FINAL REPORT

EVALUATION OF CORROSION INHIBITORS FOR CONCRETE BRIDGE DECK PATCHES AND OVERLAYS

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ABSTRACT

This report presents the results to date of a national pooled fund study initiated in August 1996 to evaluate the long-term performance of bridges and outdoor exposure slabs damaged by chloride-induced corrosion that have concrete containing corrosion inhibiting admixtures and that had topical applications of inhibitors prior to being patched and overlaid. The study includes 156 exposure slabs, 4 bridge decks with overlays, and 1 patched bridge substructure. A total of 136 exposure slabs were constructed to simulate overlay and patch repairs, and 20 full-depth slabs were constructed to simulate new construction. Each repaired slab was constructed with one of four levels of chloride to cause corrosion. The new slabs were ponded to cause corrosion. Previous reports provide details on the construction and initial condition of the exposure slabs and the construction and initial condition of the repaired bridges. The results presented here are based on quarterly nondestructive measurements between September 1997 and June 2001, visual inspections of the exposure slabs, and tensile bond test results and visual inspections of reinforcement removed from the exposure slabs that were patched and overlaid.

Overlays cracked and delaminated on exposure slabs that were fabricated with 15 lb/yd^3 of chloride ion because of corrosion of the top mat of reinforcement. There was no difference in the performance of overlays constructed with and without inhibitors and topical treatments.

Overlays and patches with and without inhibitor treatments placed on and in slabs with 3, 6, and 10 lb/yd^3 of chloride are performing satisfactorily. However, results do not show reductions in the tendency for corrosion that can be attributed to the inhibitors.

Overlays and patches with and without inhibitor treatments on and in the five bridges indicate mixed results. Corrosion is occurring in the majority of the repairs done with and without inhibitor treatments. The corrosion-inhibiting treatments do not seem to be reducing corrosion in the bridges and, in fact, may be increasing corrosion.

It is not obvious that corrosion is occurring in the full-depth slabs constructed with and without inhibitors to represent new construction. The slabs do not show signs of corrosion-induced cracking after 5 years of ponding.

Topical applications of inhibitors did not affect the bond strength of the overlays. Overlays containing Rheocrete 222+ and 7 percent silica fume had lower bond strengths. Overlays on base concretes with the higher chloride content had lower bond strengths.

In summary, this project does not show any benefit from the use of the corrosion inhibiting admixtures and the topical applications made to the chloride-contaminated concrete surfaces prior to placement of the patches and overlays. Additional years of monitoring of the exposure slabs and bridges may provide useful results.

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INTRODUCTION

Patching, overlaying, and rehabilitating chloride-contaminated and corrosion-damaged concrete structures have become a major part of state construction and maintenance programs. In many cases, only portions of a structural element are contaminated or damaged due to corrosion, allowing the element to be repaired rather than replaced. Conventional repair techniques usually include removing chloride-contaminated and deteriorated concrete and placing new concrete in the form of patches and overlays. Although new concrete generally restores a more passive environment, corrosion of the original reinforcing steel often continues and corrosion often accelerates adjacent to repaired areas because of differences in the chloride content in the adjacent old and new concretes. Corrosion further deteriorates the concrete element and significantly reduces the service life of the repaired structure.

Various types of corrosion inhibitors have been developed and marketed to mitigate corrosion in newly rehabilitated structures. When physical damage is repaired, these materials are usually incorporated into the repair procedure by applying them to the surface of the original concrete and allowing them to penetrate before patching, by including them as an admixture in the patch material, or both. These applications seem benign compared to other corrosion protection methods and add relatively little work to the conventional repair activity. Initial costs are low. Corrosion inhibiting admixtures (CIAs) would increase the cost of a cubic yard of concrete by approximately \$20. Topical applications cost approximately \$1 per square foot. In addition, there are essentially no anticipated future maintenance costs directly associated with repairs that incorporate inhibitors. Data obtained from 1999 through 2002 indicate that the Virginia Department of Transportation (VDOT) spends approximately \$3 million per year on concrete bridge deck patches and overlays. VDOT uses approximately 2,700 yd^3 of concrete for the repairs and places the concrete over approximately 50,000 yd^2 of surface. The annual cost to do bridge repairs in Virginia with concrete containing CIAs and with topical applications of inhibitors to surfaces prior to the placement of patches and overlays would be approximately \$0.5 million.

However, the question concerning whether inhibitor performance meets expectations with minimal side effects remains to be answered. Corrosion inhibitors are designed to inhibit corrosion of reinforcement by forming a barrier around the reinforcement, by reducing the permeability of the concrete, and by reducing the oxidation reduction reactions on the surface of the reinforcement. These design functions seem reasonable when inhibitors are used in chloride-free concrete used in new construction. On the other hand, these design functions do not seem possible when inhibitors are used in the repair and rehabilitation of chloride-contaminated concrete. In situations where the reinforcement is corroding because of the presence of chlorides, the inhibitor would have to displace the chlorides around the bar in order to form a chloride-free barrier around the reinforcement. In addition, an inhibitor that reduces the permeability of the concrete may reduce the quantity of new chloride that reaches the reinforcement. However, if sufficient chloride is present at the reinforcement to cause corrosion, the inhibitor will not provide a benefit. Finally, anodic inhibitors can cause accelerated corrosion and pitting if used in insufficient concentrations. Considering the nonhomogeneous nature of concrete, it is not reasonable to expect that the reinforcement will be successfully coated with inhibitor uniformly or in sufficient concentration to prevent or reduce corrosion. In fact, use of corrosion inhibitors in repair concretes and topical applications to chloride-contaminated concrete surfaces could promote corrosion. Even so, CIAs have been used in concrete specified for repairs and topically applied inhibitors have been specified for application to chloride-contaminated concrete surfaces prior to the placement of repair concretes.

In August 1996, the national pooled fund study described in this report was initiated to evaluate the long-term performance of bridge structures and exposure slabs damaged by chloride-induced corrosion that have concrete containing CIAs and that had topical applications of inhibitors prior to being patched and overlaid. The study included 156 outdoor exposure slabs, 4 bridge decks with overlays, and 1 patched bridge substructure. The departments of transportation (DOTs) that contributed to the project were Florida, Illinois, Iowa, Kansas, Maryland, Minnesota, Montana, Nebraska, New Jersey, New York, North Carolina, Virginia, and Wisconsin. DOTs contributed $250,000 for the 5-year project.

PURPOSE AND SCOPE

The purpose of this project was to evaluate the performance of admixed and topically applied corrosion inhibitors by the long-term monitoring of bridge structures and exposure slabs damaged by chloride-induced corrosion that were patched and overlaid. The evaluation included a literature review, construction of exposure slabs and bridge overlays and patches, and periodic condition evaluations over a 5-year period.

This report presents the results to date from the pooled funded study. Results are based on quarterly measurements done between September 1997 and June 2001 on 136 exposure slabs constructed to simulate overlay and patch repairs and 20 exposure slabs constructed to simulate new construction. Each repaired slab was constructed with one of four levels of chloride to cause corrosion. The full-depth slabs were ponded to cause corrosion. Measurements on each of the 156 slabs included half-cell potentials, rate of corrosion, macrocell current, macrocell potential, and resistance. Interim Report No. 1 provides details on the construction and initial condition of the exposure slabs.[1] In 2001, to quantify a reduction in the bond strength of the overlays that could be attributed to corrosion-induced cracking, tensile bond tests were conducted at the locations in which measurements were taken for the study. Bars were removed at the bond test locations and visually inspected for corrosion.

Results are also based on quarterly measurements made on corrosion probes in four bridges repaired with corrosion-inhibiting treatments. Measurements included macrocell current, macrocell potential, and resistance for each probe. Interim Report No. 2 provides details on the construction and initial condition of the bridges.[2]

LITERATURE REVIEW

During the past 15 years, CIAs in concrete have received increased attention as an alternative corrosion protection system for new construction.[3] CIAs are typically classified as anodic, cathodic, inorganic, and organic. Calcium nitrite is an anodic, inorganic inhibitor frequently used in concrete used in new construction. Admixtures of ester-amine and alcohol-amine are organic inhibitors. Both inorganic and organic admixtures for concrete and topically applied corrosion-inhibiting products have been introduced for concrete repair and rehabilitation projects.

A Transportation Research Information Systems (TRIS) search indicated that the number of reports on the use of corrosion inhibitors in transportation applications is increasing. Unfortunately, most reports are concerned with the use of CIAs in concrete used in the construction of new structures. Further, most of the reports provide details on the effects of the admixtures on the physical and mechanical properties of the concrete but little on the corrosion protection. Service life extension estimates are based on limited laboratory evaluations. The bulk of the performance data on the use of inhibitors in rehabilitation applications comes from laboratory tests conducted by product manufacturers using simulated environments.

Inhibitors in Concrete Used in New Construction

Evaluations have been done by the Federal Highway Administration (FHWA) and DOTs in Idaho, Indiana, Pennsylvania, and Virginia on the use of CIAs in concrete used in new construction. A detailed outdoor long-term exposure slab study performed by FHWA showed the benefits of using calcium nitrite.[4] The Idaho study concluded that of the four inhibitors evaluated in the laboratory using ponding block specimens, only calcium nitrite and sodium silicate reduced corrosion and deserved further study.[5] The Indiana report concluded that only calcium nitrite was effective, based on testing performed in accordance with ASTM G109 and cracked beam testing.[6] A Pennsylvania study reported that two products, calcium nitrite and an organic inhibitor, were used in the concrete in two bridges and no construction problems were encountered.[7] Two VDOT studies documented the use of calcium nitrite in prestressed piles and beams and a bridge deck and concluded that the properties of the concrete were acceptable, but no conclusions were reached on corrosion inhibition because of the short evaluation period.[8,9] A laboratory study by VDOT showed that only one of three commercially available inhibitors performed better than no inhibitor when rebars were placed in solutions of calcium hydroxide and sodium chloride.[10]

An FHWA-sponsored project is being done by the Florida DOT[11] on methods for evaluating corrosion inhibitors. The study is evaluating corrosion inhibitors used in new construction for long-term stability and performance, corrosion behavior once corrosion is initiated, and the effect of concrete composition variables on both long-term performance and corrosion behavior.

In addition, a project by the National Highway Cooperative Research Program (NCHRP) was done by Cortest Columbus Technologies.[12] The objectives of the project were to develop procedures for evaluating and qualifying CIAs and to recommend performance criteria for their acceptance.

