracks were oriented in a longitudinal direction parallel to the central embedded rebar. A central notch at the concrete surface acted as a crack originator and resulted in cracks terminating at the central rebar surface. Three crack widths were created: 0.01 in (0.25 mm), 0.02 in (0.51 mm) and 0.04 in (1.02 mm). The three rebars were interconnected at all times and were cathodically polarized to the required potential levels using a multiple-channel potentiostat. For the first half of the ~ 1 year test period the specimens were subject to chloride ingress by ponding to simulate splash-evaporation conditions using a 5 % NaCl solution, with cyclic exposure 2 weeks wet / 2 weeks dry. For the second half of the period a more severe, continuous ponding condition was used. It is noted that in that condition oxygen access is still plentiful from underneath and the sides of the block, especially to the steel bars away from the crack (always connected to the central bar). Hence on continuous ponding no substantial mitigation of overall corrosion is expected to have occurred from oxygen access limitation, which would have otherwise starved the cathodic reaction. Specimen arrangement during testing is shown in Figure 2.

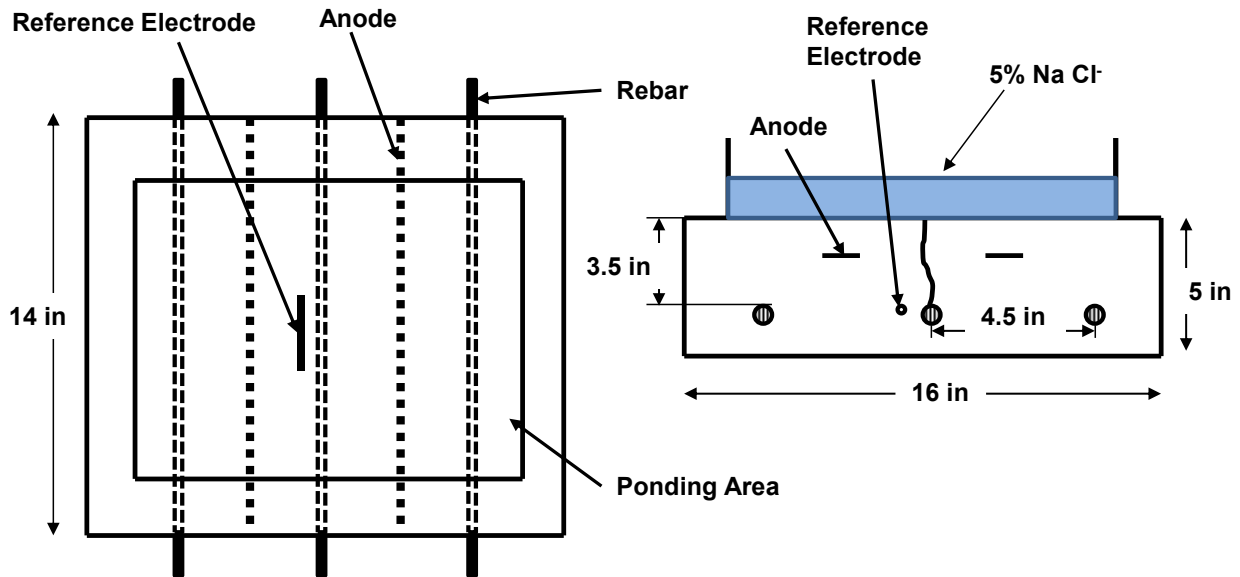


Figure 1: Schematic illustration of the concrete specimens with longitudinal crack.

The specimens were evaluated in the following polarization conditions: Open circuit (OC) (6 specimens), and potentiostated to instant-off: -330 (9 specimens), -430 (9 specimens) and -540 mV SCE (6 specimens). It is noted that the denomination OC means that the interconnected 3-bar assembly was not being connected to any external current source; macrocell currents flowed nevertheless between the bars themselves. In the potentiostated specimens the three bars were interconnected as well and the polarization was applied to all three simultaneously. Table 1 shows the crack width and potential level assigned to each specimen.

As an added control function, a 1N914 or comparable silicon switching diode was installed in the anode connection of each specimen so that current to the rebar assembly could only be

cathodic regardless of what the open circuit potential of the assembly is. That way when activation occurred (which might have caused the open circuit potential to drop to a level more negative than the initial polarization potential) the rebar assembly did not experience net anodic polarization. This arrangement was especially beneficial to the -330 mV specimens, which were after activation tentatively switched to -430 mV or -540 mV polarization to determine if that could repassivate the specimen (results of those follow up evaluations will be reported separately).



