August 7, 2013

Attn: Mr. Kurt F. von Fay
Bureau of Reclamation
Denver Federal Center, Bldg. 67, Mail Room 152
Denver, CO 80225-0007

Re: Vision 2020 – Final Report
Contract No. R10PC80497
TCG Project No.: 10124

Dear Mr. von Fay:

Tourney Consulting Group, LLC (TCG) appreciates the opportunity to evaluate the industry suggested protocol for measuring the performance of reinforcing steel corrosion mitigation and prevention technologies for concrete repairs.

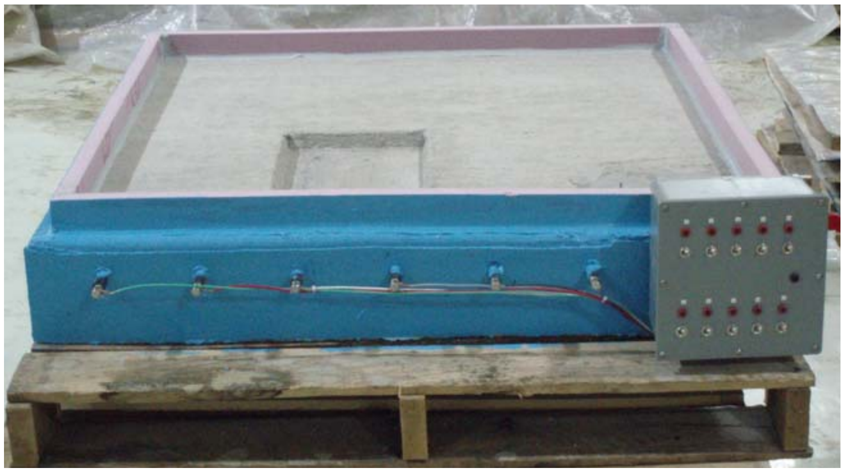
The following is a final report compiling a description of the test program (including photographs), specimen preparation, data collection, data analysis, selection and installation of treatments, forensic examinations, program findings, and protocol recommendations.

Sincerely,

Tourney Consulting Group, LLC

Brooks Bucher
Project Engineer, E.I.T.

Evaluation of an Industry Suggested Protocol for Measuring the Performance of Reinforcing Steel Corrosion Mitigation Technologies for Concrete Repairs



Prepared For:

Bureau of Reclamation

7 AUGUST 2013

Prepared By:

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Executive Summary

Tourney Consulting Group, LLC (TCG) was contracted by the Bureau of Reclamation (U.S.B.R.) to evaluate an industry suggested protocol for the performance of corrosion mitigation technologies for reinforced concrete, Contract No. R10PC80497, ***Evaluation of an Industry Suggested Protocol for Measuring the Performance of Reinforcing Steel Corrosion Mitigation Technologies for Concrete Repairs***. The need for a protocol to evaluate repair technologies was outlined in a report by the Strategic Development Council of ACI: "Vision 2020: A Vision for the Concrete Repair, Protection and Strengthening Industry."

The principal objective of the program was to evaluate a test protocol to compare various repair protection mechanisms for efficacy in mitigating active steel corrosion in concrete. This will enable the Bureau and other users to assess and specify the most appropriate and cost effective repair technologies for concrete structures.

In this study, the test protocol consisted of two specimen configurations, which were used to evaluate two types of repair systems: 1) repair treatments (integral cast materials), and 2) topical treatments (surface-applied materials). The specimens were pallet sized to be small enough for handling and placing in controlled conditions, yet large enough to properly evaluate mitigation technologies.

Based on our evaluation a test method based on this protocol that can differentiate the performance of repair/treatment technologies is feasible. Key components of the test method are highlighted in this summary.

The project scope was to:

1. Manufacture a total of 100 pallet-sized, 40-inch by 40-inch by 5.5-inch thick, test slabs using two configurations and five (5) different concrete mixtures (batches).
2. Cast concrete specimens and conduct standard concrete characterization testing on each batch of concrete.
3. Conduct corrosion monitoring and chloride penetration measurements during 24 monthly ponding cycles.
4. Conduct baseline data analysis and document findings after approximately 12 ponding cycles.
5. Apply corrosion mitigation treatment options.
6. Conduct forensic evaluation of specimens upon completion of testing.
7. Compile all data, photographs, data analysis and test protocol recommendations in a final report.

Evaluation of test variances of this project included:

- The effect of water-to-cement ratio (w/c) or concrete permeability on the time to corrosion initiation and mean corrosion rate.

