

**FINAL REPORT**

**EVALUATION OF TWO CORROSION INHIBITORS USING TWO SURFACE  
APPLICATION METHODS FOR REINFORCED CONCRETE STRUCTURES**

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Virginia Transportation Research Council  
(A Cooperative Organization Sponsored Jointly by the  
Virginia Department of Transportation and  
the University of Virginia)

Charlottesville, Virginia

December 2004  
VTRC 05-R16

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## **ABSTRACT**

This study investigated the use of penetrating corrosion inhibitors to extend the life of existing reinforced concrete bridge decks. The use of assisted (vacuum/pressure injection) and unassisted (diffusion) treatment methods and two inhibitors were evaluated. The inhibitors were FerroGard 903, from Sika Corp., and TPS-II, from Surtreat International.

Testing was performed on exposure slabs with 15 lb/yd<sup>3</sup> of NaCl in the top layer and no NaCl in the bottom layer. The slab design was a variation of the specimen design provided in ASTM G109, with each slab containing nine steel reinforcing rods instead of three. The exposure slabs had either a uniform cover over the top pieces of steel or an inclined cover over the steel. TPS-II was also evaluated on the deck of a bridge in Orange County, Virginia.

The study found that when applied to the concrete surface, neither inhibitor penetrated the concrete to reach the steel reinforcement. The vacuum/pressure injection method showed promise but requires refinement. In addition, based on macro-cell measurements, a sufficient quantity of inhibitor can be injected into the concrete to reduce the charge passed.

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# **EVALUATION OF TWO CORROSION INHIBITORS USING TWO APPLICATION METHODS FOR REINFORCED CONCRETE STRUCTURES**

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## **INTRODUCTION**

In the United States, the direct annual maintenance and capital costs associated with corrosion of concrete bridge decks is between \$1.07 billion and \$2.93 billion.<sup>1</sup> The associated indirect costs are approximately 10 times higher.<sup>1</sup> Despite these substantial costs, an estimated savings of up to 46 percent of the annual corrosion cost can be recovered by improving maintenance practices.<sup>1</sup> Therefore, technology that reduces corrosion in highway bridges financially benefits the bridge owner, especially if the corrosion mitigation technique has only a minor impact on traffic flow.

The application of corrosion inhibitors is one possible corrosion mitigation technique for reinforced concrete structures. This technique reduces the corrosion rate by hindering the anodic reaction, the cathodic reaction, or both.<sup>2</sup> Although numerous studies have investigated the influence of corrosion-inhibiting concrete admixtures in new construction, corrosion mitigation techniques designed to rehabilitate the aging infrastructures are also needed.<sup>1,3-6</sup> Currently, inhibitors designed for application to the external surface of existing structures are being evaluated for their use in revitalizing corroding structures. Some researchers have indicated that inhibitors designed to penetrate concrete provide some protection, and others have found that post-treatment of a concrete structure was not effective at mitigating corrosion.<sup>7-14</sup>

Although the idea of simply applying an inhibitor to the concrete surface is appealing, it is critical that the inhibitor not only penetrate the concrete but also reach the reinforcing steel in sufficient concentrations to inhibit corrosion. The use of a vacuum to remove residual moisture from within the concrete followed by the application of pressure to inject an inhibitor into the concrete has also been suggested by the manufacturer of one of the inhibitors evaluated in this study. The manufacturer proposed that this method of application will increase the dose applied to the structure and ensure a sufficient concentration of inhibitor reaches the steel surface. Although both techniques for applying corrosion inhibitors can be used with only a slight impact on traffic flow, the use of a vacuum/pressure injection system increases the complexity of the application process because of the need for additional equipment.

In addition, although the costs of these two methods of application are expected to be small since the material costs are relatively low, such corrosion mitigation techniques will be beneficial only if the corrosion rate is reduced for a significant duration of time.

## PURPOSE AND SCOPE

The purpose of this study was to evaluate the effectiveness of two corrosion inhibitors using two methods of application to determine if either inhibitor could be applied in a manner that would effectively decrease the rate of corrosion in concrete bridge decks.

The two corrosion inhibitors evaluated were TPS-II and FerroGard 903. The two methods evaluated for treating an exposed concrete surface and mitigating corrosion were the unassisted (topical application) and assisted (vacuum/pressure injection) treatment methods. Both field and laboratory components were included in this study, with the laboratory study being initiated after TPS-II had been topically applied to a bridge deck in Virginia. Therefore, the project was divided into two parts, which included a limited field study of the effectiveness of one of the inhibitors and application methods for a bridge deck and a laboratory study of the two inhibitors and application methods.

## METHODS

The initial focus was to evaluate the ability of TPS-II to mitigate corrosion after being topically applied to a bridge in Orange County, Virginia. However, early results cast doubt on the ability of the inhibitor to penetrate into the concrete, so the focus was broadened and a laboratory component was added. Therefore, the inhibitors and application methods were evaluated in two tasks:

1. *Field study.* During this phase of the study, the tasks included identifying a bridge deck for treatment, applying the treatment, and then evaluating the treatment. To accomplish these tasks, changes in regional temperature, the area of delamination, the resistance to chloride ion penetration, half-cell potential, corrosion rate, and the concentration of water-soluble chlorides were evaluated before and after treatment. In addition, the treated and an untreated control span were compared.
2. *Laboratory study.* The tasks performed during this phase included casting concrete specimens, determining when the specimens were ready for treatment, applying the different treatments, and monitoring these specimens following treatment. To accomplish these tasks, slump, percent air, and average compressive strength were measured and changes in regional temperature, half-cell potential, concrete resistance, and macro-cell current were recorded before and after treatment. Treated and untreated control specimens were also compared.

### Field Study: The Terry Run Bridge

To evaluate candidate structures and recommend a corrosion-inhibiting product, a representative from Surtreat International performed a visual inspection and made delamination and corrosion rate measurements of selected bridges. Based on this information, the Surtreat representative selected a reinforced concrete bridge deck on Route 629 in a rural part of Orange

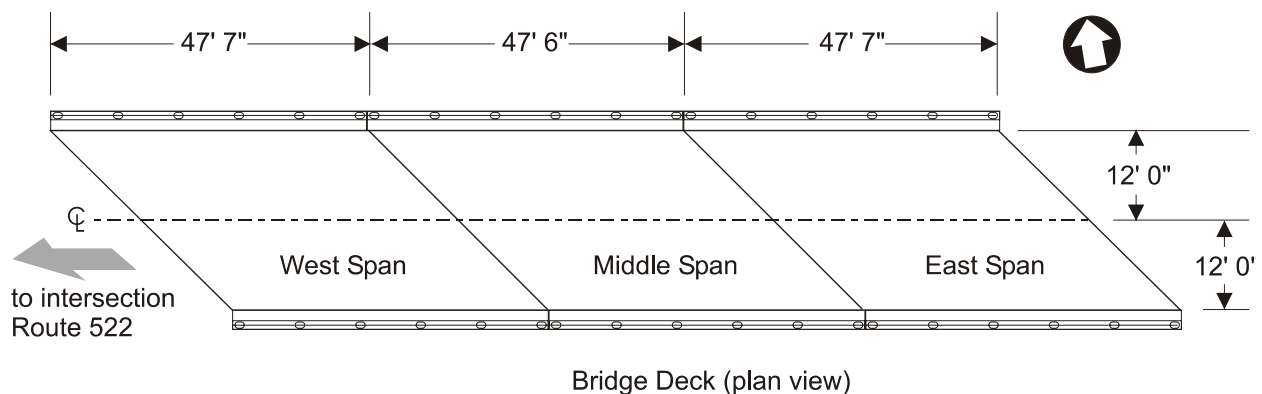
County, Virginia (Bridge 0629-068-6114). The bridge crosses the Terry Run stream. For this structure, the recommended treatment was Surtreat's proprietary corrosion inhibitor: TPS-II. TPS-II is a water-based solution designed to inhibit corrosion through the surface application of this proprietary corrosion inhibitor.

The Surtreat representative indicated that the TPS-II formulation contained chemically reactive water-soluble silicates that act as an anodic inhibitor upon reaching the surface of the reinforcing steel. Based on Surtreat's experience with this product, the representative suggested that the capillary porosity would change within a period of days, whereas the inhibitor would penetrate 2 inches of concrete cover in approximately 60 days. Therefore, it was expected that multiple measurements over a series of months would be required to see changes associated with the application of this product.

On September 17, 2002, TPS-II was applied to the bridge deck surface. The bridge has three simple spans, each 48 feet in length. The west and middle spans were the most similar based on initial delamination, half-cell, and corrosion rate measurements. Therefore, the east and west spans were treated with TPS-II and the middle span was left untreated as a control. Figure 1 is a plan view illustration of the selected bridge deck.

This corrosion mitigation technique involved applying inhibitor to the bridge deck and allowing sufficient time for the inhibitor to diffuse into the concrete before permitting traffic to resume travel in the treated lane. To allow for the movement of traffic across the bridge during the treatment process, one lane was treated at a time instead of the entire span. The application process was as follows (see Figure 2).

1. The bridge deck was cleared of debris and blown clean with compressed air.
2. Product was applied using a compression sprayer until the treated area appeared wet; if too much inhibitor was applied, the area became slippery.
3. A broom was used to distribute the product across the deck surface and work the product into the concrete.



**Figure 1. Plan View Illustration of Terry Run Bridge.**



**Figure 2. Application of TPS-II. (a) Bridge deck surface cleaned. (b) Inhibitor applied to surface. (c) Broom used to distribute product across surface. (d) Treated surface kept moist through periodic applications of water. (e) After a second treatment cycle, water used to rinse residue off treated surface. (f) Treatment complete.**

4. The surface was kept moist for 2 hours through repeated applications of water as the inhibitor soaked into the concrete.
5. Repeating steps 2 through 4, a second application was applied before the previously treated area dried. According to Surtreat, future applications of TPS-II could be problematic due to changes in the porosity).
6. The bridge was rinsed with water to remove any residue.