A number of documents prepared by product manufacturers support the use of CIAs in new construction.[13,14,15]

Use of Inhibitors in Repair and Rehabilitation Applications

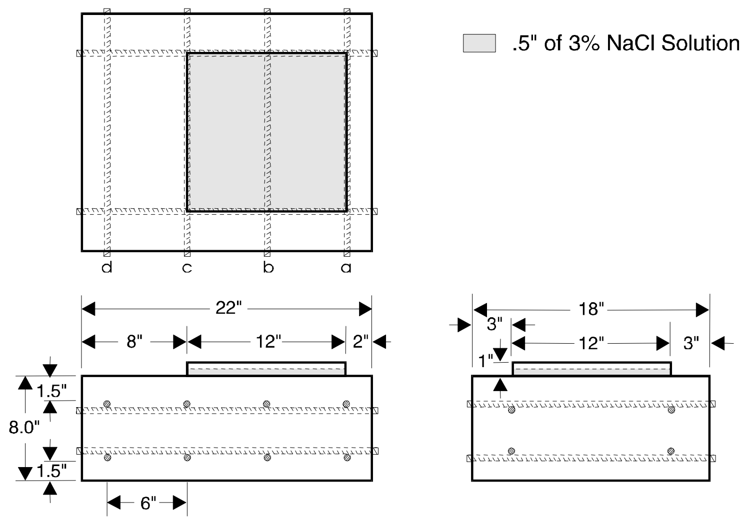
Few reports are available on the performance of structures in which concrete containing CIAs or topically applied corrosion-inhibiting products were used for the repair or rehabilitation of a structure. Several corrosion inhibitor treatments suitable for these applications have been tested and evaluated to varying degrees under laboratory conditions.[16] The Strategic Highway Research Program (SHRP) sponsored the application and short-term evaluation of two inhibitor-modified concrete systems.[17] These studies provided valuable data supporting the potential of these treatments for long-term corrosion protection. Most of these studies also called for more long-term field performance data and continued to label most of the inhibitor treatments as "experimental" rather than standard protection methods.[18] FHWA has funded annual evaluations of the five sites constructed as part of the SHRP C103 project. These 1992 installations include deck patches in Washington; pier cap, column, and abutment repairs in New York (patches) and Pennsylvania (shotcrete); a deck overlay placed in Minnesota; and a bridge deck and column in Virginia.[19] A study by the Virginia Polytechnic Institute & State University concluded that the topical application of calcium nitrite had no significant influence on the dynamic response of rehabilitated slabs and slightly increased the shear bond strength of overlays.[20] Literature from a product manufacturer reported on the benefits of a topically applied inhibitor in repair applications.[21]

Corrosion inhibitors used in repairs are being evaluated by the Florida DOT[11] for their ability to mitigate corrosion in short-term and long-term repairs, effect on the behavior of anodic regions around repairs, and compatibility with portland cement (PC)–based repair mortars and concrete mixtures. The Florida DOT project is scheduled to end in June 2005.

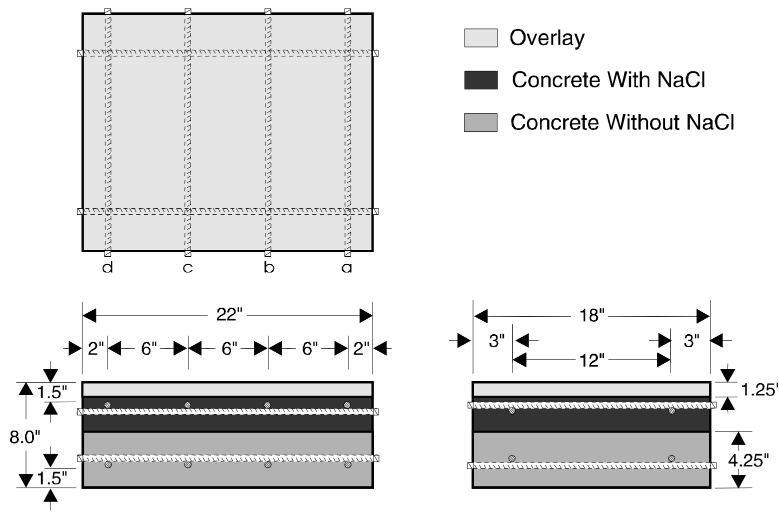
METHODOLOGY

Construction of Exposure Slabs

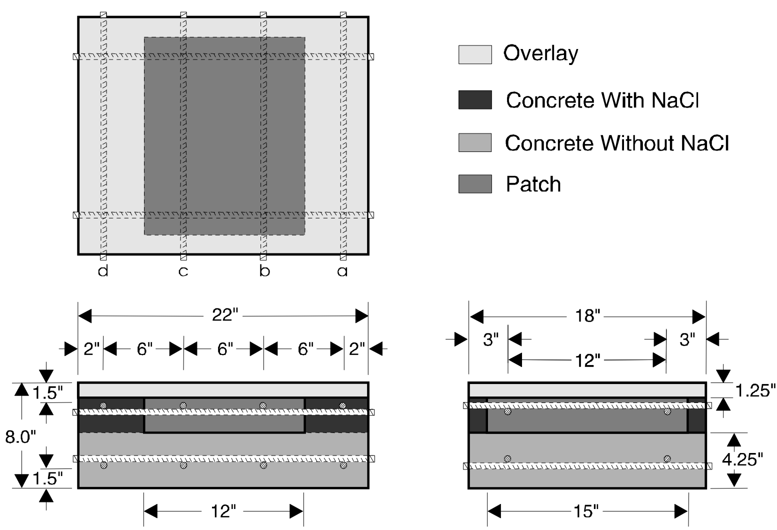
One hundred fifty-six slabs were fabricated in the laboratory at the Virginia Transportation Research Council. The four slab designs are shown in Figure 1. Forty-eight slabs were fabricated with either 3, 6, 10, or 15 lb/yd^3 (1.8, 3.5, 5.9, or 8.9 kg/m^3) of chloride in



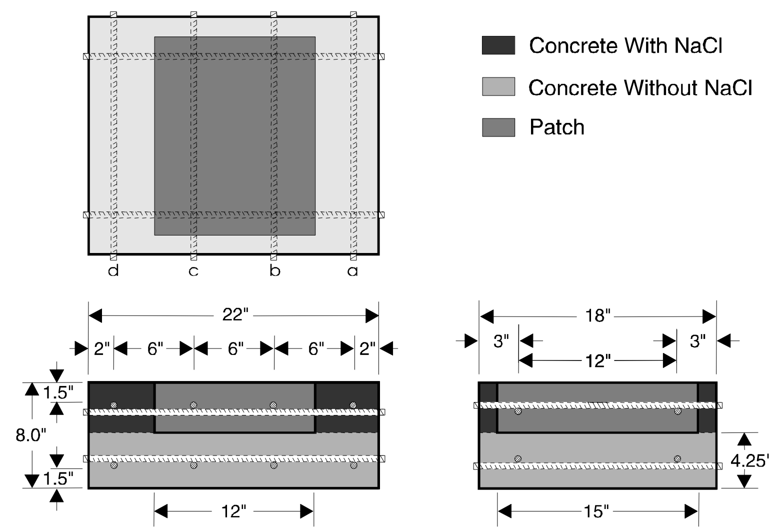
Full depth exposure slab



Slab with 1.25 inch overlay



Slab with 1.25 inch Overlay and Patch



Slab with patch

Figure 1. Slab Designs

the concrete cast into the top portion of the slab prior to receiving an overlay 1.25 in (32 mm) thick. Fifty-two slabs were fabricated with 3, 6, or 10 lb/yd^3 (1.8, 3.5, or 5.9 kg/m^3) of chloride in the concrete cast into the top portion of the slab before being patched and overlaid. Thirty-six slabs were fabricated with 3, 6, or 10 lb/yd^3 (1.8, 3.5, or 5.9 kg/m^3) of chloride in the concrete cast into the top portion of the slab before being patched. With the exception of the chloride admixture, the slabs were constructed with concrete mixtures typically used in bridge decks. The slabs were overlaid and patched to simulate typical repairs to bridge decks. In addition, 20 slabs were designed to simulate new construction and were ponded with 3 percent NaCl solution (2-week wet and 2-week dry cycle) as shown in Figure 1.

Full-depth slabs, overlays, and patches were cast with concrete containing no inhibitor; an inorganic inhibitor; Derex Corrosion Inhibitor (DCI) (4 gal/yd^3 [20 L/m^3]); an organic inhibitor, Ferrogard 901 (2 gal/yd^3 [10 L/m^3]); or Rheocrete 222+ (1 gal/yd^3 [5 L/m^3]). Before being patched or overlaid, some slabs received three applications of a topical inorganic inhibitor, Postrite (P) (125ft^2/gal [3.1 m^2/L]), or two applications of an organic inhibitor, Ferrogard 903 (300 ft^2/gal [7.4 m^2/L]). The surfaces treated with Ferrogard 903 were power washed before being patched and overlaid.

Repairs were done with concretes typically used in overlays and patches, concrete containing Type I/II PC and concrete containing PC and 7 percent silica fume (SF) by weight of cement (7% SF). Slabs constructed with 3, 6, and 10 lb/yd^3 (1.8, 3.5, and 5.9 kg/m^3) chloride were overlaid and patched approximately 3 months after being cast. Slabs constructed with 15 lb/yd^3 (8.9 kg/m^3) chloride were overlaid 9 months after being cast.

Tables 1, 2, and 3 show the chloride contents, type of repair concrete, and the type and dosage of CIAs and topical treatments for slabs that were repaired with an overlay, an overlay and patch, and a patch, respectively, as shown in Figure 1. Table 4 shows the type of concrete and the type and dosage of CIA for full-depth exposure slabs, which simulate new construction, that are being ponded as shown in Figure 1. All PC concrete contained 635 lb/yd^3 of Type I/II PC. All SF concretes contained 590 lb/yd^3 of PC and 45 lb/yd^3 of SF. Fly ash concretes contained 477 lb/yd^3 of PC and 159 lb/yd^3 of Class F fly ash. All concretes contained silica sand. Base and full-depth concretes contained No. 57 granite, and repair concretes contained No. 78 granite. Slumps ranged from 2.8 to 6.5 in. Air contents ranged from 5 to 8 percent. Slabs 125 through 132 and Slabs 137, 138, 141 and 142 (see Table 2) were patched and overlaid with alternative systems (special mixtures) that were not part of the original group of inhibitor repairs. Some of these slabs were repaired with additional inhibitors that were supplied after the project started (Migrating Corrosion Inhibitor [MCI], Catexol and AXIM), and others were repaired with Rapid Set (RS), latex-modified concrete (LMC), RSLMC, and asphalt. Full-depth Slabs 133 through 136 were also prepared with additional CIAs. With the exception of the chloride admixtures, all concretes complied with the requirements for bridge deck concrete, overlays, and patches in VDOT's *Road and Bridge Specifications*.[22]

Table 1. Chloride Contents, Repair Concretes, and Corrosion Inhibiting Admixture Used for Slabs That Were Overlaid

Slab Number	chl pcy	Type Repair Concrete	Type, dosage CIA, gcy
1	3	PC	None, 0
2	3	7% SF	None, 0
3	3	PC	DCI-S, 4
4	3	7% SF	DCI-S, 4
5	3	PC	Ferrogard 901, 2
6	3	7% SF	Ferrogard 901, 2
7	3	PC	Rheocrete 222+, 1
8	3	7% SF	Rheocrete 222+, 1
9	3	PC/P	DCI-S, 4
10	3	7% SF/P	DCI-S, 4
11	3	7% SF/903	Ferrogard 901, 2
12	3	PC/903	Ferrogard 901, 2
13	6	PC	None, 0
14	6	7% SF	None, 0
15	6	PC	DCI-S, 4
16	6	7% SF	DCI-S, 4
17	6	PC	Ferrogard 901, 2
18	6	7% SF	Ferrogard 901, 2
19	6	PC	Rheocrete 222+, 1
20	6	7% SF	Rheocrete 222+, 1
21	6	PC/P	DCI-S, 4
22	6	7% SF/P	DCI-S, 4
23	6	7% SF/903	Ferrogard 901, 2
24	6	PC/903	Ferrogard 901, 2
25	10	PC	None, 0
26	10	7% SF	None, 0
27	10	PC	DCI-S, 4
28	10	7% SF	DCI-S, 4
29	10	PC	Ferrogard 901, 2
30	10	7% SF	Ferrogard 901, 2
31	10	PC	Rheocrete 222+, 1
32	10	7% SF	Rheocrete 222+, 1
33	10	PC/P	DCI-S, 4
34	10	7% SF/P	DCI-S, 4
35	10	7% SF/903	Ferrogard 901, 2
36	10	PC/903	Ferrogard 901, 2
145	15	PC	None, 0
146	15	7% SF	None, 0
147	15	PC	DCI-S, 4
148	15	7% SF	DCI-S, 4
149	15	PC	Ferrogard 901, 2
150	15	7% SF	Ferrogard 901, 2
151	15	PC	Rheocrete 222+, 1

Slab	chl	Type Repair	Type, dosage
Number	pcy	Concrete	CIA, gcy
152	15	7% SF	Rheocrete 222+, 1
153	15	PC/P	DCI-S, 4
154	15	7% SF/P	DCI-S, 4
155	15	PC/903	Ferrogard 901, 2
156	15	7% SF/903	Ferrogard 901, 2

Chl = chloride content, PC = portland cement, SF = silica fume, CIA = corrosion inhibiting admixture, DCI-S = Derex Corrosion Inhibitor with Retarder, P = Postrite Topical Inhibitor, 903 = Ferrogard Topical Inhibitor.