Figure 2: Testing arrangement for cracked concrete specimens.

**Table 1
Specimen test conditions**

Crack width (in)	Non-Polarized (Control-OC)		E_1 -330 mV*		E_2 -430 mV*		E_3 -540 mV*	
	X	(#)	X	(#)	X	(#)	X	(#)
0.01	X	(11)	X	(2)	X	(9)	X	(5)
	X	(28)	X	(13)	X	(18)	X	(24)
		-	X	(23)	X	(12)		-
0.02	X	(4)	X	(3)	X	(1)	X	(6)
	X	(14)	X	(15)	X	(21)	X	(27)
		-	X	(25)	X	(29)		-
0.04	X	(7)	X	(16)	X	(10)	X	(8)
	X	(20)	X	(17)	X	(19)	X	(30)
		-	X	(26)	X	(22)		-

*All Potentials are in the SCE scale. Specimen numbers are in parenthesis.

Current measurements included macrocell current for the OC specimens (total current flowing from the two bars on the side to the bar in the center, shown as positive when the center bar is anodic to the other two), and for the potentiostated specimens the current demand given as the total cathodic current (shown as negative) provided by the potentiostat to the group of three bars. The OC specimen macrocell current measurement results were converted to current densities via division by the exposed surface area of the central bar (~ 122 cm²); for the other specimens only the total cathodic current demand is presented in this paper.

RESULTS AND DISCUSSION

Non-polarized (OC) Control Specimens

Steel Potentials and Macrocell Current.

Evolution of the average steel potentials for the open circuit specimens is summarized in Figure 3. Exposure times were counted from the beginning of the first wet cycle (time = 0 days). Before the wet cycling was initiated (~ day -30) the steel potential readings were around -50 mV vs SCE as shown in Figure 3, indicating that after a short exposure period (< 1 week /first wet cycle) activation occurred for all crack widths, as manifested by a negative shift in potential. Average potentials after one year of exposure are typical of corroding steel (~-450 to -500 mV SCE). The initiation of the continuing ponding stage is clearly visible in Figure 3 and subsequent figures as a relative stabilization of results sometime after a time around day 200.

Evolution of average macrocell current density for non-polarized specimens are summarized in Figure 4. Typical current densities (~1 to 3 $\mu\text{A}/\text{cm}^2$) were much greater than the values normally associated with a passive regime (< ~0.2 $\mu\text{A}/\text{cm}^2$) indicating a distinctly active corrosion regime as expected.¹³ Notably, and as expected, the largest crack width (0.04 in) corresponded to the highest macrocell current density indicating more corrosion activity.