During this phase of the study, the initial measurements and control span were used to assess the ability of TPS-II to reduce the corrosion rate. Measurements were made before and following treatment in accordance with the appropriate standard.<sup>15-18</sup> Measurements included half-cell potential (versus copper-copper sulfate reference electrode [CSE]), corrosion rate (by measuring the polarization resistance), and degree of delamination.

Measurements were made on the resistance of the concrete to chloride ion penetration in accordance with ASTM C 1202.<sup>19</sup> During the bridge evaluation, tests were performed prior to treatment, after 28 days, and after 190 days. Each time, testing was performed on three cores

from each span, with each span having cores extracted from three locations: adjacent to the parapet, along the wheel path, and in the center of the bridge.

In addition, changes in the water-soluble chloride concentrations were evaluated in accordance with AASHTO T-260.<sup>15</sup> Six locations were sampled on each span, three near the wheel path and three near the middle of the travel lane, with sample depths from ½ up to 1 inch, from 1 up to 1½ inches, and from 1½ to 2 inches from the surface of the concrete. The average depth of cover in this bridge deck was 2 inches. Samples were collected before treatment and 1 and 6 months after treatment.

### Laboratory Study: Reinforced Concrete Specimens

To reduce variability among the reinforcing steel specimens, all of the steel used to construct the reinforced concrete specimens was from the same heat of steel. The reinforcing steel was a Grade 60, No. 5 bar. The chemical and physical test results for the steel (ASTM A615) are listed in Tables 1 and 2.<sup>20</sup>

Two configurations of reinforced concrete specimens with sodium chloride admixed (approximately 15 lb/yd<sup>3</sup> NaCl) into the top half of the specimen were cast to evaluate the influence of the corrosion inhibitor on the upper and lower reinforcing steel bars. ASTM G-109 functioned as a guide in designing the reinforcing steel specimens, as well as during their casting and evaluation.<sup>21</sup> Since this technology is designed for older structures, the test blocks had a water to cement ratio of 0.47, with the mix design based on the 1970 VDOT specifications.<sup>22</sup> The mix design is shown in Table 3. After initial data were gathered, the test specimens were treated with TPS-II or FerroGard 903 (Sika Corp.) using either a roller (topical application) or vacuum/pressure injection, which is shown in Figure 3. The vacuum/pressure injection device was a flat plate divided into two zones, an outer zone that circles an inner zone. The outer zone kept the plate held to the concrete while the inhibitor was injected through the inner zone region. The operating sequence used during vacuum/pressure injection was as follows:

**Table 1. Chemical Composition (wt%) of Reinforcing Steel**

<b>C</b>	<b>Mn</b>	<b>P</b>	<b>S</b>	<b>V</b>	<b>Si</b>	<b>Cr</b>	<b>Cu</b>	<b>Ni</b>	<b>Sn</b>	<b>Mo</b>
0.33	0.73	0.023	0.041	0.003	0.17	0.27	0.45	0.11	0.006	0.017

**Table 2. Results of Physical Tests**

<b>Test</b>	<b>Reported Values</b>
Yield point	95,700 psi (659.83 MPa)
Tensile strength	114,100 psi (786.69 MPa)
% Elongation in 8 in	12.5
Bend	Ok
Average deformation height	0.036 in (0.91 mm)
% Light/heavy	4.0 L



**Table 3. Mix Design**

<b>Materials</b>	<b>Quantity/yd<sup>3</sup></b>
Cement, lb (Lehigh Type I/II)	681.5
Stone, lb *	1869
Sand, lb	982
Water, gal	38.4
Air entrainment, oz <sup>†</sup>	5.3
Set retarder, oz <sup>†</sup>	20
NaCl, lb	15

\*Virginia Department of Highways – 57 (3/4 inch) 100% passing 1-inch.

<sup>†</sup>Based on manufacturer/s recommendations.



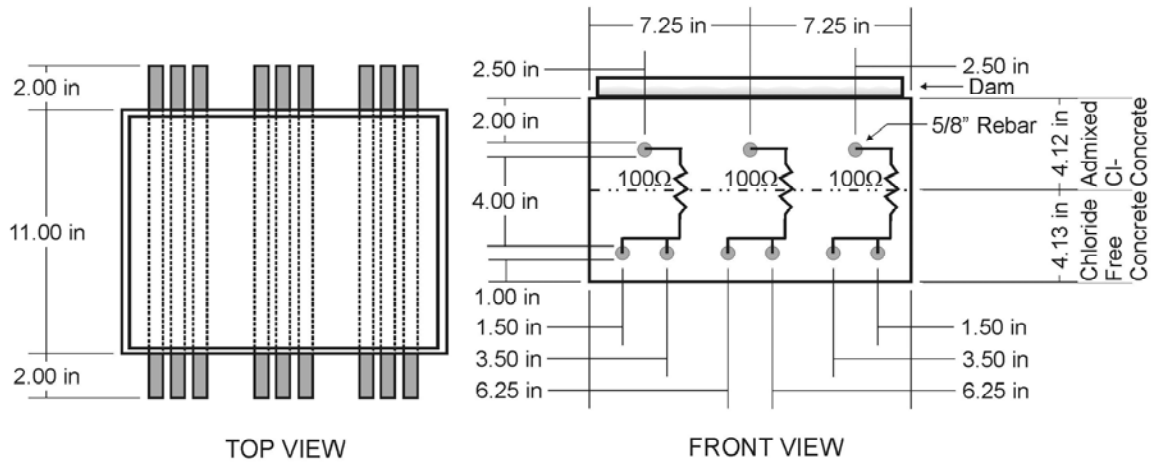
**Figure 3. (a) Inhibitor applied using roller. (b) Inhibitor applied using vacuum/pressure injection.**

1. The two-zone plate is placed on the concrete surface.
2. A vacuum (20 mm Hg) is drawn on the inner and outer zones.
3. The vacuum on the inner zone draws in the inhibitor (such that it is no longer a vacuum).
4. Pressure (22 psi) is forced into the inner zone, which drives the inhibitor into the concrete.

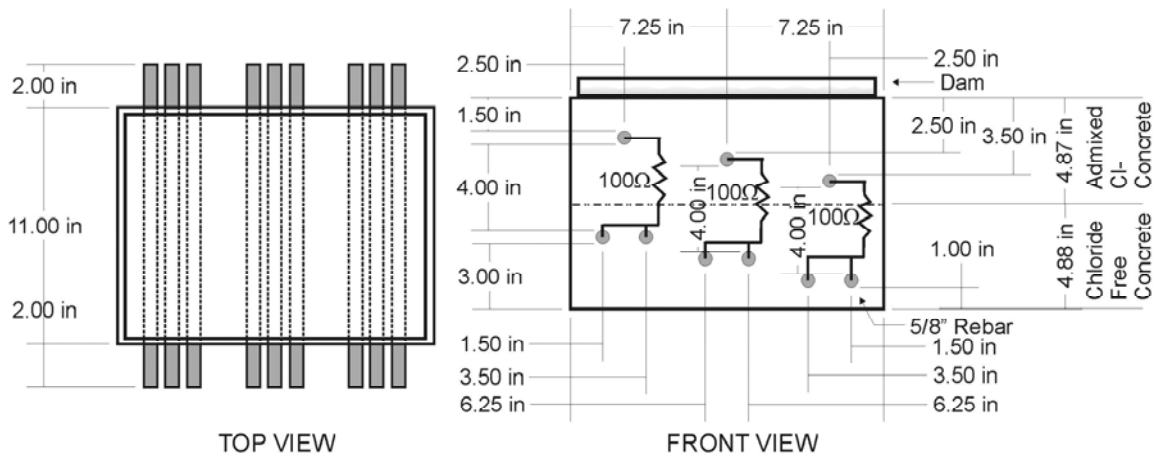
The pressure and vacuum are released, and the injection process is complete. To aid in evaluating the inhibitors, approximately 200 days after treatment, test specimens were ponded with a saturated sodium chloride solution. In addition, compatibility issues between the vacuum/pressure injection system and the FerroGard 903 led to fewer specimens being tested than originally intended. Table 4 lists the specimen and inhibitor type, method of application, amount of inhibitor applied, and the actual number of specimens tested. Illustrations of the test specimens are shown in Figures 4 and 5.

**Table 4. Description of Reinforced Concrete Test Blocks**

Specimen Type	Inhibitor Type	Method of Application	Inhibitor Dose (gal/ft <sup>2</sup> )	No. of Blocks Tested
Uniform	None (Control)	N/A	N/A	3
Uniform	FerroGard 903	Topical	0.01	3
Uniform	TPS-II	Topical	0.01	3
Uniform	TPS-II	Vacuum/pressure injection	0.03	1
Uniform	TPS-II	Vacuum/pressure injection	0.05	1
Uniform	TPS-II	Vacuum/pressure injection	0.10	1
Inclined	None (Control)	N/A	N/A	3
Inclined	FerroGard 903	Vacuum/pressure injection	0.10	2
Inclined	TPS-II	Vacuum/pressure injection	0.04	1
Inclined	TPS-II	Vacuum/pressure injection	0.05	1
Inclined	TPS-II	Vacuum/pressure injection	0.10	1



**Figure 4. Illustration of Concrete Specimen with Uniform Cover Depth (modified ASTM G-109 specimen).**



**Figure 5. Illustration of Concrete Specimen with Inclined Cover Depth (modified ASTM G-109).**

Measurements were made twice before treatment (laboratory specimens were treated on the 15<sup>th</sup> day in the following figures) and then routinely following treatment. In addition, to aid in evaluating the inhibitors and application methods, uniform and inclined cover depth control specimens were cast. The data from the different specimens were used to establish the ability of the inhibitors and method of application to reduce the corrosion rate. Measurements included half-cell potential, concrete resistance, and macro-cell current. Potential measurements were made using a saturated CSE. Concrete resistance was monitored using a two-point configuration, with measurements being made between the surface of the concrete and the upper reinforcing steel bar. Macro-cell current measurements were made across a 100-ohm resistor; these values were then integrated with respect to time to estimate the total charge passed.