Table 2. Chloride Contents, Repair Concretes, and Corrosion Inhibiting Admixture Used for Slabs That Were Overlaid and Patched

Slab Number	chl pcy	Type Repair Concrete	Type, dosage CIA, gcy
37	3	PC	None, 0
38	3	PC	None, 0
39	3	PC	DCI-S, 4
40	3	PC	DCI-S, 4
41*	3	PC	Ferrogard 901, 2
42	3	PC	Ferrogard 901, 2
43	3	PC	Rheocrete 222+, 1
44	3	PC	Rheocrete 222+, 1
45	3	PC/P	DCI-S, 4
46	3	PC/P	DCI-S, 4
47	3	PC/903	Ferrogard 901, 2
48	3	PC/903	Ferrogard 901, 2
49	6	PC	None, 0
50	6	7% SF	None, 0
51	6	PC	DCI-S, 4
52	6	7% SF	DCI-S, 4
53	6	PC	Ferrogard 901, 2
54	6	7% SF	Ferrogard 901, 2
55	6	PC	Rheocrete 222+, 1
56	6	7% SF	Rheocrete 222+, 1
57	6	PC/P	DCI-S, 4
58	6	7% SF/P	DCI-S, 4
59	6	7% SF/903	Ferrogard 901, 2
60	6	PC/903	Ferrogard 901, 2
61	10	7% SF	None, 0
62	10	7% SF	None, 0
63	10	7% SF	DCI-S, 4
64	10	7% SF	DCI-S, 4
65	10	7% SF	Ferrogard 901, 2
66	10	7% SF	Ferrogard 901, 2
67	10	7% SF	Rheocrete 222+, 1
68	10	7% SF	Rheocrete 222+, 1
69	10	7% SF/P	DCI-S, 4
70	10	7% SF/P	DCI-S, 4
71	10	7% SF/903	Ferrogard 901, 2
72	10	7% SF/903	Ferrogard 901, 2
125	6	PC/2020	MCI 2005, 0.3
126	6	PC/AXIM	Catexol, 3
127	6	Rapid Set	None, 0
128	6	15% LMC	None, 0
129	10	PC/2020	MCI 2005, 0.3
130	10	PC/AXIM	Catexol, 3
131	10	Rapid Set	None, 0

Slab Number	chl pcy	Type Repair Concrete	Type, dosage CIA, gcy
132	10	15% LMC	None, 0
137	6	RS/LMC	None, 0
138	6	ASPHALT	None, 0
139	6	PC/P	DCI-S, 4
140	6	PC/903	Ferrogard 901, 2
141	10	RS/LMC	None, 0
142	10	ASPHALT	None, 0
143	10	PC/P	DCI-S, 4
144	10	PC/903	Ferrogard 901, 2

*The base of Box 41 was dropped and damaged prior to the placement of the patch and overlay.
Chl = chloride content, PC = portland cement, SF = silica fume, CIA = corrosion inhibiting admixture,
DCI-S = Derex Corrosion Inhibitor with Retarder, P = Postrite Topical Inhibitor, 903 = Ferrogard Topical Inhibitor,
MCI = Migrating Corrosion Inhibitor, 2020 = MCI Topical Inhibitor, LMC = Latex Modified Concrete,
Rapid Set = Rapid Set Cement, AXIM = AXIM Topical Inhibitor.

Table 3. Chloride Contents, Repair Concretes, and Corrosion Inhibiting Admixture Used for Slabs That Were Patched

Slab Number	chl pcy	Type Repair Concrete	Type, dosage CIA, gcy
73	3	PC	None, 0
74	3	PC	None, 0
75	3	PC	DCI-S, 4
76	3	PC	DCI-S, 4
77	3	PC	Ferrogard 901, 2
78	3	PC	Ferrogard 901, 2
79	3	PC	Rheocrete 222+, 1
80	3	PC	Rheocrete 222+, 1
81	3	PC/P	DCI-S, 4
82	3	PC/P	DCI-S, 4
83	3	PC/903	Ferrogard 901, 2
84	3	PC/903	Ferrogard 901, 2
85	6	PC	None, 0
86	6	7% SF	None, 0
87	6	PC	DCI-S, 4
88	6	7% SF	DCI-S, 4
89	6	PC	Ferrogard 901, 2
90	6	7% SF	Ferrogard 901, 2
91	6	PC	Rheocrete 222+, 1
92	6	7% SF	Rheocrete 222+, 1
93	6	PC/P	DCI-S, 4
94	6	7% SF/P	DCI-S, 4
95	6	PC/903	Ferrogard 901, 2
96	6	7% SF/903	Ferrogard 901, 2
97	10	7% SF	None, 0
98	10	7% SF	None, 0
99	10	7% SF	DCI-S, 4
100	10	7% SF	DCI-S, 4
101	10	7% SF	Ferrogard 901, 2
102	10	7% SF	Ferrogard 901,2
103	10	7% SF	Rheocrete 222+, 1
104	10	7% SF	Rheocrete 222+, 1
105	10	7% SF/P	DCI-S, 4
106	10	7% SF/P	DCI-S, 4
107	10	7% SF/903	Ferrogard 901, 2

Chl = chloride content, PC = portland cement, SF = silica fume, CIA = corrosion inhibiting admixture, DCI-S = Derex Corrosion Inhibitor with Retarder, P = Postrite Topical Inhibitor, 903 = Ferrogard Topical Inhibitor, 2020 = MCI Topical Inhibitor.

Table 4. Concretes and Corrosion Inhibiting Admixtures Used for Slabs That Were Ponded

Slab	SF	FA	HRWR Dosage	Type	CIA Dosage
Number	%	%	gcy	CIA	gcy
109	0	0	0	None	0
110	0	0	0	None	0
111	7	0	0.4	None	0
112	0	25	0	None	0
113	0	0	0	Ferrogard 901	2
114	0	0	0	Ferrogard 901	2
115	7	0	0.3	Ferrogard 901	2
116	0	25	0	Ferrogard 901	2
117	0	0	0.4	Rheocrete 222+	1
118	0	0	0.4	Rheocrete 222+	1
119	7	0	0.5	Rheocrete 222+	1
120	0	25	0	Rheocrete 222+	1
121	0	0	0	DCI-S	3
122	0	0	0	DCI-S	3
123	7	0	0.3	DCI-S	2
124	0	25	0	DCI-S	2
133	0	0	0	MCI 2005	0.2
134	0	0	0	Catexol 1000	3
135	0	0	0	Impasse	1.5
136	0	0	0	DCI-S	2

SF = silica fume, FA = fly ash, HRWR = high-range water reducer, CIA = corrosion inhibiting admixture, DCI-S = Derex Corrosion Inhibitor with Retarder, MCI = Migrating Corrosion Inhibitor.

Evaluation of Exposure Slabs

The following measurements were made on each of the 156 slabs each quarter between September 1997 and June 2001 in the following order:

- *half-cell potentials over Bars b and d (see Figure 1),* (mV copper sulfate electrode [CSE]) (ASTM C 876)
- *rate of corrosion over Bar b (mils per year),* measured using the polarization resistance (PR) monitor (discontinued in the July–September quarter of 1999); a final set of measurements was done in June 2001
- *macrocell current, between top and bottom rebar mats (mA),* measured with a 10-ohm resistor
- *macrocell potential (mV),* measured immediately after the top and bottom rebar mats were discontinued

- *resistance between top and bottom rebar mats (ohms),* measured using a Nilsson Model 400 soil resistance meter using a two-pin method.

The top and bottom mats of reinforcement in the slabs are connected by banana plugs that have male and female connections. Half-cell potentials are recorded by connecting the lead wire of the half-cell device to the male end of the connected banana plugs and placing the tip of the half-cell over pre-marked locations above Bars b and d. Rate of corrosion measurements are made by connecting the lead wire to the banana plug and centering the circular corrosion ring over the pre-marked location above Bar b. Macrocell current measurements are made by connecting the two lead wires of the voltmeter to the ends of the two banana plugs (positive red wire to top mat and negative black wire to bottom mat) and to a 10-ohm resistor and disconnecting the banana plugs. Macrocell potential measurements are made by reconnecting the banana plugs, removing the resistor from the circuit, and recording the initial potential measurement as the banana plugs are disconnected. Resistance measurements are made by connecting the leads of the resistance meter to the disconnected banana plugs. The banana plugs are reconnected after the resistance measurements are made.

Construction of Bridge Repairs

Overlays and patches were constructed on five bridges for the evaluation of CIAs and topical applications of inhibitors. CIAs and topical treatments of corrosion inhibitors were used in the construction of overlays and patches at Virginia Beach, Abingdon, Wytheville, and Marshall, Virginia, and in shotcrete repairs on bridge piers on I-77 at Walker Mountain, Virginia. Corrosion probes were placed in the patches on four of the projects. Details of the construction and initial condition of the repairs are reported in Interim Report No. 2.[2]

Evaluation of Bridge Repairs

The initial condition of the repairs was determined by using a chain drag to identify delaminations and half-cell potential measurements (ASTM C876) to identify areas with high and low potentials for corrosion. Tensile bond strength tests (VTM-92) were done to provide an indication of the initial bond strength of the repairs.

Corrosion probe readings were taken during the initial condition evaluation and quarterly thereafter. Each probe in the bridges is connected to a lead wire that goes to a junction box. A ground wire is connected to the top mat of reinforcement. Macrocell current measurements are made by connecting the two leads of the voltmeter to a probe wire (positive red wire) and the ground wire (negative black wire) and to a 10-ohm resistor and disconnecting the probe wire from the ground wire. Macrocell potential measures are made by reconnecting the probe and ground wires, removing the resistor from the circuit, and recording the instant potential with the volt meter as the probe and ground wire are disconnected. Resistance measurements are made by connecting the probe and ground wire to the resistance meter. The probe and ground wires are reconnected after the resistance measurement is made.

RESULTS FROM EXPOSURE SLABS

Half-Cell Potentials

Figure 2 shows a plot of the *average* half-cell potential data in the vicinity of Bar b for quarterly readings between September 1997 and June 2001 for the 156 slabs. Half-cell data are shown as a function of chloride content for the slabs representing repairs and as a function of concrete mixtures for the full-depth slabs. Average values are shown because temperature and moisture conditions affect the readings and because readings did not change much over the evaluation period but rather fluctuated with temperature and moisture. Measurements more negative than –0.35V (CSE) indicate a 90 percent probability that corrosion is occurring in the vicinity of Bar b.