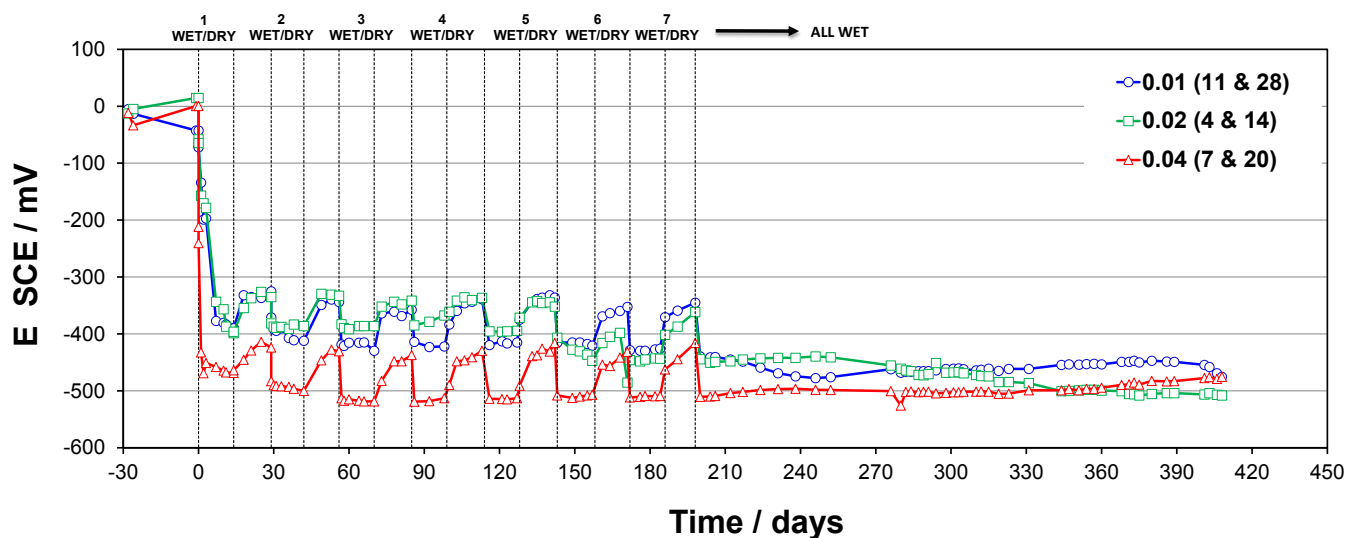


Figure 3: Evolution of the steel potential for the open circuit specimens (average of indicated specimens). Legend indicates crack width (in).

The increases in current density corresponded with the sharp decreases in potential noted earlier (Figure 3), so both indicators consistently suggested an early onset (8 days or less, first wet cycle) of corrosion activity for the unpolarized control specimens. Corrosion severity was greater for the greatest crack width (0.04 in), also as expected. The results indicated that with no form of corrosion protection or prevention, in the presence of cracks (even at the smallest width investigated, 0.01 in) in a simulated marine environment reinforcing steel was liable to corrode quickly. Such early onset of corrosion would be clearly detrimental to achieving the typically multi-decade desired service life in the part of the structure affected by the cracks.¹³

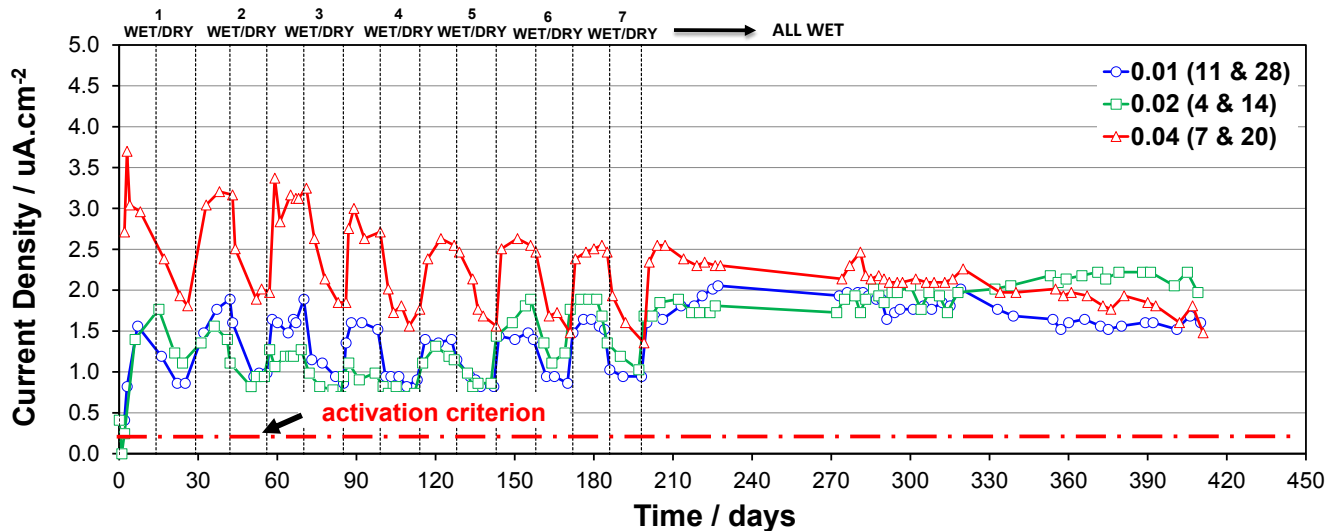


Figure 4: Evolution of average macrocell current density for open circuit specimens. Legend indicates crack width (in) of group.

Polarized Specimens

Steel Potentials and Cathodic Current Demand.

The steel assembly of each specimen was cathodically polarized to maintain a preset potential, regardless of corrosion behavior; therefore, it was not possible to determine corrosion activation based on potential transitions.