## RESULTS

### Field Study: The Terry Run Bridge

#### Regional Temperature

In this region, seasonal changes in the weather influence the values measured using half-cells and the amount of chlorides to which a bridge is exposed because of the use of deicing salts during the colder months. Therefore, the middle span was designated a control span. Figure 6 shows the change in temperature recorded during this study for this region, which was gathered from the National Climatic Data Center (NCDC), Piedmont Research Station. This weather station is approximately 8 miles from the structure.

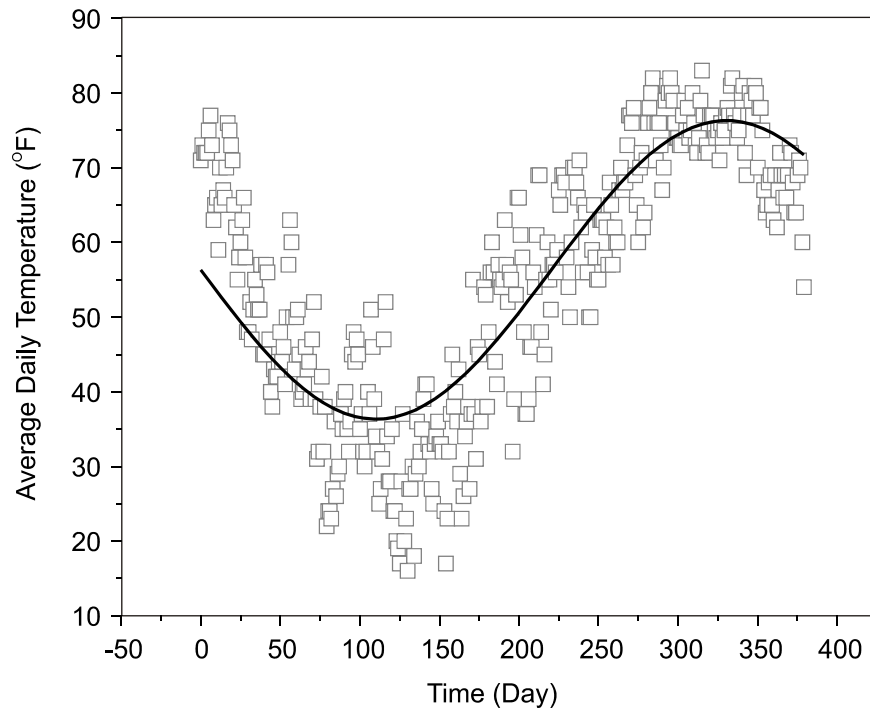


Figure 6. NCDC Reported Regional Temperature for Bridge.

## Delamination

Figure 7 shows the delamination percentage for each span following treatment. Throughout the evaluation period, the percentage of delamination increased in the west and control spans, whereas the percentage of delaminated area in the east span increased very little.

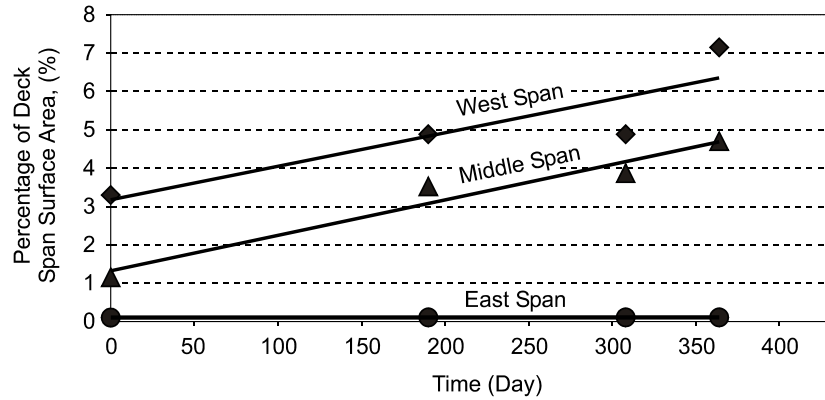


Figure 7. Delamination Percentage of Bridge Spans.

## Resistance to Chloride Ion Penetration

As shown in Figure 8, overall, an average change in resistance to chloride ion penetration did not occur. All three spans exhibited moderate chloride ion penetrability before and after treatment. It is interesting to note that in Figure 8, the east span initially becomes less resistive and then decreases to its untreated value whereas the west span does the opposite.

The charge passed through each core and the location of the core are given in Table 5. All but three measurements indicated a moderate to high chloride ion penetrability. In addition, two of the three measurements that did not fall in this category were made on cores that were extracted before the western and eastern spans were treated.

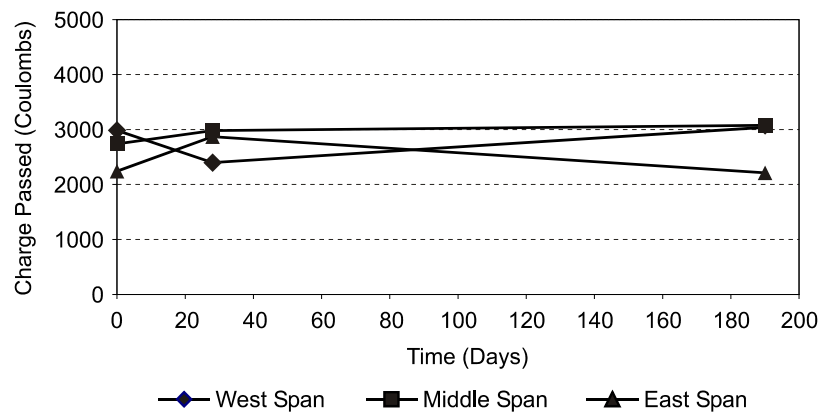


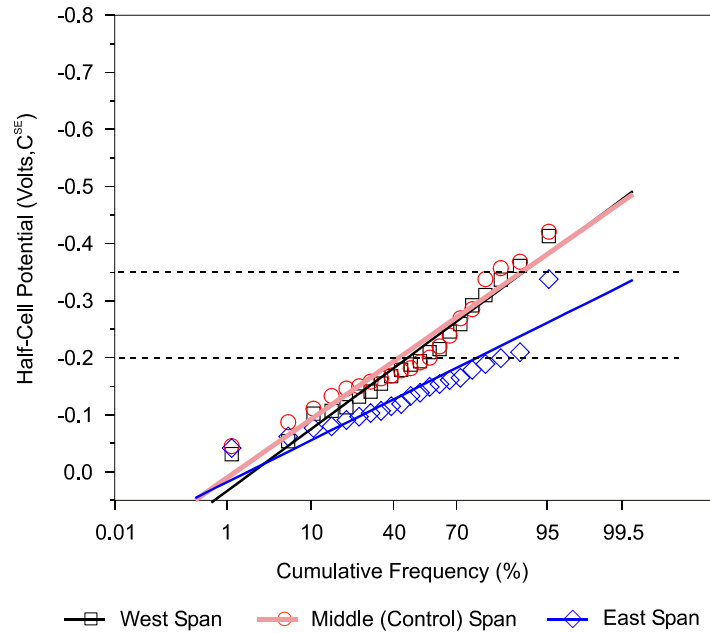
Figure 8. Average Charge Passed Based on Measurements Adjacent to Parapet, Along Wheel Path, and Along Centerline of Bridge Deck.

**Table 5. Charge Passed (coulombs)**

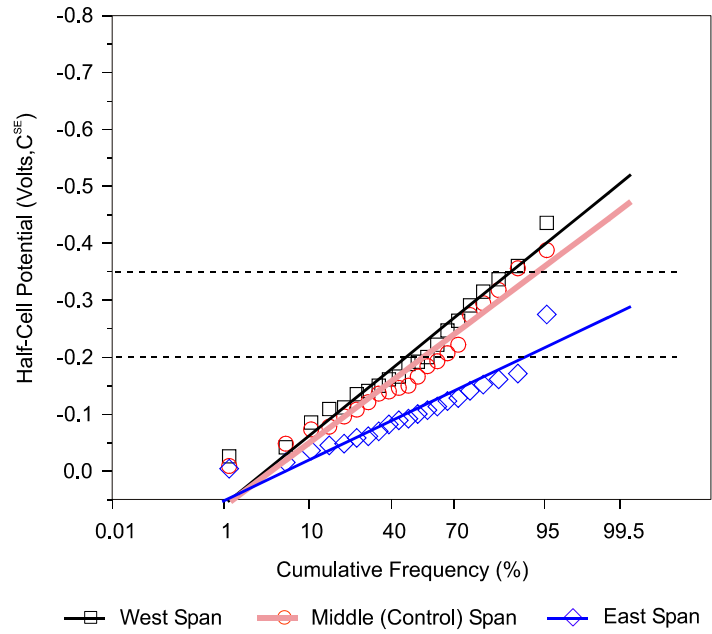
Location	Western Span			Middle (Control) Span			East Span		
Time, days	Adjacent to Parapet	Wheel Path	Center Line	Adjacent to Parapet	Wheel Path	Center Line	Adjacent to Parapet	Wheel Path	Center Line
0 (before treatment)	3169	2816	2972	4039	2262	1912	2491	2460	1777
28	3213	2033	1943	3458	2366	3121	3808	2107	2700
190	3564	3550	2003	4495	2167	2565	2106	2104	2435