Based on the half-cell potential data, the following slabs had corrosion occurring in the vicinity of Bar b when the last measurements were made in June 2001:

- *slabs with overlay and 10 lb/yd^3 of chloride* (Slab 26, Table 1, 7% SF, and no inhibitors)
- *slabs with overlays and 15 lb/yd^3 of chloride* (Slabs 145, 147 through 151, 153 through 156, Table 1); only two slabs, 146 (7% SF, and no inhibitors) and 152 (7% SF and Rheocrete 222+), had potentials slightly less negative than –0.35 in June 2001
- slabs with an overlay and patch (special mixture OL/P) and 10 lb/yd^3 of chloride (Slab 141, Table 2, RSLMC)
- *full-depth slabs being ponded* (Slabs 109 [no inhibitor or pozzolan], 133 [MCI 2005], 134 [Catexol 1000], see Table 4).

Based on the average half-cell values in Figure 2, all but two slabs with overlays and 15 lb/yd^3 chloride had half-cell potentials more negative than –0.35V (CSE). Slabs 152 (7% SF and Rheocrete 222+) and 153 (7% SF and DCI and P) had average values slightly less negative than –0.35V (CSE). The only conclusive results to report at this time are that all slabs constructed with 15 lb/yd^3 chloride and overlaid have cracks and delaminations in the overlays. The half-cell data support the corrosion-induced cracking and spalling in the overlays. Slabs with and without inhibitor treatments have failed. The inhibitor treatments did not make a difference. The only other slab in Figure 2 with an average half-cell potential more negative than –0.35V (CSE) is the special mixture Slab 141 (RSLMC). All other slabs have values less negative than –0.35V (CSE), indicating no corrosion.

Rate of Corrosion

Figure 3 shows a plot of the average rate of corrosion in the vicinity of Bar b for quarterly readings between September 1997 and May 1999 and a final set taken in June 2001. Rate of corrosion data are shown as a function of chloride content for the slabs representing repairs and as a function of concrete mixtures for the full-depth slabs. The criteria for corrosion based on data taken with the PR monitor are as follows: high (>2 mpy), moderate (1 to 2 mpy), low (0.2 to 1 mpy), and passive (<0.2 mpy). Based on these criteria and the average readings shown in Figure 3, corrosion is occurring in the vicinity of Bar b in all but the two slabs that were overlaid

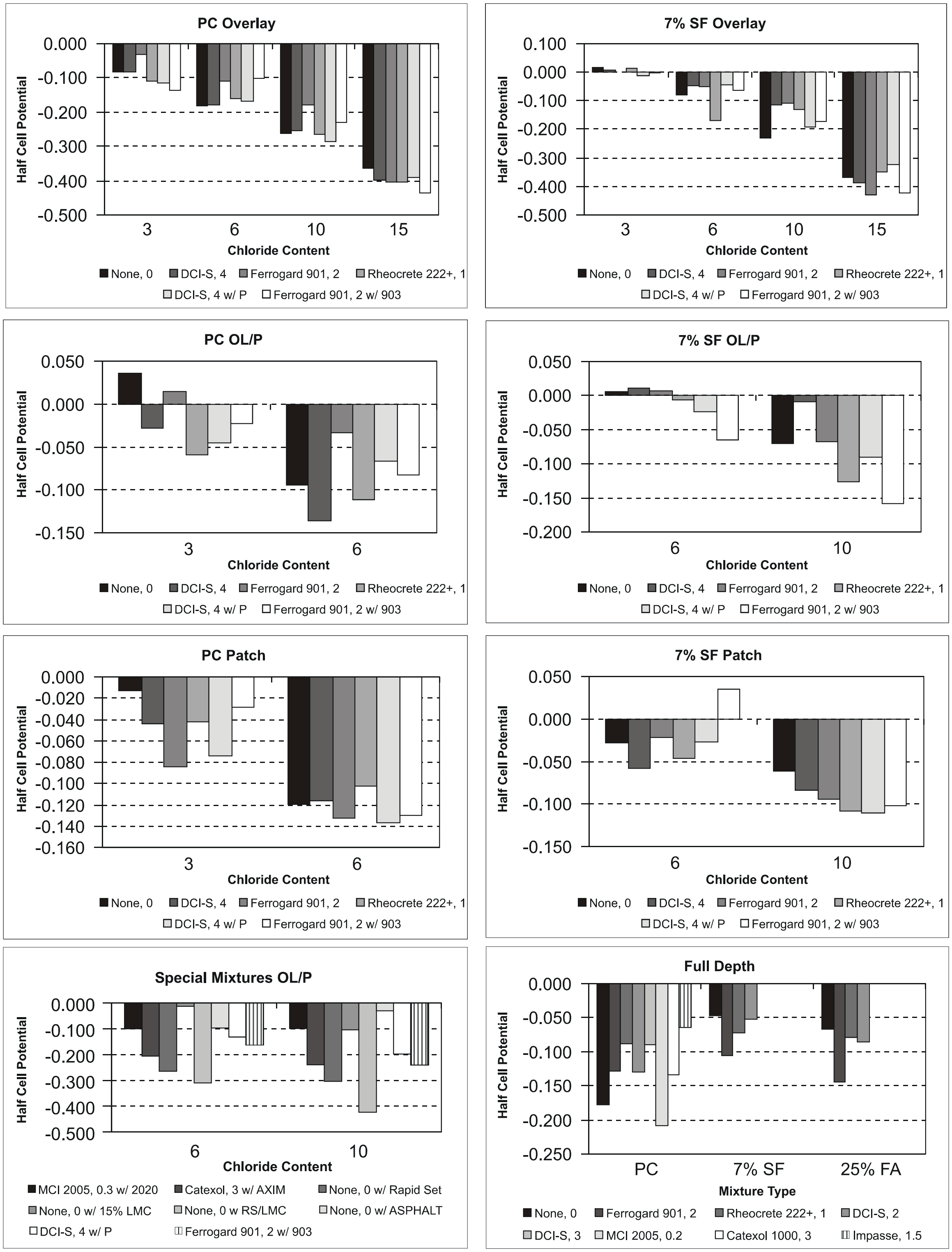


Figure 2. Average Half-Cell Potentials Bar B (V CSE) as Function of Chloride Content (Cementitious Material/Full Depth)

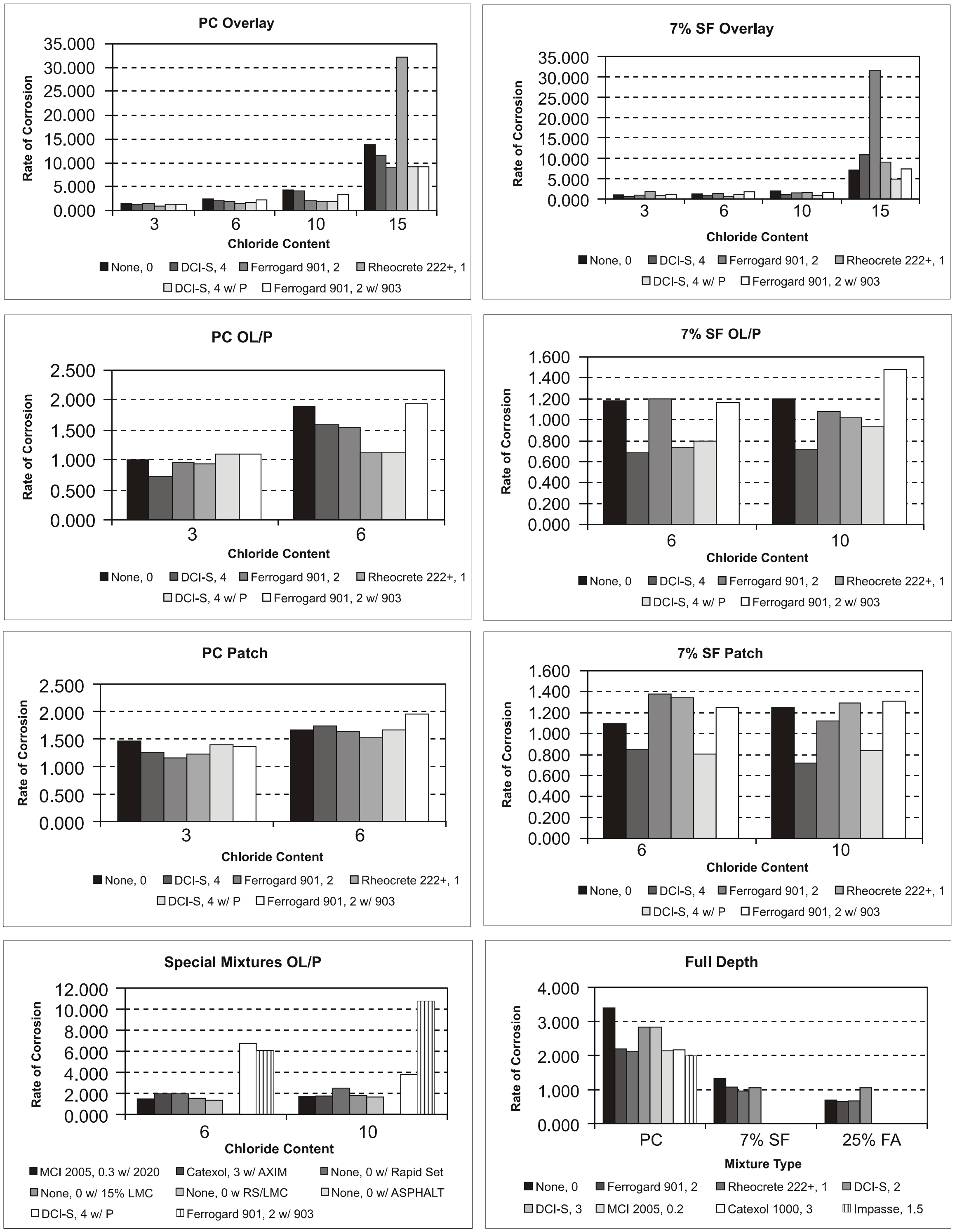


Figure 3. Average Corrosion Rate (mil/yr) Bar B as Function of Chloride Content (Cementitious Material/Full Depth)

and patched with asphalt (see bars for special mixtures OL/P in Figure 3). Since the visual inspection of the reinforcement (to be discussed later) shows Bar b to be corroding in these two slabs, the PR monitor must not work on asphalt surfaces. Readings taken in June 2001, the last set taken, indicated the following rates of corrosion:

- *slabs with 3 pcy chloride:* passive 65 percent, low 26 percent, moderate 3 percent, high 6 percent
- *slabs with 6 pcy chloride:* passive 63 percent, low 25 percent, moderate 6 percent, high 6 percent
- *slabs with 10 pcy chloride:* passive 61 percent, low 32 percent, moderate 5 percent, high 2 percent
- *slabs with 15 pcy chloride:* passive 50 percent, low 50 percent, moderate 0 percent, high 0 percent
- *slabs being ponded:* passive 60 percent, low 25 percent, moderate 5 percent, high 10 percent.

Readings in June 2001 were much lower than the ones for May 1999. Evidently, the readings in June 2001 are not valid for the slabs with 15 pcy chloride because the steel has corroded so much and the concrete has cracked so much along the reinforcement because of corrosion deposits. The cause for the lower corrosion rate in June 2001 for the other slabs is not known at this time.

In summary, the rate of corrosion data in Figure 3 mirror the half-cell data in Figure 2. Unfortunately, the rate of corrosion data, based on the criteria for the PR monitor, indicate corrosion is occurring in more slabs than is indicated by the half-cell potential data in Figure 2 and by the visual inspection of the rebars (to be discussed later).

Macrocell Current

Figure 4 shows a plot the average stabilized macrocell current between the top and bottom mats of reinforcement in slabs. Macrocell current data are shown as a function of chloride content for the slabs representing repairs and as a function of concrete mixtures for the full-depth slabs. Based on ASTM G 109 criteria, macrocell currents greater than 10 μA are an indication that corrosion is occurring. The surface area of the top mat of reinforcement of the slabs is approximately 10.5 times greater than that of the one bar in the G 109 test. Consequently, the criteria for corrosion for the top mat of rebar in the slabs should be greater than 105 μA (0.1 mA).