Figure 5 displays the time-averaged potential distribution for all polarized specimens in the pre-activation condition, showing that specimens were generally polarized and maintained near the target potential level. Instead, sustained corrosion activation was declared to occur when the cathodic current demand of the 3-rebar group vanished, since at that point there was enough intrinsic anodic reaction (from the central bar) to provide an electron flow to itself plus the other two bars comparable to that provided by the substantial external cathodic current when initially applied. Alternatively, it could be said that the system had evolved to an active corrosion point where its own open circuit potential equaled the appreciable negative polarization provided initially - and indication of active corrosion per potential drop criteria such as that in ASTM C-876.¹⁴

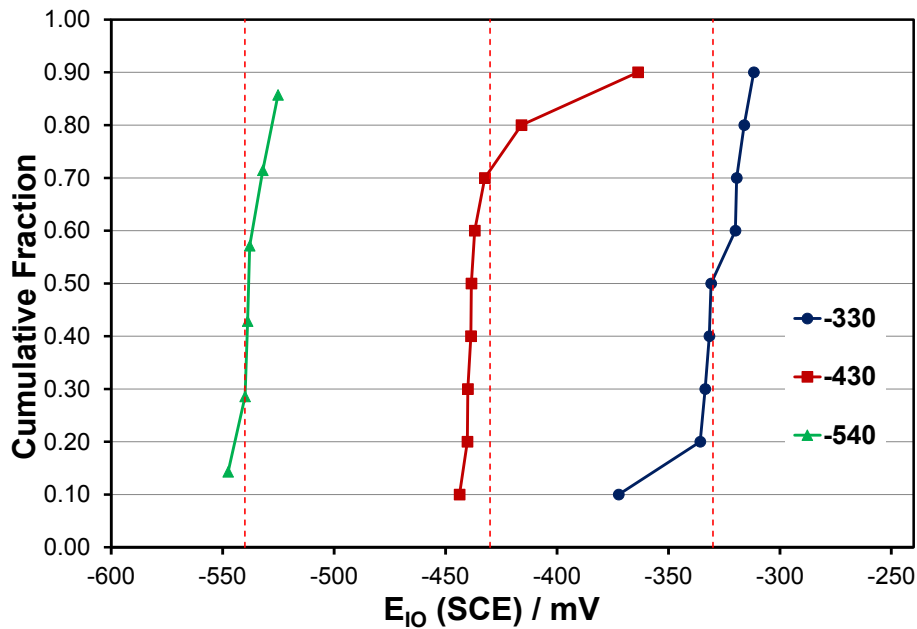


Figure 5: Cumulative Distribution of Instant-off Potentials. Potentials are averaged over the exposure period for all polarized specimens in the pre-activation condition. Legend indicates the target potential (mV SCE) for each group.

The evolution of the current demand for the polarized specimens is summarized in Figure 6 for each target potential level (-330 mV, -430 mV and -540 SCE mV). Exposure times were counted from the time since energizing (same as the beginning of the first wet cycle). After a period of a few days, current demand stabilized. Eight of the 9 specimens polarized to -330 mV exhibited corrosion initiation after 50 days of being energized. Specimens with 0.04 in crack widths activated within 10 days, before specimens with 0.01 and 0.02 in crack widths. There was no correlation between crack width and time to corrosion activation for specimens with 0.01 in and 0.02 in crack widths. As noted above, the moment of activation was declared when the current reached a value of 0.0 mA. The increase in time to corrosion activation of the -330 mV SCE group compared to those of the OC specimens was minimal. From the data obtained, it appears that CPrev at -330 mV is likely not a feasible means of providing marked service life increase for reinforced concrete structures in marine service in the part of the structure affected by the cracks.

For specimens polarized to -430 mV SCE, 8 of 9 specimens activated within 240 days of being energized. One specimens polarized to -430 mV SCE have not activated after 1 year of exposure. Specimens with 0.04 in crack widths all activated within 90 days of being energized. Again, there was no distinction between crack width and time to initiation for specimens with crack widths of 0.01 in and 0.02 in. Activated specimens were afterwards polarized to -540 mV. Though specimens polarized to -430 mV showed an increase in time to corrosion activation when compared to those for specimens polarized to -330 mV, the increase was not substantial, especially considering that some specimens containing large width cracks activated before specimens polarized to -330 mV. These data are indicative that applying CPrev at even -430 mV is not an effective means of providing marked service life increase for reinforced concrete structures in marine service at cracks.