### Half-Cell Potentials

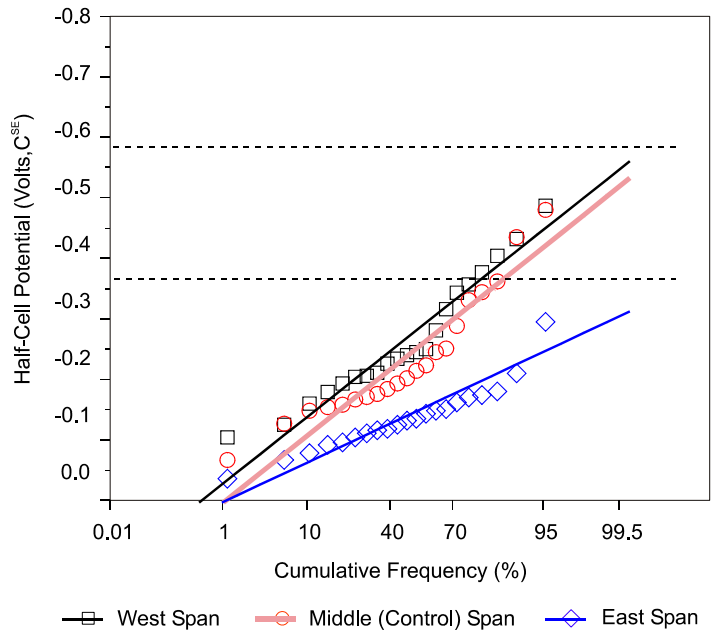
The cumulative frequency plots shown in Figures 9 through 12 indicate how the treated spans changed in relation to the untreated span. It is apparent that during the evaluation period the half-cell potential distribution in the east span (treated) was more positive than the potential in either of the other two spans. It is also apparent that the distribution of half-cell measurements was either the same or more negative for the west span (treated) when compared to the control span (untreated).



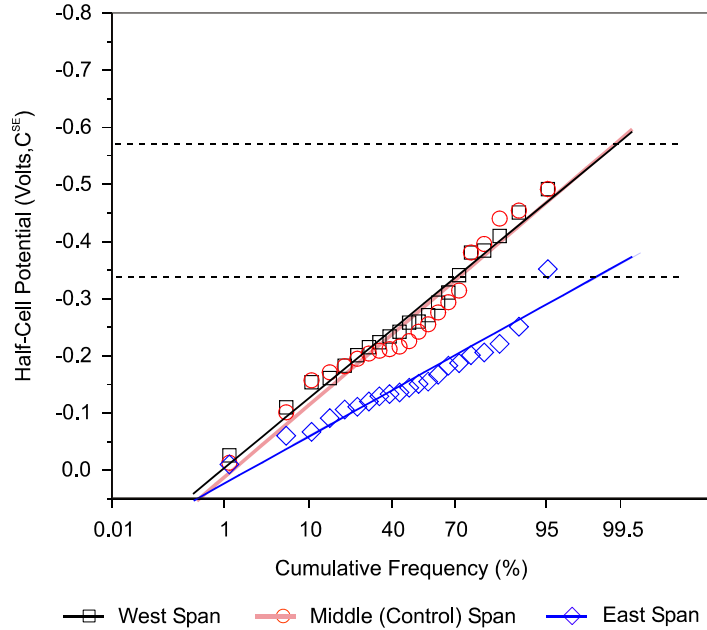
**Figure 9. Comparison of Cumulative Frequency Plots for Spans Before Treatment.**



**Figure 10. Comparison of Cumulative Frequency Plots for Treated and Control Spans After 1 Month.**



**Figure 11. Comparison of Cumulative Frequency Plots for Treated and Control Spans After 6 Months.**



**Figure 12. Comparison of Cumulative Frequency Plots for Treated and Control Spans After 1 year.**

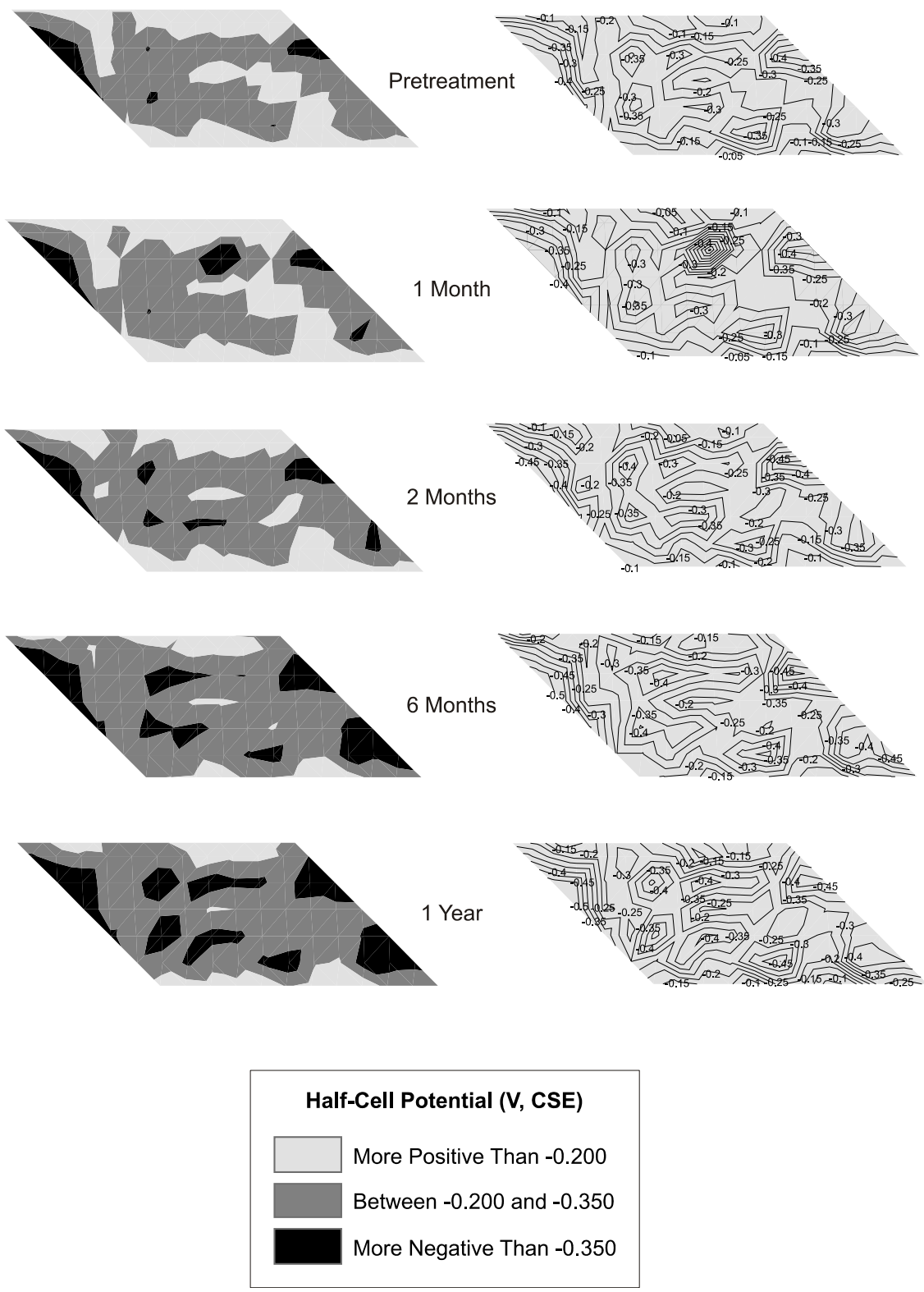
Half-cell potential maps were also generated for all three spans. The west span is shown in Figure 13, the control span in Figure 14, and the east span in Figure 15. As was evident in the half-cell potential vs. cumulative frequency plots, the probability of corrosion within the structure was not reduced by the surface application of the inhibitor. In Figures 13 through 15, the regions in all three spans with values more negative than  $-0.350$  V vs. CSE increased in area during the year following treatment.

### Corrosion Rate

Figure 16 provides a summary of the average corrosion rate after treating the western and eastern spans of the bridge with the TPS-II. The west span was associated with the largest corrosion rate before the inhibitor was applied and 1 year after treatment. The 6- and 10-month measurements increased only slightly from the pretreatment measurements. It is interesting that the west span did not follow the same trend as did the control and east spans: corrosion activity increased, was the highest (average) at 10 months, and then began to decrease. As was indicated in Figure 6, the measurements at 10 months were made when the average daily temperatures are hottest in this region.