Figure 4 indicates corrosion is occurring in the following slabs:

- *PC overlay:* all slabs with 10 and 15 lb/yd^3 chloride
- *7% SF overlay:* all slabs with 10 and 15 lb/yd^3 chloride, and some slabs with 6 lb/yd^3 chloride
- *7% SF OL/P:* 1 slab with 6 lb/yd^3 chloride and 3 slabs with 10 lb/yd^3 chloride
- *PC patch:* no slabs

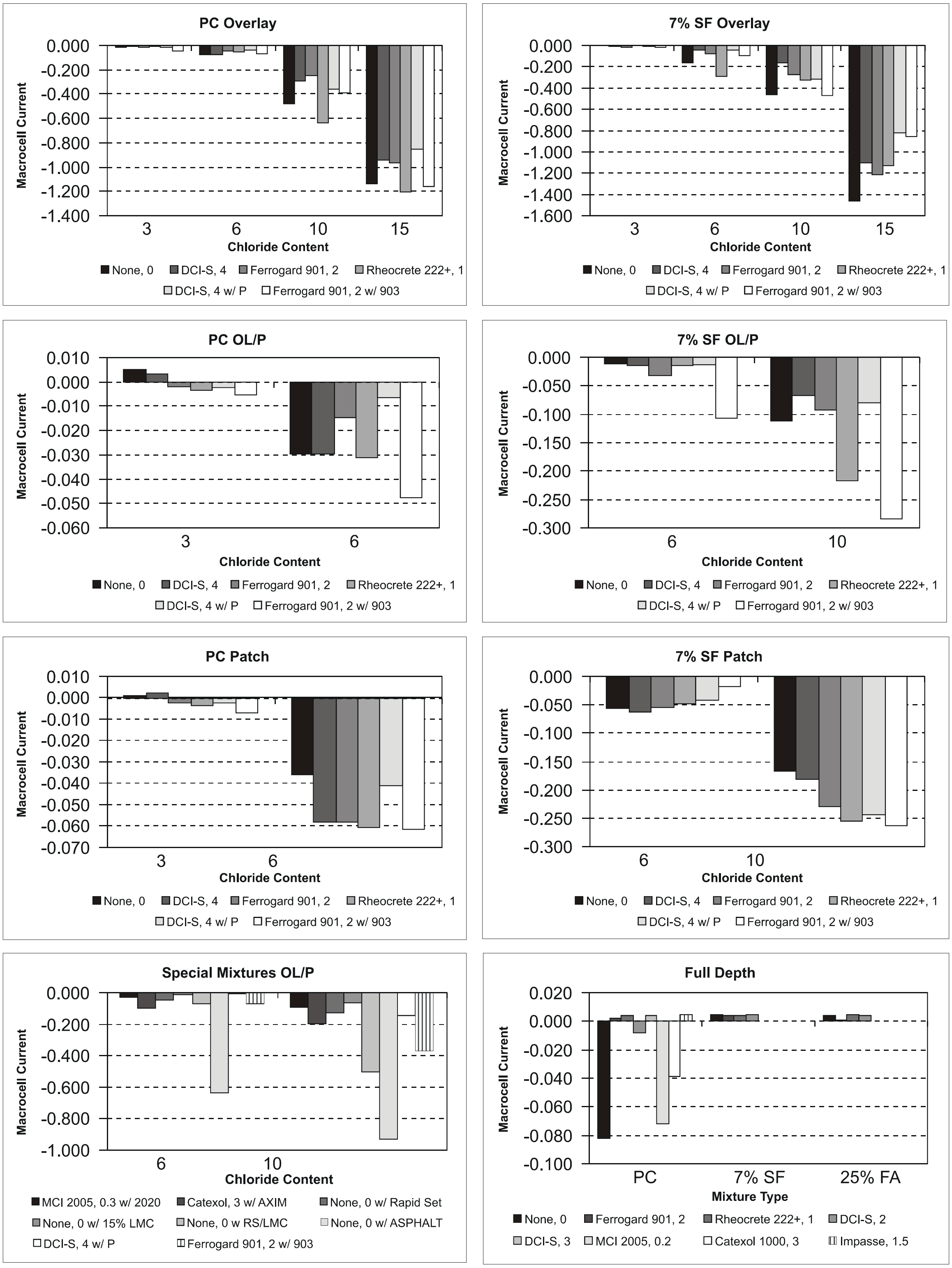


Figure 4. Average Macrocell Current (mA) as Function of Chloride Content (Cementitious Material/Full Depth)

- *7% SF patch:* all slabs with 10 lb/yd3 chloride
- *Special mixtures OL/P:* 1 slab with 6 lb/yd^3 chloride and all but 1 slab with 10 lb/yd^3 chloride.

Based on the macrocell current data in June 2001, the last set taken, all 12 slabs constructed with 15 lb/yd^3 of chloride ion, 37 slabs constructed with 10 lb/yd^3 of chloride ion, and 8 slabs constructed with 6 lb/yd^3 of chloride ion are corroding. All slabs constructed with 3 lb/yd^3 of chloride ion and full-depth slabs that are being ponded (except Slabs 109, 133, 134, and 136) are not corroding. The June 2001 data are more important than the data in Figure 4 for the full-depth slabs because the slabs are being ponded and the chloride content is increasing with time. The June 2001 data suggest corrosion may be beginning in four slabs.

In summary, the microcell current data in Figure 4 mirror the half-cell data in Figure 2. Unfortunately, based on the threshold criteria for corrosion of 0.1 mA, corrosion is occurring in more slabs than indicated by the half-cell data in Figure 2 and by the visual inspection of the reinforcement (to be discussed later).

Macrocell Potential

Figure 5 shows a plot of the average macrocell potentials between the top and bottom mats of reinforcement in the slabs. Macrocell potential data are shown as a function of chloride content for the slabs representing repairs and as a function of concrete mixtures for the full-depth slabs. The macrocell potential data mirror the macrocell current data in that the potentials are the most negative for the slabs with the highest chloride contents. June 2001 potentials are negative for 15 of the 20 of the slabs being ponded, indicating that sufficient chloride may have reached the reinforcement to initiate the mechanism for corrosion in 15 slabs. Additional years of ponding and monitoring of the slabs may provide conclusive results.

Resistance

Figure 6 shows the average resistance between the top and bottom mats of reinforcement in the slabs. Resistance data are shown as a function of chloride content for the slabs representing repairs and as a function of concrete mixtures for the full-depth slabs. The resistance tends to decrease with an increase in the chloride content for the slabs with overlays. Mixed results were obtained for the slabs that were overlaid and patched because of the many factors other than chloride content that can affect resistance. For the full-depth slabs, resistance increases with the addition of 7 percent SF and 25 percent fly ash as compared to plain PC. The highest resistance was obtained for slabs with 25 percent fly ash. High resistance correlates with high corrosion resistance.

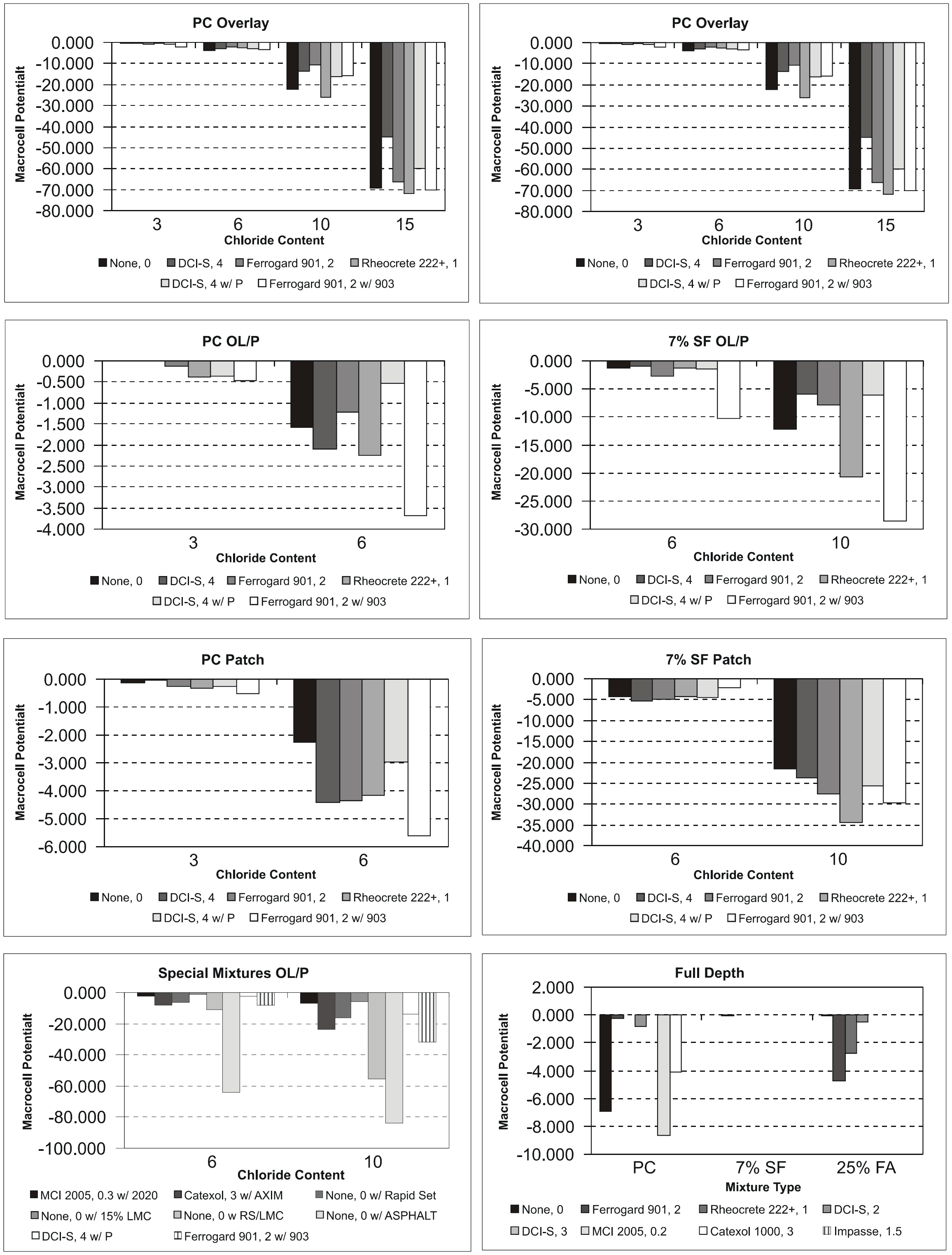


Figure 5. Average Macrocell Potential (mV) as Function of Chloride Content (Cementitious Material/Full Depth)