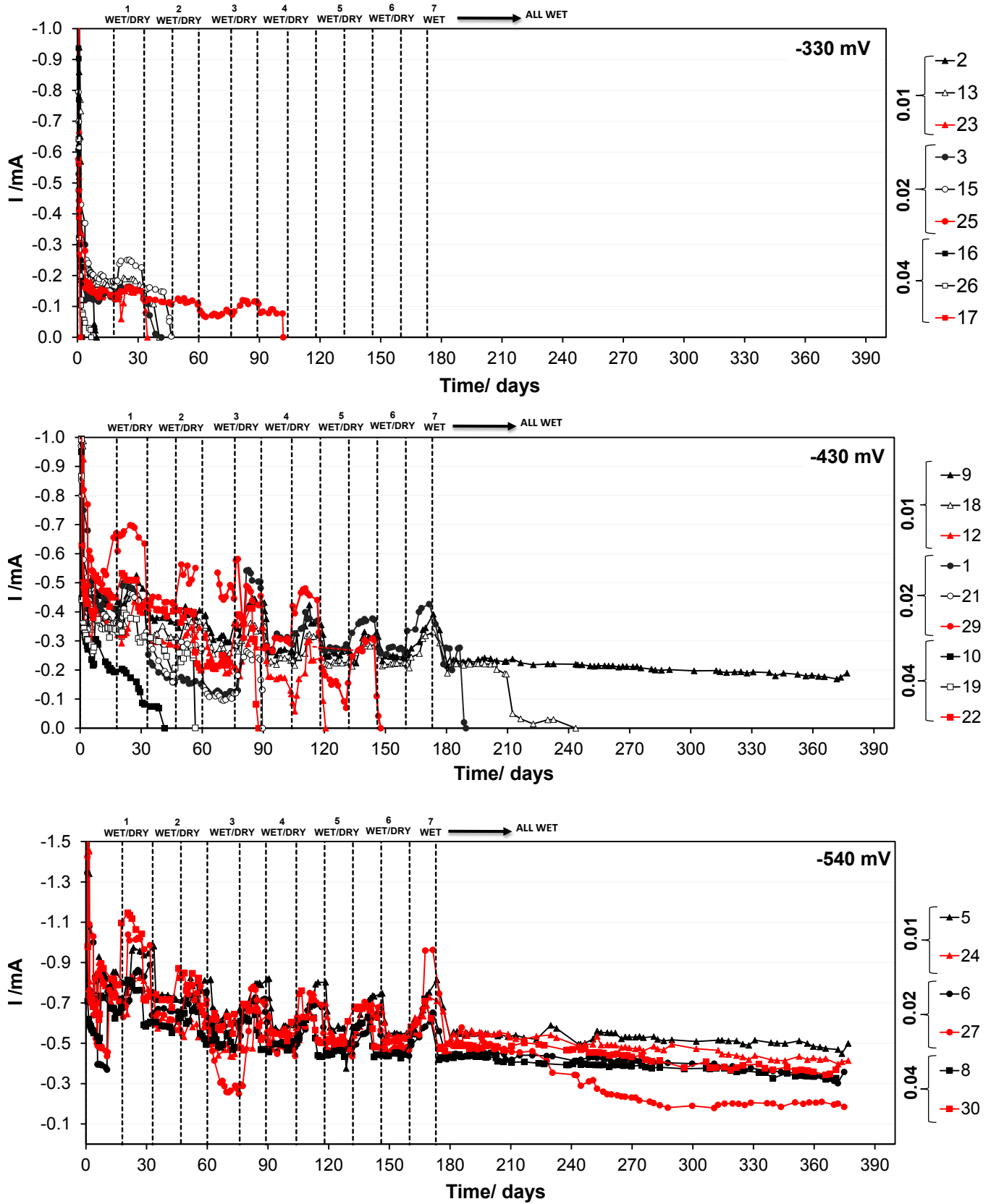


Figure 6: Current evolution for polarized specimens. Legend indicates crack width (in) of each group.

After ~1 year since energizing and exposure to chlorides, no specimen polarized at -540 mV SCE has activated in cracked concrete. The results hence indicate a significant increase in time to corrosion activation when compared to OC specimens and specimens polarized to -330 mV and -430 mV.