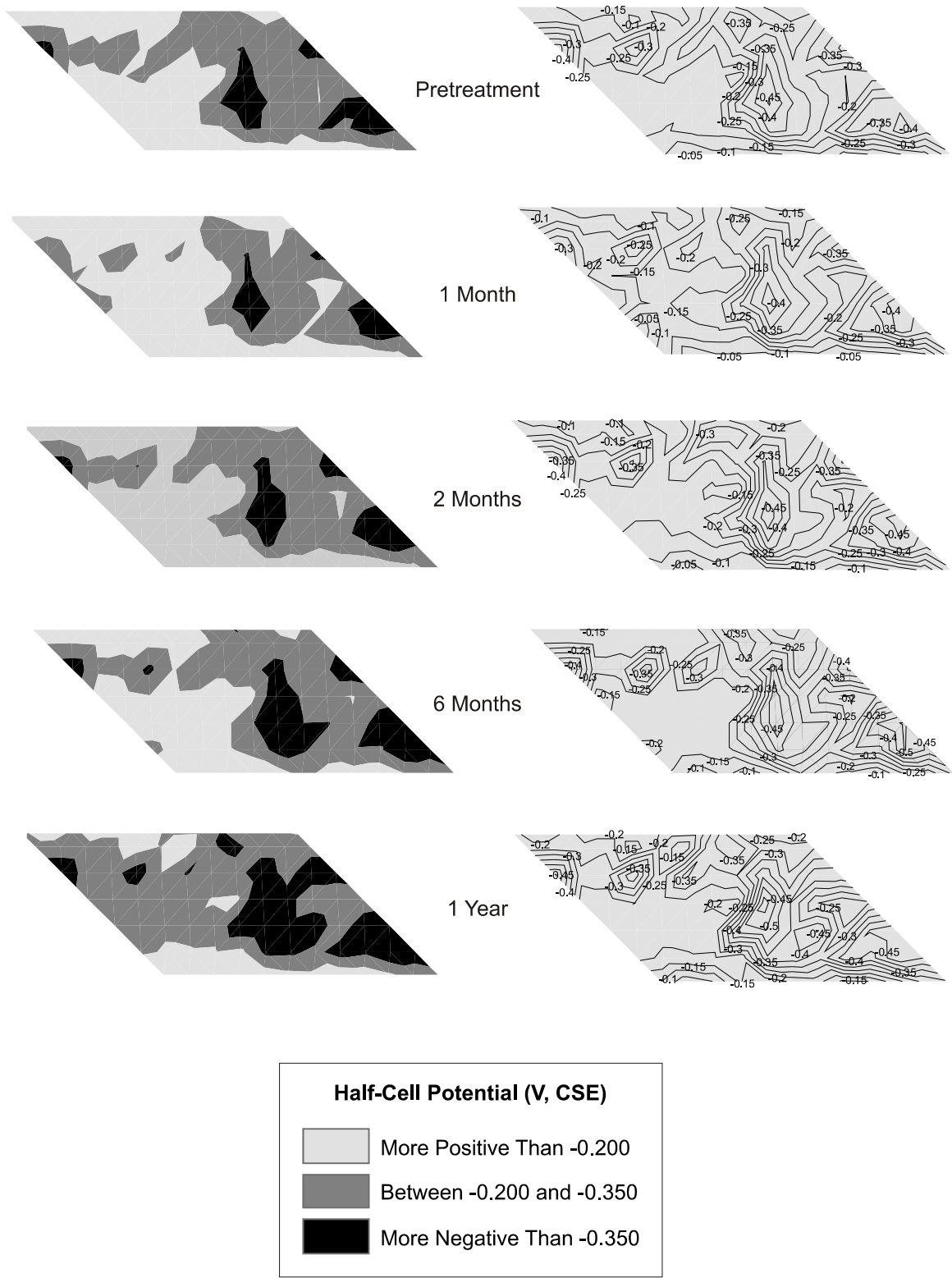
### Chloride Concentration

As is evident in Figure 17, the water-soluble chloride concentration was highest for the west span at each depth when compared with those for the other spans. The east span had the lowest chloride concentration near the reinforcing steel. The chloride concentrations in the western and eastern spans support the nondestructive potential and corrosion measurements, which indicate high corrosion activity in the west span and relatively lower activity in the east span. A clear trend that could be associated with the treatment of the bridge deck was not evident.

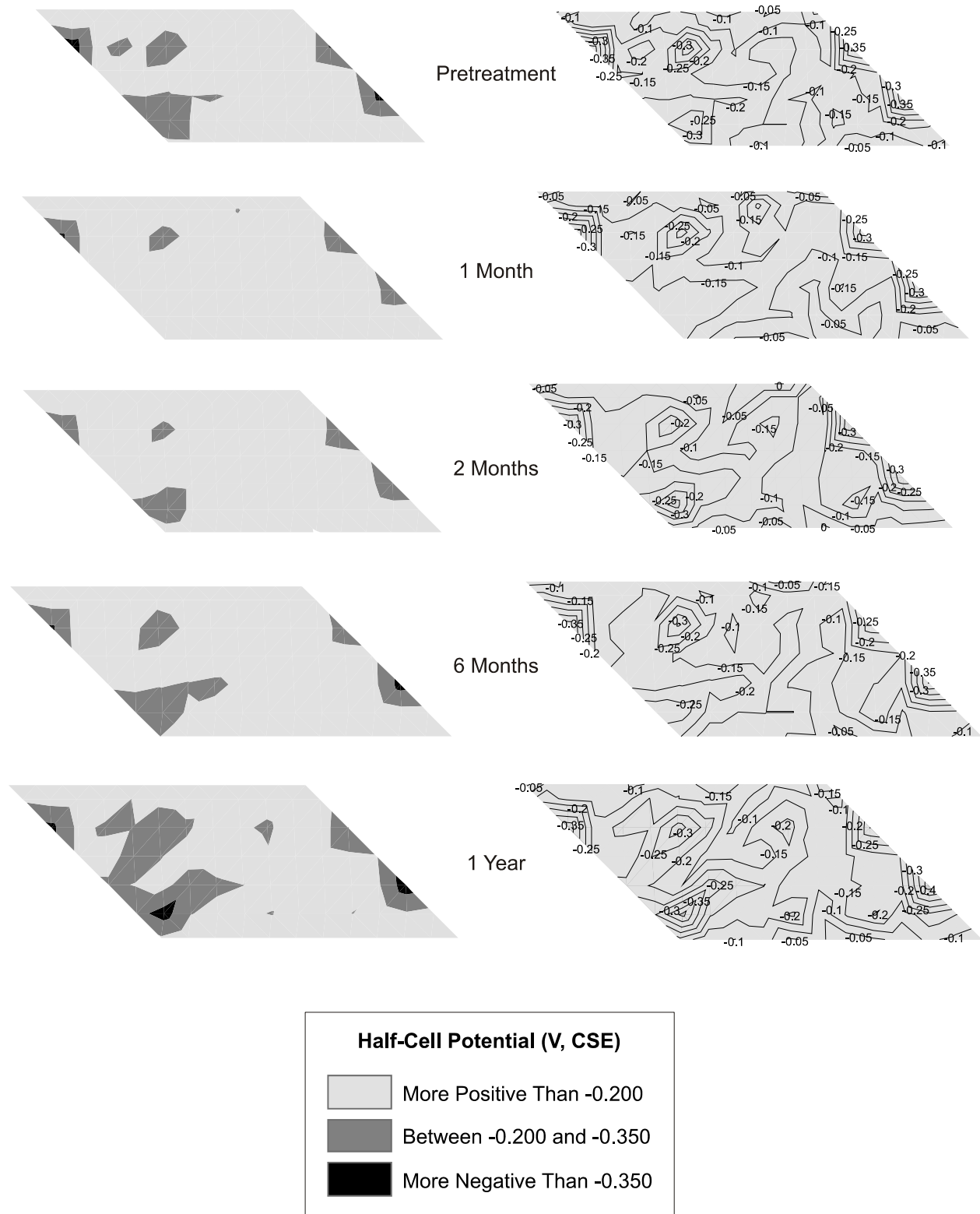


**Figure 13. Influence of TPS-II on West Span Half-Cell Potential Measurements During First Year Following Treatment.**

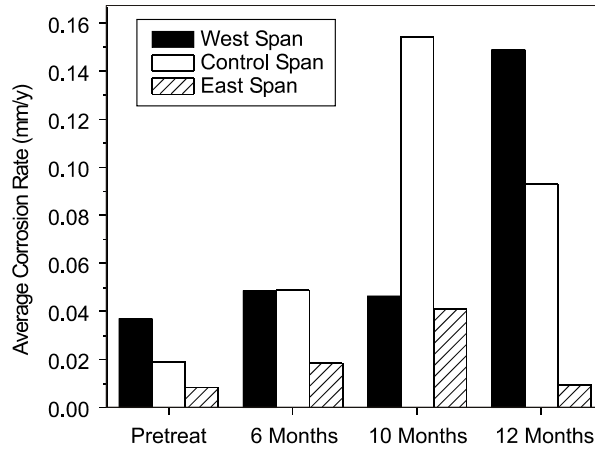




**Figure 14. Middle (Control) Span Half-Cell Potential Measurements During First Year Following Treatment.**



**Figure 15. Influence of TPS-II on East Span Half-Cell Potential Measurements During First Year Following Treatment.**



**Figure 16. Average Corrosion Rate for Bridge Following Treatment.**

### Laboratory Study: Reinforced Concrete Specimens

Initially, tests were performed to ensure that the physical properties of these specimens were similar to those found in actual bridge decks constructed in accordance with VDOT specifications. It was determined that the slump measurements for both batches of concrete were greater than the range provided in the specifications. Measured values of the percentage of air entrained and the compressive strengths, however, were acceptable. The measured values and the VDOT specifications are listed in Table 6.

**Table 6 . Concrete Specimen Test Results**

Result	NaCl Admixed Concrete	Chloride-Free Concrete	1970 VDOT Specification	Applicable Standard
Slump, in	5.25	4.25	2-4	ASTM C 143
Air entrained, %	5.3	5.2	6.5 ± 1.5	ASTM C 231
Average 28-day compressive strength, psi	4320	4850	4000	ASTM C 39

### Regional Temperature

The laboratory specimens were outside in a region that undergoes seasonal fluctuations in temperature. In general, the hottest period is during the summer months and coldest during the winter. Figure 18 shows the change in temperature recorded during this study for this region, which was gathered from NCDC, Monticello Station. This weather station is approximately 7 miles from the laboratory specimens.