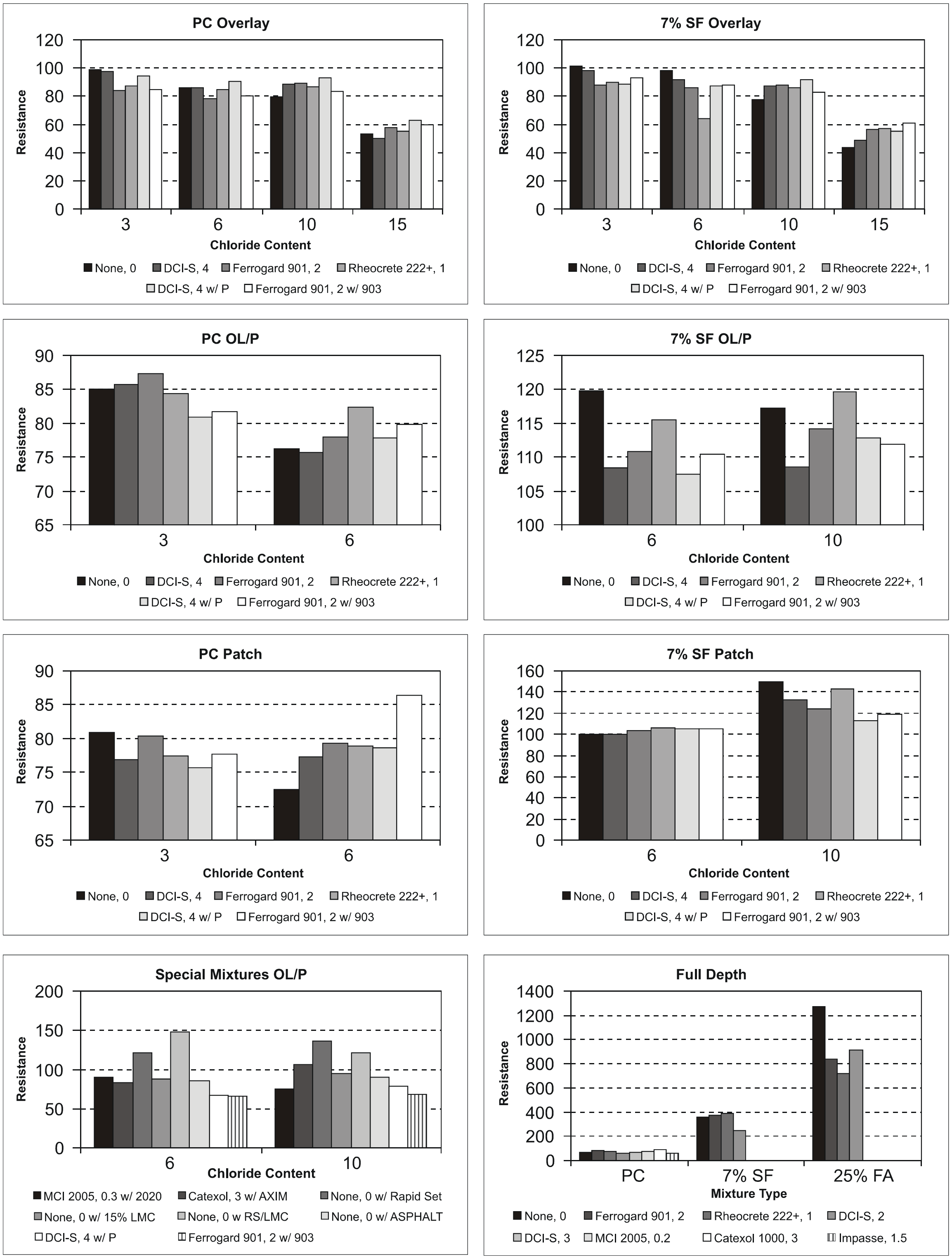


Figure 6. Average Resistance (ohms) as Function of Chloride Content (Cementitious Material/Full Depth)

Tensile Bond Tests, Visual Inspections of Bars B and D, and Chloride Ion Content Determinations

In the quarter that ended September 30, 2001, the scheduled final evaluation of the 136 slabs that represent repairs was completed. The final evaluation included tensile bond tests, visual inspections for corrosion products, and chloride content determinations adjacent to Bars b and d. The centers of Bars b and d were selected for evaluation because half-cell and corrosion rate measurements were made at these locations. Slabs were cored with a 2.25-in diameter core barrel to the depth of Bars b and d. The cores were pulled in tension to measure bond strength (ACI 503R). The exposed bars were cut, removed, and inspected for corrosion products. The concrete adjacent to Bars b and d was analyzed for chloride content.

Tables 5, 6, and 7 show the results from the tensile bond tests and the condition evaluation of Bars b and d at the tensile bond test locations for slabs with an overlay, an overlay and patch, and a patch, respectively. It was anticipated that a reduction in bond strength could be caused by either the presence of a corrosion inhibitor or corrosion-induced cracking in the vicinity of a rebar. Slabs in which the average bond strength over Bars b and d was <100 psi were considered to have a low bond strength. Table 5 and Figure 7 show that all overlays on slabs constructed with 15 lb/yd^3 of chloride ion had a low bond strength, which is consistent with the observation that the overlays were delaminated from the corrosion of the reinforcement. Slabs 8 (7% SF and Rheocrete), 18 (7% SF and Ferrogard 901), 19 (PC and Rheocrete), 20 (7% SF and Rheocrete), 26 (7% SF and no CIA), 31 (PC and Rheocrete), and 36 (PC and Ferrogard 901 and 903) also had low bond strengths. Figure 7 also shows lower strengths for overlays with Rheocrete and SF and with increasing chloride content. Topically applied inhibitors did not reduce bond strength. Table 6 shows results for slabs with overlays and patches. The overlays are bonded to the base concrete at the Bar d test location. The Bar b test location is in the patch so that a bond failure is not possible. Low bond strengths at the Bar d test location were obtained for 14 slabs (5 with Rheocrete, 2 with asphalt, 2 with Ferrogard 901 and 903, 2 with Catexol, 1 with Ferrogard 901, 1 with DCI and P, and 1 with RSLMC). Table 7 shows results for slabs with patches. The patches are bonded to the base concrete below the top reinforcement, and therefore no bond failures can occur. The four low test values cannot be explained.

After the tensile bond tests were completed, the exposed bars were cut, removed, and inspected for corrosion products. The concrete adjacent to Bars b and d was analyzed for chloride content. Table 8 shows the scale used to rate the bars. The scale goes from 0 for bars with no mill scale to 6 for bars with section loss and cracking in the concrete above the bar. The numbers in between are relative. Table 5 shows that bars from slabs with overlays and 3, 6, and 10 lb/yd^3 of chloride ion were rated mostly as 0 or 1 and bars from several slabs were rated as 2. These ratings support the half-cell potential measurements in Figure 2, indicating little or no corrosion at the test locations. Slabs with overlays and15 lb/yd^3 of chloride ion were rated as 3 through 6. However, twelve of the ratings were 5, five were 6, five were 4, and two were 3. These ratings also support the half-cell potential measurements in Figure 2, the observation of the delamination of the overlays, and the low bond strengths, all of which indicate corrosion of the reinforcement. Table 6 shows that bars from slabs with overlays and patches and 3, 6, and 10 lb/yd^3 of chloride ion were rated mostly as 0 or 1; bars from six slabs were rated as 2; bars from three slabs as 3; and from one slab as 4. These ratings support the half-cell potential

Table 5. Tensile Bond Strength Test Results at B and D for Slabs With Overlay

Slab #	Bar	Str. psi	OL %	Bond %	Base %	Bar Cond.
1	B	277	-	-	100	0
1	D	279	-	-	100	1
2	B	259	-	75	25	0
2	D	254	-	50	50	1
3	B	264	-	-	100	0
3	D	269	-	-	100	0
4	B	0	-	95	5	0
4	D	231	-	-	100	1
5	B	300	-	50	50	0
5	D	264	-	-	100	1
6	B	302	-	-	100	0
6	D	310	-	-	100	0
7	B	178	-	95	5	0
7	D	104	-	95	5	1
8	B	46	-	100	-	0
8	D	91	-	75	25	0
9	B	269	-	-	100	0
9	D	183	-	-	100	1
10	B	264	-	-	100	0
10	D	300	-	-	100	0
11	B	211	-	-	100	1
11	D	203	-	10	90	0
12	B	178	-	-	100	1
12	D	140	-	30	70	1
13	B	218	-	100	-	1
13	D	350	-	100	-	1
14	B	96	-	100	-	1
14	D	264	60	-	40	1
15	B	277	-	-	100	2
15	D	284	-	20	80	1
16	B	84	-	100	-	1
16	D	246	-	100	-	1
17	B	198	-	100	-	1
17	D	272	-	100	-	1
18	B	86	-	100	-	2
18	D	96	-	100	-	1
19	B	61	-	100	-	0
19	D	122	-	100	-	0
20	B	0	-	100	-	2
20	D	0	-	100	-	1
21	B	305	-	-	100	0
21	D	320	-	-	100	1
22	B	203	-	-	100	1
22	D	251	-	-	100	1
23	B	198	-	20	80	1
23	D	185	-	20	80	1
24	B	343	-	-	100	1
24	D	277	-	-	100	1
25	B	142	-	-	100	2
25	D	71	-	-	100	2
26	B	0	-	60	40	2
26	D	175	-	100	-	2
27	B	315	-	15	85	1
27	D	201	-	-	100	1
28	B	69	-	100	-	1
28	D	223	-	-	100	1
29	B	180	-	-	100	2
29	D	203	-	-	100	2
30	B	223	-	-	100	1
30	D	51	-	-	100	2
31	B	36	-	100	-	1
31	D	0	-	100	-	2
32	B	223	-	-	100	1
32	D	213	-	-	100	1
33	B	302	-	-	100	0
33	D	216	-	-	100	2
34	B	130	-	-	100	0
34	D	297	-	-	100	0
35	B	165	100	-	-	1
35	D	107	0	5	95	1
36	B	74	20	-	80	1
36	D	96	30	-	70	1
145	B	0	5	5	90	5
145	D	0	-	15	85	5
146	B	0	5	15	80	5
146	D	0	5	5	90	5
147	B	0	-	-	100	5
147	D	0	-	5	95	4
148	B	0	10	-	90	3
148	D	23	-	-	100	5
149	B	0	10	-	90	5
149	D	0	25	-	75	6
150	B	0	-	-	100	4
150	D	0	-	-	100	5
151	B	0	-	-	100	6
151	D	0	-	-	100	5
152	B	0	-	-	100	6
152	D	0	-	-	100	6
153	B	0	-	-	100	5
153	D	46	-	-	100	6
154	B	0	-	-	100	4
154	D	0	-	-	100	3
155	B	0	-	100	-	4
155	D	0	25	75	-	5
156	B	18	25	75	-	4
156	D	0	30	75	-	5

B = Bar b in Fig. 1, D = Bar d in Fig. 1, Str. = tensile bond strength, OL = overlay, Cond. = corrosion rating of bar.