- The effects of concrete cover depth on time to corrosion and mean corrosion rate.
- The effectiveness of different reinforcing bar end treatments on test results.
- Methods to accelerate corrosion in concrete repair specimens.
- The effect of non-proprietary corrosion mitigation treatments on the corrosion rate and the ability of the test protocol to identify corrosion rate reduction mechanisms.

Repair Treatment Specimens (Integral Cast Materials)
A total of thirty repair specimens were constructed from two of the concrete batches, fifteen each at 0.4 and 0.6 w/c. Three types of accelerated corrosion zones, "hotspots", were evaluated to establish the anodic "ring" effect. The hotspots evaluated in this study included: 1) Chloride-spiked concrete, 2) High-water content concrete (high w/c), and 3) Depressed cover area (low-cover area). Figure 1 shows one of the hotspot slabs with reduced cover. The other hotspot slabs have the hotspot in the same location.

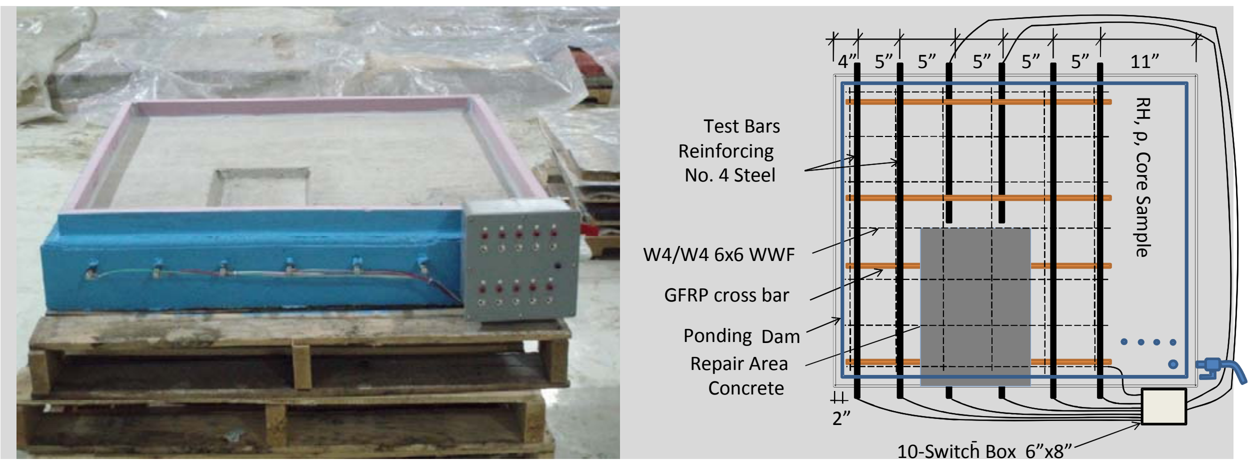


Figure 1 – Repair slab and schematic.

After corrosion cells were established and the rebars outside the hotspot initiated corrosion, the hotspot areas were removed and replaced with one of four repair corrosion mitigating technologies including a typical repair mixture (control), repair mixture + rebar coating, repair mixture + galvanic anode, and repair mixture + silane sealer.

Topical Treatment Specimens
Seventy topical treatment specimens were constructed encompassing five concrete batches, three w/c ratios, 0.40, 0.50 (3 Batches), and 0.60, two concrete covers, 0.75-inch and 1.5-inches, and three rebar end treatments designed to eliminate erroneous measurement errors, common to some corrosion testing programs. The three batches at w/c = 0.5, included specimens with the same mixture cast at different dates, and were used to evaluate the tests experimental repeatability. Figure 2 shows a typical topical treatment slab.

After sustained corrosion activity, the slabs were treated with one of three surface-applied topical treatments including a corrosion inhibitor, 40% silane sealer, and epoxy/urethane traffic membrane.

Figure 2 – Topical treatment slab and schematic.

Data Analysis

Corrosion potentials and macrocell corrosion currents were determined at the end of each ponding cycle for each rebar. The macrocell currents were integrated over time for each bar and totaled for each slab. Several rebars behaved as cathodes and their current was treated as being zero for the integration process. The integrated macrocell current is an indication of the corrosion damage.

Corrosion initiation for an individual bar was defined to be:

1. **Half-cell potential**, $E_{corr} \leq$ -350 mV CSE_{77}; **<u>AND</u>**
2. **Macrocell current**, $I_m \geq$ 0.036 mA (short rebars $I_m \geq$ 0.018 mA).

The times to initiation for one and three of the six rebars per slab were statistically analyzed for each concrete batch and compared to one another, as were the times for all of the rebars to corrode.