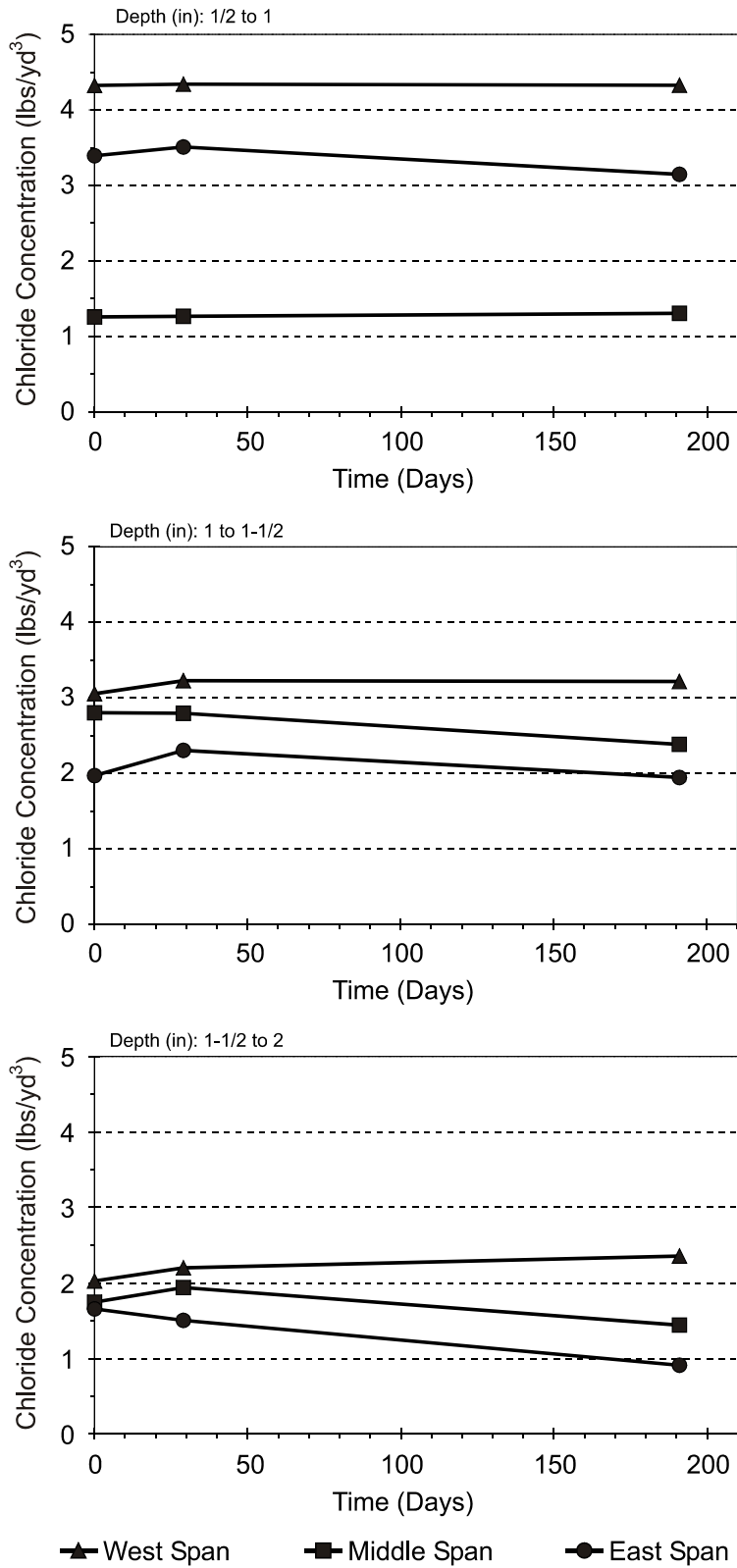


Figure 17. Average Water-Soluble Chloride Concentration at Different Sample Depths.

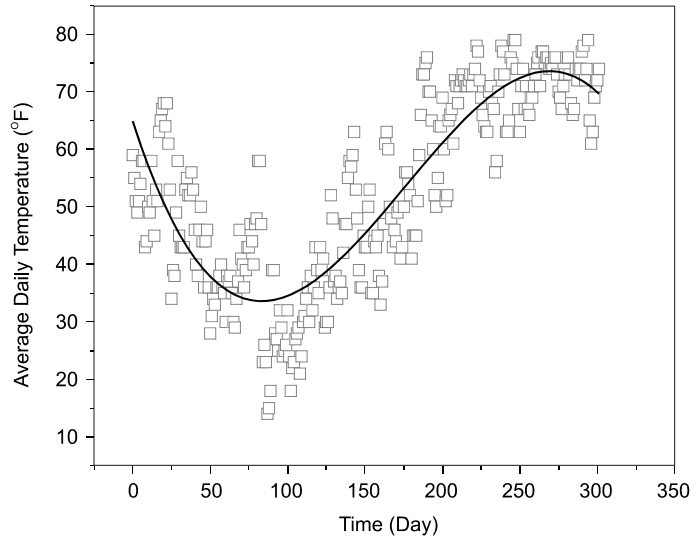


Figure 18. NCDC Reported Regional Temperature for Laboratory Specimens.

### Half-Cell Potentials

Potential measurements on the uniform specimens indicated that the surface application of these inhibitors did not independently influence the half-cell potentials. As shown in Figure 19, the measured potentials in the samples treated with the surface-applied inhibitor followed the same trend as did the control specimens. In Figure 20, it can be seen that the response of the control and the FerroGard 903 specimens was so similar that the linear fit lines for these data overlay each other. The TPS-II data, however, did vary slightly from those of the control specimen, which resulted in a change in slope of the linear fit line. However, this change did not shift toward a more positive or negative potential but instead was more of a rotation around the center of the graph. This indicates that some of the potential readings became more positive while others became more negative. This can be seen in Figure 19, with the TPS-II specimens having the most positive potential within the first 100 days but then having the most negative during the latter part of this study.

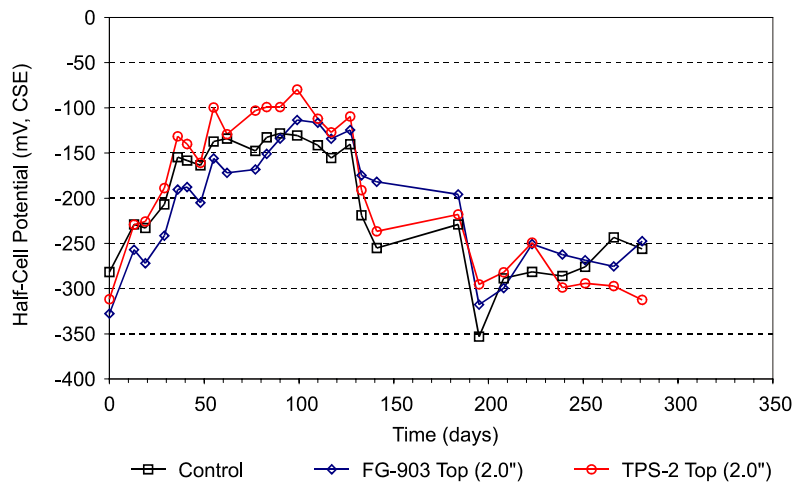
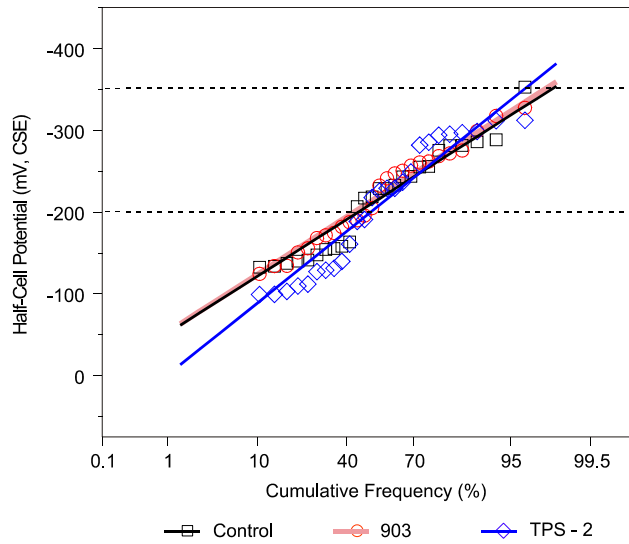
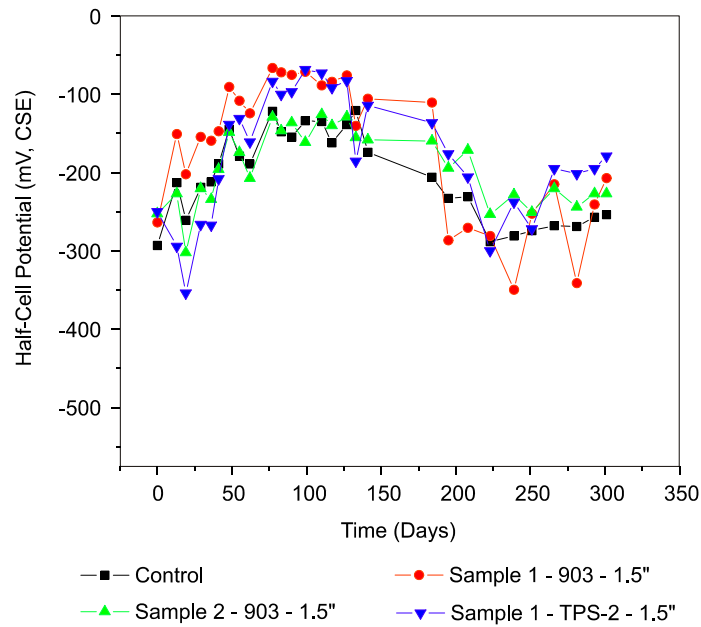


Figure 19. Half-Cell Potential of Specimens With 2-Inch Uniform Cover.