Table 6. Tensile Bond Strength Test Results at B and D for Slabs With Overlay and Patch

Slab #	Bar	Str. psi	OL %	Bond %	Base %	Bar Cond.	Slab #	Bar	Str. psi	OL %	Bond %	Base %	Bar Cond.
37	B	381	100	-	-	1	61	B	411	100	-	-	0
37	D	338	-	-	100	1	61	D	208	-	40	60	1
38	B	254	100	-	-	0	62	B	394	100	-	-	0
38	D	262	-	-	100	1	62	D	272	-	-	100	1
39	B	345	100	-	-	0	63	B	295	100	-	-	0
39	D	274	-	5	95	1	63	D	188	-	90	10	1
40	B	335	100	-	-	0	64	B	361	100	-	-	0
40	D	223	-	-	100	1	64	D	234	-	-	100	1
41	B	353	100	-	-	0	65	B	401	100	-	-	0
41	D	279	-	-	100	1	65	D	279	-	-	100	1
42	B	381	100	-	-	0	66	B	383	100	-	-	0
42	D	317	-	-	100	1	66	D	185	-	-	100	1
43	B	302	100	-	-	0	67	B	411	100	-	-	0
43	D	0	-	100	-	2	67	D	36	-	25	75	1
44	B	267	-	-	100	0	68	B	432	100	-	-	0
44	D	185	-	50	50	2	68	D	56	-	95	25	1
45	B	401	100	-	-	0	69	B	399	100	-	-	0
45	D	381	-	-	100	1	69	D	239	-	-	100	1
46	B	394	100	-	-	0	70	B	404	100	-	-	0
46	D	366	-	100	-	1	70	D	310	-	-	100	1
47	B	406	100	-	-	0	71	B	432	100	-	-	0
47	D	404	-	-	100	0	71	D	112	-	25	75	1
48	B	411	100	-	-	1	72	B	411	100	-	-	0
48	D	168	-	-	100	1	72	D	30	-	30	70	1
49	B	396	100	-	-	1	125	B	389	100	-	-	0
49	D	315	-	100	-	1	125	D	275	-	5	95	1
50	B	419	100	-	-	0	126	B	350	-	-	100	0
50	D	206	-	100	-	1	126	D	0	-	100	-	0
51	B	404	100	-	-	1	127	B	20	100	-	-	2
51	D	277	-	10	90	1	127	D	251	100	-	-	1
52	B	315	100	-	-	1	128	B	414	100	-	-	0
52	D	244	-	100	-	1	128	D	376	-	10	90	0
53	B	373	100	-	-	1	129	B	407	100	-	-	0
53	D	201	-	100	-	1	129	D	126	-	-	100	1
54	B	325	100	-	-	1	130	B	401	100	-	-	0
54	D	5	-	100	-	0	130	D	0	20	80	-	2
55	B	401	100	-	-	1	131	B	282	100	-	-	3
55	D	0	-	100	-	2	131	D	246	-	-	100	1
56	B	437	100	-	-	1	132	B	416	100	-	-	1
56	D	5	-	100	-	1	132	D	203	-	-	100	1
57	B	363	100	-	-	0	137	B	477	100	-	-	1
57	D	416	-	-	100	1	137	D	122	-	100	-	1
58	B	378	100	-	-	0	138	B	0	-	-	-	3
58	D	358	-	-	100	1	138	D	0	-	-	-	1
59	B	391	100	-	-	0	139	B	356	100	-	-	0
59	D	112	-	25	75	1	139	D	401	-	-	100	1
60	B	396	100	-	-	0	140	B	239	100	-	-	0
60	D	256	-	-	100	1	140	D	15	-	100	-	1

Slab #	Bar	Str. psi	OL %	Bond %	Base %	Bar Cond.
141	B	350	100	-	-	1
141	D	0	50	50	-	1
142	B	0	-	-	-	3
142	D	0	-	-	-	2
143	B	409	100	-	-	0
143	D	5	90	10	-	3
144	B	315	100	-	-	1
144	D	0	50	50	-	4

B = Bar b in Fig. 1, D = Bar d in Fig. 1, Str. = tensile bond strength, OL = overlay, Cond. = corrosion rating of bar.

Table 7. Tensile Bond Strength Test Results at B and D for Slabs With Overlay

Slab #	Bar	Str. psi	OL %	Bond %	Base %	Bar Cond.
73	B	409	100	-	-	0
73	D	378	-	-	100	0
74	B	416	100	-	-	0
74	D	350	-	-	100	1
75	B	371	100	-	-	0
75	D	368	-	-	100	1
76	B	361	100	-	-	0
76	D	312	-	-	100	0
77	B	317	100	-	-	0
77	D	302	-	-	100	1
78	B	356	100	-	-	0
78	D	325	-	-	100	0
79	B	371	100	-	-	0
79	D	269	-	-	100	1
80	B	427	100	-	-	0
80	D	333	-	-	100	1
81	B	356	100	-	-	0
81	D	317	-	-	-	1
82	B	356	100	-	-	0
82	D	325	-	-	-	1
83	B	396	100	-	-	0
83	D	373	-	-	-	1
84	B	0	100	-	-	0
84	D	315	-	-	100	1
85	B	383	100	-	-	0
85	D	257	100	-	-	1
86	B	371	100	-	-	0
86	D	0	-	-	100	1
87	B	361	100	-	-	1
87	D	213	-	-	100	0
88	B	383	100	-	-	0
88	D	820	-	-	100	1
89	B	325	100	-	-	0
89	D	305	-	-	100	1
90	B	409	100	-	-	0
90	D	325	-	-	100	1
91	B	358	100	-	-	1
91	D	163	-	-	100	1
92	B	401	100	-	-	1
92	D	317	-	-	100	1
93	B	396	100	-	-	0
93	D	284	-	-	100	1
94	B	289	100	-	-	0
94	D	330	-	-	100	1
95	B	323	100	-	-	0
95	D	267	-	-	100	1
96	B	391	100	-	-	0
96	D	188	-	-	100	1
97	B	363	100	-	-	0
97	D	241	-	-	100	1
98	B	361	100	-	-	0
98	D	274	-	-	100	1
99	B	376	100	-	-	0
99	D	241	-	-	100	1
100	B	386	100	-	-	0
100	D	279	-	-	100	1
101	B	378	100	-	-	0
101	D	183	-	-	100	1
102	B	371	100	-	-	0
102	D	198	-	-	100	2
103	B	396	100	-	-	0
103	D	325	-	-	100	2
104	B	404	100	-	-	0
104	D	145	-	-	100	3
105	B	338	100	-	-	0
105	D	5	-	-	100	3
106	B	341	100	-	-	1
106	D	239	-	-	100	2
107	B	479	100	-	-	0
107	D	0	-	-	100	3
108	B	389	100	-	-	1
108	D	257	-	-	100	2

B = Bar b in Fig. 1, D = Bar d in Fig. 1, Str. = tensile bond strength, OL = overlay, Cond. = corrosion rating of bar.

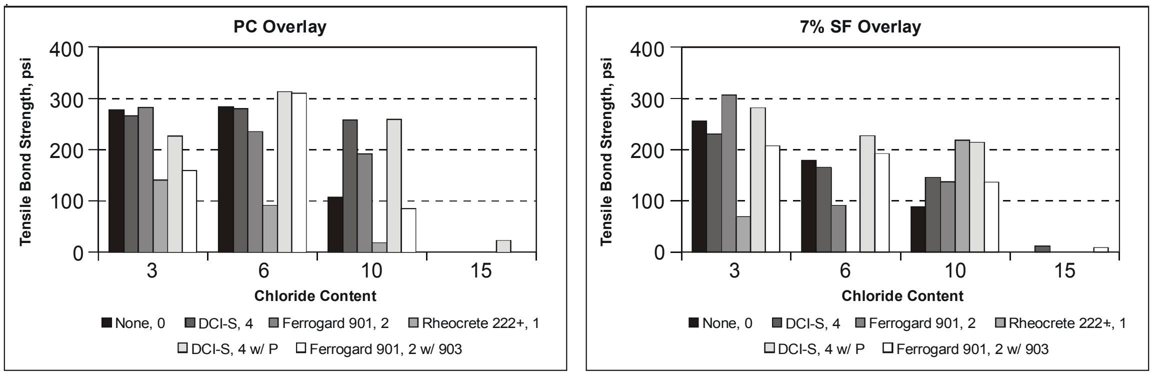


Figure 7. Tensile Bond Strength Test Results for Slabs with Overlays

Table 8. Scale Used to Rate Reinforcement Removed From Slabs at B and D Test Locations

Condition of Reinforcement	Rating Number
No rust or mill scale	0
Mill scale	1
Mill scale and spots of rust	2
Light rust covers most of bar	3
Medium rust covers bar	4
Heavy rust (some loss of ridges on bars) but no crack above bar	5
Heavy rust (some loss of ridges on bars) and cracking above bar	6

B = Bar b in Fig. 1, D = Bar d in Fig. 1.

measurements in Figure 2, indicating little or no corrosion at the test locations. Likewise, Table 7 shows that bars from slabs with patches and 3, 6, and 10 lb/yd^3 of chloride ion were rated mostly as 0 or 1, bars from four slabs were rated as 2, and bars from three slabs as 3. These ratings also support the half-cell potential measurements in Figure 2, indicating little or no corrosion at the test locations.

After the tensile bond tests were completed, the concrete adjacent to Bars b and d was analyzed for chloride content. Table 9 shows the chloride content by design as well as the quantity that was found in the slabs. The average actual chloride content is the same as the design chloride content at 3 lb/yd^3. The average actual chloride content is 0.2 percent lower than the design chloride content at 6 lb/yd^3, 0.8 percent lower at 10 lb/yd^3, and 2.4 percent lower at 15 lb/yd^3. Water-soluble chloride contents were found to be approximately 50 percent of the design chloride ion contents. Tests indicated the water soluble contents were 1.5, 2.9, 4.6, and 8.2 lb/yd^{3,} respectively, for design chloride ion contents of 3, 6, 10, and 15 lb/yd^3. It is interesting that after approximately 5 years, there is no corrosion in slabs with 3, 6, and 10 lb/yd^3 of chloride. Evidently, because the slabs were constructed in the laboratories with high-quality bridge deck concrete, the quantity of chloride required to initiate corrosion is higher than 1.2 lb/yd^3, or the time to corrosion is longer than for concretes of lesser quality.

Table 9. Chloride Content (Acid Soluble) at Top Rebar in Selected Slabs

Design Chloride, lb/yd^3	3		6		10		15	
Type Slab Overlay	**PC**	**SF**	**PC**	**SF**	**PC**	**SF**	**PC**	**SF**
Average	2.85	3.12	5.78	5.80	9.11	9.23	11.42	13.79
Standard deviation	0.54	0.43	1.03	0.59	1.44	1.02	1.78	1.38
Average	2.99		5.79		9.17		12.60	
Standard deviation	0.49		0.80		1.19		1.96	
COV, %	16.4		13.8		13.0		15.6	

PC = portland cement, SF = silica fume, COV = coefficient of variation.

RESULTS FROM BRIDGE REPAIRS

Four bridges were instrumented with probes prior to being repaired with corrosion-inhibiting treatments. Details of the construction and instrumentation of the patches and overlays on the bridges can be found elsewhere.[2] Readers are encouraged to review that work prior to reading the results on bridge repairs. The probes were measured quarterly for macrocell current, macrocell potential, and resistance.

Macrocell Current

Figures 8, 9, and 10 show the average macrocell current data from the quarter readings of the corrosion probes. The surface area of a probe is about half that of the top rebar in the G 109 test. Using 50 percent of the G 109 criterion, corrosion is occurring when macrocell currents exceed 5 µA (0.005 mA). Based on the 0.005 mA criterion, approximately 60 percent of the probes are corroding at Wytheville and Abingdon and all of the probes are corroding at Big Walker and Marshall. Some probes in patches with corrosion-inhibiting treatments are corroding more than the patches without the treatments and visa versa. The value of the corrosion-inhibiting treatments cannot be seen from the data.

Macrocell Potential

Macrocell potential readings mirror the macrocell current readings.

Resistance

The resistance readings mirror the macrocell current and potential readings in that the resistance tends to be less for the more negative current and potential readings.