The previous observations are best seen in a graphic summary of time to activation for all cracked specimens, as shown in Figure 7, arranged by potential level and crack width. The unprotected, open circuit specimens (2 for each crack width tested: 0.01, 0.02 and 0.04 inch) all experienced activation after only 8 days of salt water ponding. Results showed that all but one of the specimens polarized to -330 mV, independent of the crack width, experienced activation within 50 days. Eight specimens polarized to -430 mV had experienced activation after about 240 days of exposure. Specimens polarized to -540 mV had not experienced well-defined activation after about 1 year of exposure. More detailed analysis is in progress to process the data for any alternative indications of early activation for those specimens. The results to date nevertheless suggest that cathodic prevention with moderate cathodic polarization levels (such as only -330 mV or -430 mV) may be of limited benefit in the presence of cracks aligned lengthwise to the rebar, while polarization at -540 mV holds more promise of being effective but longer term testing is needed for evaluation at that level.

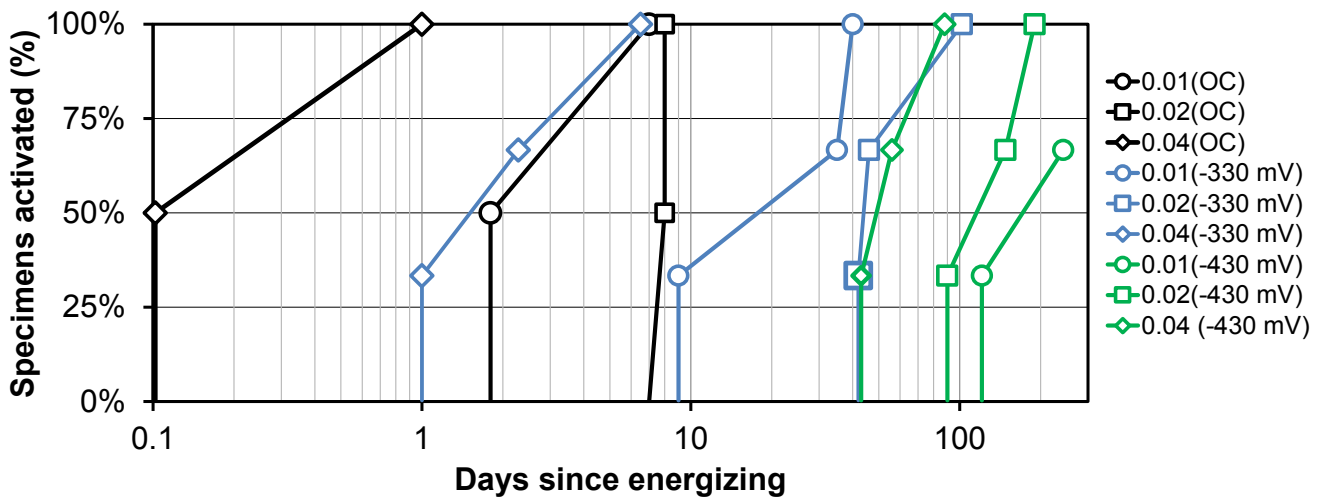


Figure 7: Detailed Summary of each Specimen's Time to Activation. Specimens are arranged by potential level and crack width plotted against days since energizing.

CONCLUSIONS

- With no form of corrosion protection or prevention, in the presence of cracks ranging from 0.01 in to 0.04 in width in a simulated marine environment, reinforcing steel was liable to corrode quickly. Such early onset of corrosion would be clearly detrimental to achieving a demanding service life goal in the part of the structure affected by the cracks.
- Experiments on feasibility of CPrev in cracked concrete were successfully implemented. Testing to date (~1 year testing interval) revealed that polarization at potentials equal to or less negative than -430 mV SCE was insufficient to prevent corrosion initiation in cracks of any tested size (0.01 to 0.04 in wide). Polarization to -540 mV SCE resulted in no corrosion initiation events for any crack size during the test interval.
- The increase in time to corrosion activation for specimens polarized to -330 mV and -430 mV (SCE) was not substantial compared to OC specimens. These results suggest that CPrev with these levels of cathodic polarization may be of limited or no benefit in the case of cracks aligned lengthwise to the rebar.
- The observation that no specimen polarized to -540 mV (SCE), regardless of crack size, has activated after 1 year of exposure to NaCl solution, suggests that CPrev with cathodic polarization levels of -540 mV (SCE) may provide sufficient CPrev of steel in cracked concrete in a marine environment to be considered effective, but longer evaluation should be conducted for verification.

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