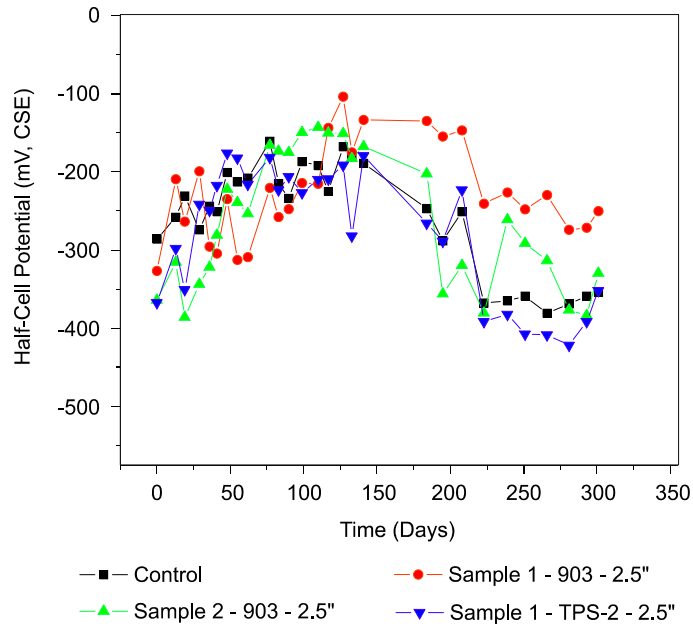


**Figure 20. Cumulative Frequency of Half-Cell Potentials for Group of Uniform Specimens Treated Topically.**

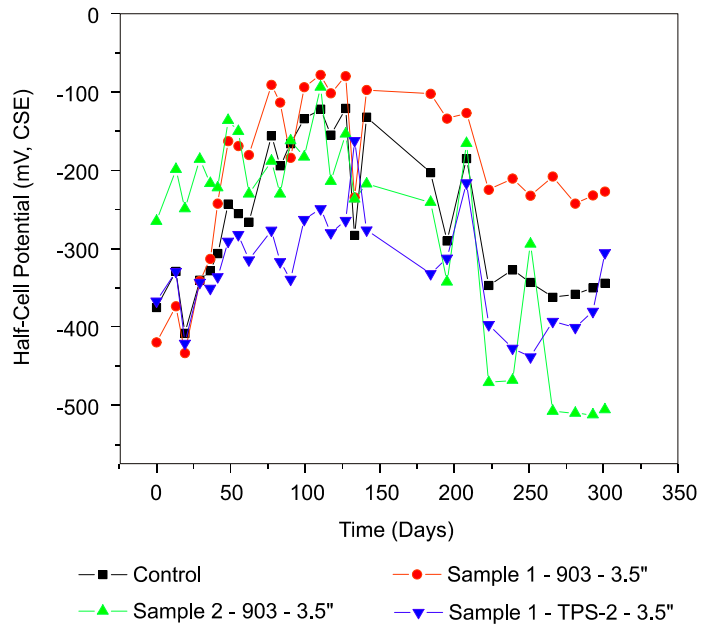
By placing bars at various depths, it was possible to evaluate the ability of the inhibitor to influence the potential of the steel after vacuum/pressure injection. In Figures 21 through 23, a couple of trends are evident for the three different cover depths. First, all treated specimens followed the pattern shown by the control specimens: initially increasing, reaching a plateau, decreasing, then beginning to increase again. There is also not a clear separation between the potential measurements for the control and the treated specimens.



**Figure 21. Influence on Half-Cell Potential of Vacuum/Pressure Injection With Cover Depth of 1.5 Inches.**



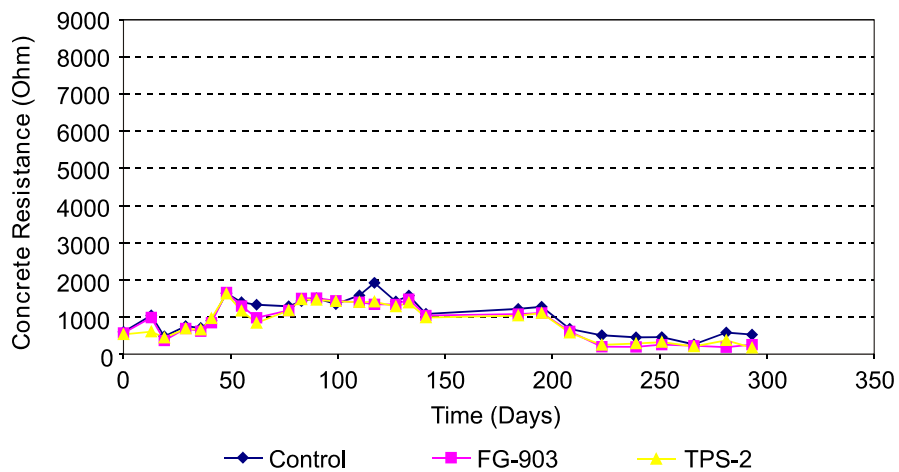
**Figure 22. Influence on Half-Cell Potential of Vacuum/Pressure Injection With Cover Depth of 2.5 Inches.**



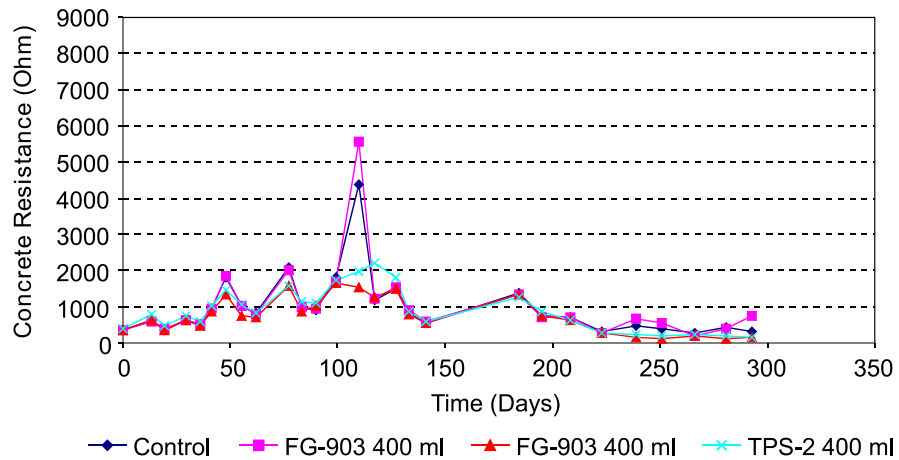
**Figure 23. Influence on Half-Cell Potential of Vacuum/Pressure Injection With Cover Depth of 3.5 Inches.**

## Concrete Resistance

Upon examining the concrete resistance following treatment, it is clear from Figure 24 that applying the inhibitor to the surface of the concrete does not increase the resistance of the concrete above that of the control specimens. During the entire duration these specimens were monitored, the resistance in the treated specimens remained equal to or less than that of the untreated specimens. In Figures 25 through 27, the data points for the treated specimens when vacuum/pressure injection was used generally did not deviate far from the line for the control specimen. In addition, the data at the one point in these three figures (day 110) where a spike occurs consistently were gathered during the coldest part of the year.

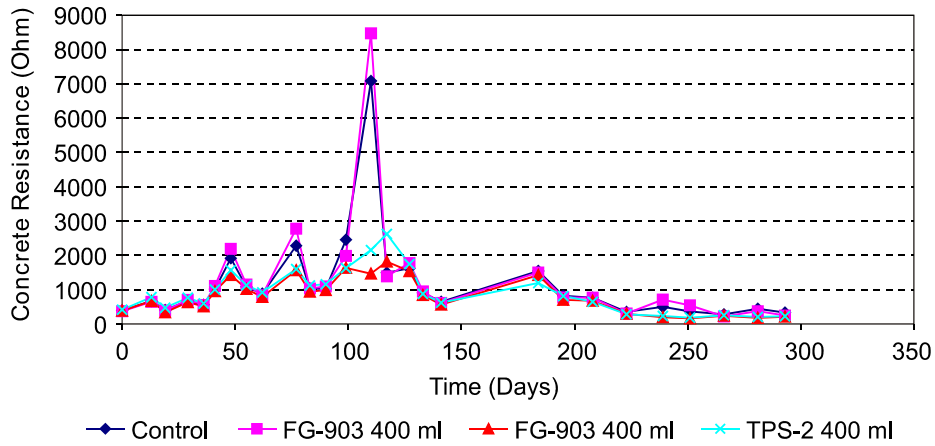


**Figure 24. Effect on Concrete Resistance of Surface Application Following Treatment.**

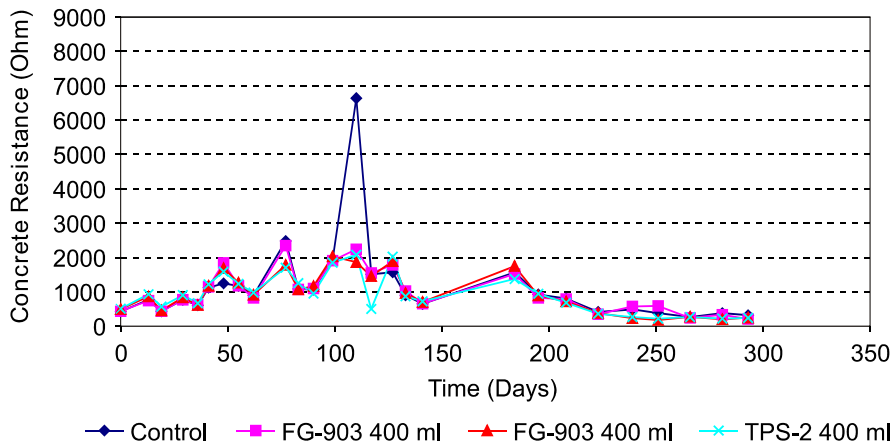


**Figure 25. Effect on Concrete Resistance of Vacuum /Pressure injection of inhibitor (400 ml) with 1.5-inch Cover Depth.**





**Figure 26. Effect on Concrete Resistance of Vacuum /Pressure injection of inhibitor (400 ml) with 2.5-inch Cover Depth.**



**Figure 27. Effect on Concrete Resistance of Vacuum /Pressure injection of inhibitor (400 ml) with 3.5-inch Cover Depth.**

### Macro-Cell Current

Macro-cell currents were measured to enable the calculation of the charge passed, which is given in Table 7. For the specimens treated by applying the inhibitor to the surface of the concrete and allowing it to diffuse in, the charge passed was greater for the treated specimens than for the control specimens. However, the majority of the specimens treated with the vacuum/pressure injection showed lower quantities of charge passed when compared to the control specimens. The exceptions are highlighted in bold in Table 7.