All of the batches at 0.75-inch cover had at least one rebar corroding within 42 days of the start of salt applications, and three bars corroding by 98 days. Whereas, at 1.5-inches of cover only 17 of 30 slabs had at least one rebar corroding after two years of salt applications.

Statistical analysis showed that the three batches at 0.5 w/c at 0.75-inch of cover were part of the same population, indicating repeatability was achieved. There was insufficient corroding reinforcement to compare results at 1.5-inches of cover. However, a reliability analysis indicated that the time to corrosion was following a normal distribution. The mean time for at least one rebar to corrode per slab at 1.5-inches of cover is over 600 days, and would require over two years of testing to have at least one corroding rebar in each slab.

Chloride analyses at the reinforcing bar level at the time of three rebars corroding were determined. For the 0.75-inch cover slabs the mean value was 580 ppm of the concrete, and there was no statistical difference between the batches. This is similar to the 500 ppm used in several modeling programs. At 1.5-inches of cover the value was 900, but only a few slabs had three corroding bars, and the time between corrosion initiation in one rebar and three rebars was at least two times longer than at 0.75-inch.

Time to perform repairs was a chosen after consultation with the Research Advisory Panel. The minimum criteria for repair was based on a total integrated macrocell current, as waiting for all the bars to corrode could result in cracking over one or more bars that initiate corrosion earlier.

- For the repair slabs, the critical value to be exceeded was 2,500 Coulombs of integrated corrosion outside of the repair hotspot, after disconnection of the hotspot from the rest of the bars.
- For topical treatments, the critical value was 5,000 Coulombs of integrated macrocell current.
- Destructive analysis was performed as indicated below to correlate these values to the amount of corrosion damage on the rebars.

Destructive Analysis

During this project, several slabs were destructively analyzed to evaluate the quantity and severity of visual corrosion damage on rebars at the time corrosion mitigating technologies were applied and at the end of testing. The destructive analysis consisted of a final evaluation of corrosion parameters including half-cell potential mapping of the entire concrete surface and chloride profiles. Each rebar was then physically removed by saw-cutting adjacent slots in the concrete, then photographed, visually observed, and rated according to two scales to estimate the quantity and severity of corrosion.

SUMMARY OF KEY FINDINGS

The key findings from this evaluation are summarized as follows:

- Corrosion Initiation
    - Concrete cover played a significant role in the time to corrosion initiation where the majority of 0.75-inch cover slabs initiated corrosion within the first few cycles and 1.5-inch cover slabs remained passive beyond one year of testing or longer.
    - In 0.75-inch cover, slabs constructed with higher permeable concrete resulted in slightly reduced times to corrosion initiation. However, the shallow concrete cover already produced early corrosion initiation times making it harder to distinguish between the effects of concrete quality.
    - The first rebar in the slab to corrode best defines the time of corrosion initiation.
- Corrosion Rate
    - Corrosion rate was inversely related to concrete cover. After corrosion initiation, slabs with 0.75-inch concrete cover exhibited high corrosion rates resulting from the rapid ingress of chlorides beyond the chloride threshold at the level of the

rebar. 1.5-inch cover slabs corroded at slower rates as chlorides ingress at a slower rate.
  - Concrete with higher permeability corroded at higher rates. As chloride contents at corrosion initiation were statistically the same for the 0.75-inch cover slabs, the main role of increasing permeability was the more rapid ingress of chlorides.
- Methods to Accelerate Corrosion
  - Chloride-spiked hotspots all successfully initiated corrosion quickly, however in some cases did not sustain active corrosion.
  - High-water content hotspots produced a more gradual increase in corrosion activity, however in some cases did not result in a significant acceleration compared to rebar outside the hotspot.
  - Depressed cover hotspots accelerated corrosion in all cases, however resulted in concrete cracking in the hotspot before the time of repair.
- Corrosion Mitigation
  - The effectiveness of the treatments was quantitatively measured by reductions in corrosion activity after application of the treatments.
  - The experimental program was designed to measure corrosion reduction and efficacy of various product technologies. A format to compare the performance of corrosion mitigation technologies based upon the Tuutti model of corrosion behavior is applicable.

    An example, Figure 3, is shown below of improvement with a repair treatment. Different treatments can be compared as to how efficient they are in reducing the corrosion at the time of the control failure, and by how much they increase the service life.