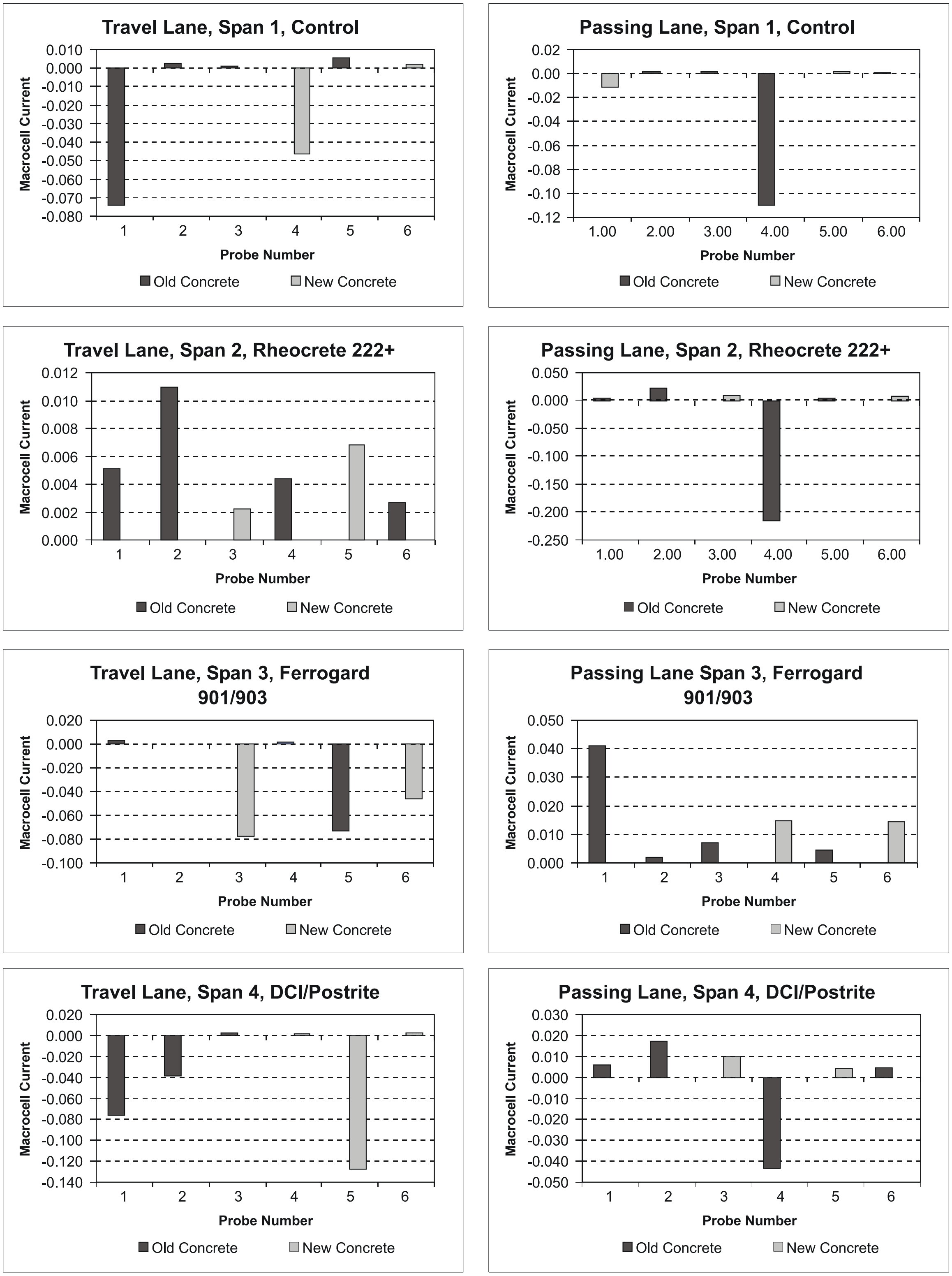


Figure 8. Macrocell Current Data for Probes at Wytheville (mA)

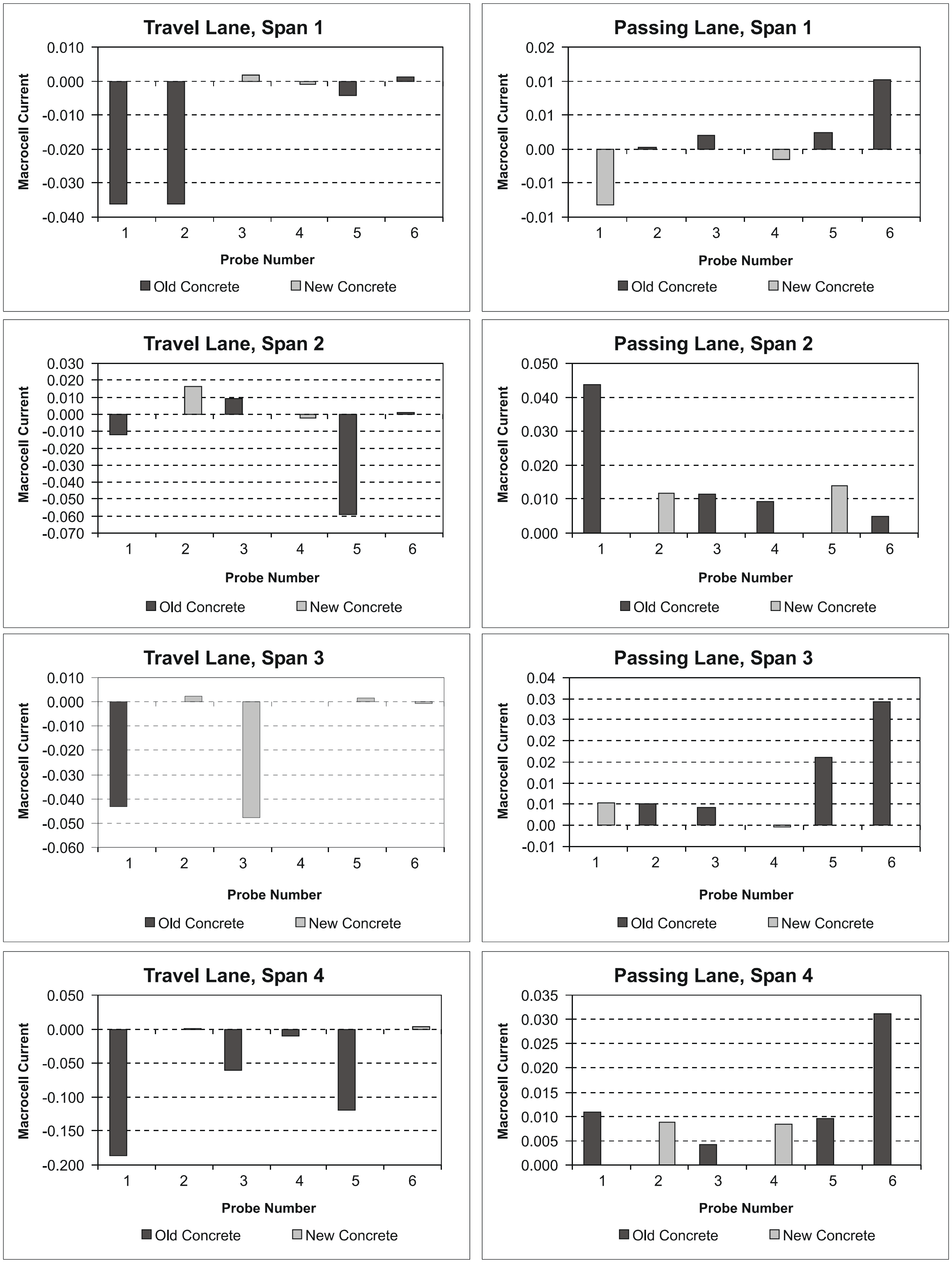
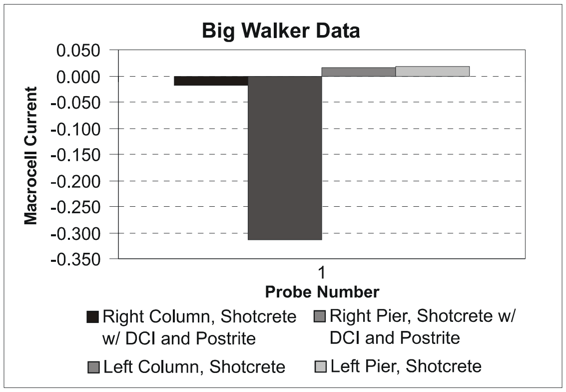


Figure 9. Macrocell Current Data for Probes at Abingdon (mA)



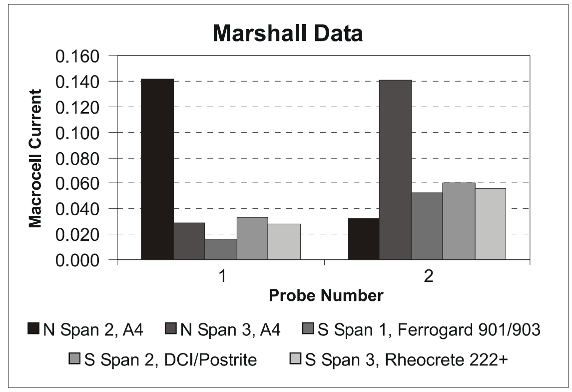


Figure 10. Macrocell Current Data for Probes at Big Walker Mountain and Marshall (mA)

CONCLUSIONS

- *Overlays with and without inhibitor treatments placed on slabs constructed with 15 lb/yd^3 of chloride ion cracked and delaminated because of corrosion of the top mat of reinforcement.* Half-cell potential data, tensile bond test data, and visual inspections of the reinforcement indicated corrosion of the reinforcement. Use of CIAs in the overlays and application of inhibitors to the surface of the concrete prior to placing the overlays provided no benefit.

- *Overlays and patches with and without inhibitor treatments placed on and in slabs with 3, 6, and 10 lb/yd^3 of chloride are performing satisfactorily at this time.* Half-cell potential data, tensile bond test data, and visual inspection of the reinforcement indicate that corrosion of the reinforcement is not occurring. Further, these indicators do not show reductions in the tendency for corrosion that can be attributed to the inhibitors. More exposure time may show benefits that can be attributed to some of the inhibitor treatments.

- *Overlays and patches with and without inhibitor treatments on and in five bridges are performing erratically.* Corrosion probes placed in the overlays and patches indicate mixed results. In some situations, the repairs with the inhibitor treatments are performing better than the repairs without the treatments, and in some situations, the reverse is true. Corrosion is occurring in the majority of the repairs done with and without inhibitor treatments. The corrosion-inhibiting treatments do not seem to be reducing corrosion in the bridges and may be *increasing* corrosion. More exposure time may show benefits that can be attributed to some of the inhibitor treatments.

- *It is not obvious that corrosion is occurring in the full-depth slabs constructed with and without inhibitors to represent new construction.* The slabs did not show signs of corrosion-induced cracking after 5 years of ponding. A longer period of ponding may show benefits that can be attributed to use of some of the inhibitors in the concrete.

- *Topical applications of inhibitors did not affect the bond strength of the overlays.* Overlays containing Rheocrete 222+ and 7 percent SF had lower bond strengths. Overlays on base concretes with the higher chloride contents had lower bond strengths.

- *This project does not show any benefit from the inhibitor admixtures used in the patches and overlays and the topical applications made to the chloride-contaminated concrete surfaces prior to placing the patches and overlays.*

RECOMMENDATIONS

1. Continue to evaluate the slabs and bridge repairs prepared for this study.

2. Do not use the CIAs evaluated in this study in patching and overlay situations similar to those evaluated in this study

3. Do not use the topically applied inhibitors evaluated in the study in patching and overlay situations similar to those evaluated in this study.

WORK PLANNED FOR THE FUTURE

- Continue to perform annual evaluations on the 156 slabs and the 5 bridges.

- Analyze the data obtained from the 156 slabs and the 5 bridges.

- Perform a complete autopsy on the exposure slabs once nondestructive evaluations indicate corrosion damage.

- Prepare a report on the 156 slabs and the 5 bridges when the data justify a report. The final results will be based on the autopsy.

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