Table 7. Charge Passed

Specimen Type	Cover Depth, in	Inhibitor	Application	Amount of Inhibitor Applied, ml	Charge Passed, C
Uniform cover (Figure 4)	2.0	Control	T	N/A	247
	2.0	903	T	40	357
	2.0	TPS-II	T	40	353
	2.0	TPS-II	V/P	100	101
	<b>2.0</b>	<b>TPS-II</b>	<b>V/P</b>	<b>200</b>	<b>263</b>
	2.0	TPS-II	V/P	400	224
Inclined cover (Figure 5)	1.5	Control	N/A	N/A	195
	1.5	903	V/P	400	129
	1.5	903	V/P	400	88
	1.5	TPS-II	V/P	150	48
	<b>1.5</b>	<b>TPS-II</b>	<b>V/P</b>	<b>200</b>	<b>241</b>
	<b>1.5</b>	<b>TPS-II</b>	<b>V/P</b>	<b>400</b>	<b>233</b>
	2.5	Control	N/A	N/A	890
	2.5	903	V/P	400	314
	2.5	903	V/P	400	583
	2.5	TPS-II	V/P	150	110
	2.5	TPS-II	V/P	200	221
	2.5	TPS-II	V/P	400	633
	3.5	Control	N/A	N/A	884
	3.5	903	V/P	400	464
	<b>3.5</b>	<b>903</b>	<b>V/P</b>	<b>400</b>	<b>1287</b>
	3.5	TPS-II	V/P	150	298
	3.5	TPS-II	V/P	200	615
	<b>3.5</b>	<b>TPS-II</b>	<b>V/P</b>	<b>400</b>	<b>1034</b>

T = topical; V/P = vacuum/pressure.

## DISCUSSION

### Surface Application of Migratory Inhibitors

Half-cell potential measurements indicated that applying the corrosion inhibitor to the surface of the concrete and allowing it time to migrate did not significantly alter the potential of the steel. This was evident in both the reinforced concrete specimens cast for this study and the bridge deck evaluated. Comparisons of the half-cell measurements with those of the control specimens indicated that the response of the FerroGard 903 and TPS-II was similar to that of the controls.

Since care must be taken when evaluating potential measurement because of the sensitivity of the corrosion potential to the type of inhibitor used, the reinforced concrete test specimens were also designed for making macro-cell measurements.<sup>23, 24</sup> After calculating the charge passed and comparing the treated and untreated specimens, not only was applying the inhibitor to the surface and relying on its ability to migrate into the concrete ineffective but the charge that passed through the treated specimens was 150 percent of that of the control.

Corrosion rate data from the bridge also supported the findings from the macro-cell measurements. Although the western span did not necessarily follow the same trend as the control span, the corrosion rate did increase from the average initial pretreatment value. More important, the average corrosion rate in the eastern span and the control span followed the same trend. Therefore, the ability to apply the TPS-II to the surface and have it migrate to the reinforcing steel unaided was not demonstrated.

Finally, the TPS-II did not appear to alter the concrete or the water-soluble chlorides within the concrete. The concrete resistance did not change following the application of either inhibitor to the surface of the test specimens. The treated specimens maintained similar or lower resistance following treatment when compared to the control specimens. In addition, analysis of cores from the bridge indicated that a change in the resistance to chloride ion penetration was not evident following treatment with TPS-II. Moreover, measurements of the water-soluble chloride concentration did not indicate a reduction, even though the first measurement after treating the bridge were made before the first winter storm necessitated the use of deicing salts on the roads.

### **Vacuum/Pressure Injection of Migratory Inhibitors**

The same trend in potential measurements when the inhibitors were applied to the surface and allowed to migrate in was observed when vacuum/pressure injection was used to apply the inhibitors. Variations in the type of inhibitor used or the depth of cover did not appear to alter the response of the inhibitors when compared to the control specimens.

Again, similar to the surface-applied migratory inhibitors, macro-cell measurements were made on these specimens, but this time a significant number of specimens demonstrated lower quantities of charge passed when compared to the control specimens. Unfortunately, a clear trend between the estimated amount of inhibitor injected and the amount of charge passed was not evident.

Although vacuum/pressure injection might be useful for applying inhibitors, the process requires additional work. During the demonstration, two major weaknesses were evident with this method. First, it was sometimes difficult to create and/or maintain a vacuum on the test block because of leaks between the seal and the concrete. This was particularly disturbing since these test blocks were ideal in that they were smooth, which should facilitate achieving and maintaining a seal. Occasionally, the inhibitor was not injected but instead leaked from under the seals of the vacuum/pressure injection plate. Second, the equipment needed repair during the demonstration. The time required to repair the equipment hindered the treatment process. During this study, it resulted in fewer blocks being treated by pressure/vacuum injection, but in the field, such delays could equate to longer lane closure times and greater delays for the motorist.

### **FerroGard 903 vs. TPS-II**

As discussed previously, both inhibitors responded in a similar manner. Applying the inhibitors to the surface of a concrete specimen and relying on its ability to penetrate through the

concrete to the reinforcing steel proved ineffective in both cases. Introducing the inhibitor using vacuum/pressure injection, however, revealed the possibility that this method might offer benefits as a corrosion mitigation technique. According to the macro-cell measurements, when vacuum/pressure injection was used to apply the inhibitor, FerroGard 903 reduced the amount of charge passed 83 percent of the time when compared to the control specimen, and the TPS-II succeeded 67 percent of the time. Although these values for the FerroGard 903 and TPS-II indicate that the vacuum/pressure injection appears promising, the inability of this application method to operate consistently without failure must be addressed. Leaks during injection result in material loss, and with inhibitors, this is crucial since a sufficient concentration of inhibitor is required at the steel surface to reduce the rate of corrosion. Therefore, the concept of vacuum/pressure injection appears promising, but additional testing on other blocks with these inhibitors should be performed to validate these macro-cell values while also demonstrating that the method is reproducible.

### Cost

Cost savings were not calculated for the surface-applied inhibitors because it was not demonstrated that this approach provided any benefit. Vacuum/pressure injection, however, seems promising. Therefore, savings for VDOT might be realized using this technique, but before cost savings are calculated, it should be evaluated to determine if it damages or destroys a structure during the application process.

The Surtreat representative indicated that the cost to pressure/vacuum inject an inhibitor into a bridge deck is related to the size of the deck being treated, with the larger the deck area, the lower the per unit area cost. For example, the cost to treat a 2,000 ft<sup>2</sup> deck would be approximately \$4.00/ft<sup>2</sup>. However, to treat a 4,000 ft<sup>2</sup> deck, the cost decreases to \$3.50/ft<sup>2</sup>. These costs include materials, equipment, labor (for applying the inhibitor), overhead, and profit but not traffic control, utilities, and extraordinary surface preparation. These costs are based on the assumption that the deck is treated at a rate of 2 gal/100 ft<sup>2</sup>, with the cost divided 60/40 between materials and injection cost.

For the FerroGard 903 only material cost are reported because the same pressure/vacuum injection equipment was used to inject both inhibitors. According to the Sika representative, the cost of material for treating a 2,000 ft<sup>2</sup> deck is approximately \$0.85/ft<sup>2</sup>, whereas the cost decrease to \$0.65/ft<sup>2</sup> for a 4,000 ft<sup>2</sup>. These cost are based on the deck being treated at a rate of 1 gal/100 ft<sup>2</sup>, which is based on the manufactures recommendation that FerroGard 903 be applied in two coats at an application rate of 200 ft<sup>2</sup>/gal/coat.

Currently, one method for rehabilitating a bridge deck is to remove the contaminated concrete and place an overlay. The approximate cost associated with placing a 1 ½ in overlay is between \$4.40/ft<sup>2</sup> and \$5.00/ft<sup>2</sup>. This price is assuming the material is a latex-modified concrete or a silica fume overlay. In addition, both of these overlays would have an expectant life of approximately 18.5 years.<sup>1</sup> However, without knowing the additional life expectancy resulting from pressure/vacuum injecting either of these inhibitors, a fair comparison between the inhibitor opposed to an overlay as a method of rehabilitation cannot be made.

## CONCLUSIONS

- The topical application of inhibitor for corrosion mitigation is ineffective.
- The vacuum/pressure injection method shows promise, but the methodology requires refinement.
- Macro-cell measurements indicate that if a sufficient quantity of inhibitor can be injected into the concrete, the charge passed can be reduced.

## RECOMMENDATIONS

1. VDOT's Structure & Bridge Division should not apply either inhibitor investigated in this study to the surface of a concrete structure under the premise that it will migrate to the steel and mitigate corrosion.
2. The Virginia Transportation Research Council should continue to pond and monitor uniform and inclined test specimens, estimate the increase in service life for each inhibitor relative to the controls for the vacuum/pressure injection method, perform an autopsy on uniform and inclined samples to evaluate the effects of the treatments on steel, explore potential methods for improving the vacuum/pressure injection method, and investigate the possibility of physical damage to the reinforced structure caused by vacuum/pressure injection.

## ACKNOWLEDGMENTS

The author recognizes C. M. Apusen, J. H. Lee, E. F. Aiken, M. W. Burton, A. J. Mills, and A.W. Ordell for their contributions to this project.

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