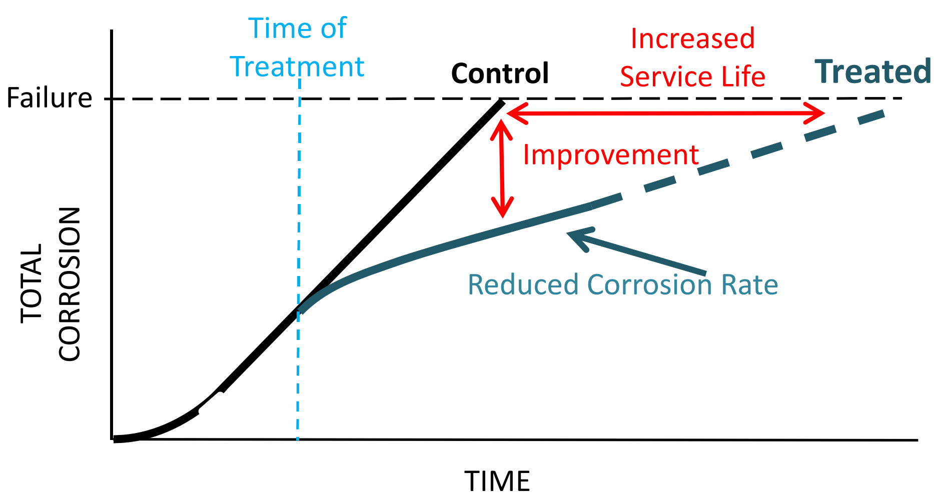


Figure 3 – Performance of a mitigation treatment vs. the control.

- Two topical treatments, 40% silane sealer and epoxy/urethane traffic membrane, were able to show a reduction in corrosion activity, while a third treatment, calcium nitrite inhibitor, was shown to be not effective. It is possible that another topically-applied inhibitor could have better performance.
- The chloride content at the application of the topical or repair treatment, and the reduced rate of corrosion afterwards, can be used to predict the increase in service life and performance of different corrosion mitigation systems. Figure 4 shows the mean performance of the three topical treatments for one of the batches. These data clearly show that the performance of different topical treatments can be compared and differentiated.

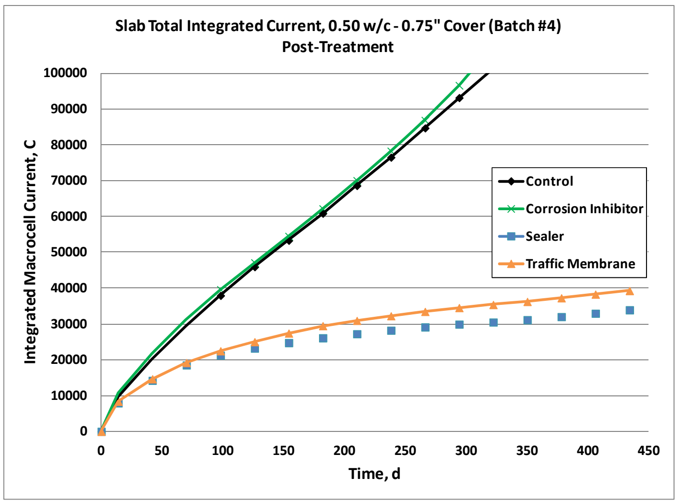


Figure 4 – Slab total integrated current after application of topical treatment.

- The three repair treatments, coating the rebars in the patch, installing a galvanic anode in the patch, and treating the slab with a 40% silane sealer showed an improvement over the control treatment of just patching the repair with the same concrete. Figure 5 shows the mean performance of the repairs. The method differentiates performance and the data show that relative performance over time can change.

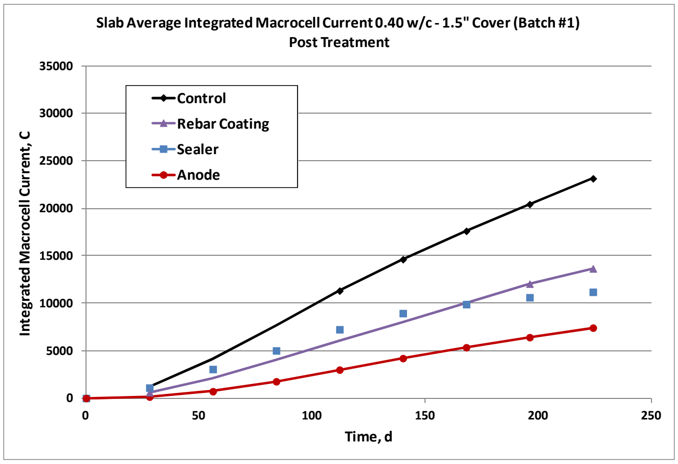


Figure 5 - Slab total integrated current after application of repairs.

- Detailed surface maps of corrosion potentials and integrated corrosion currents compared to visual reinforcing bar corrosion determined by destructive analysis were in good agreement with each other. In repaired/surface treated specimens, the potential maps showed a decrease in potential gradients and more positive potentials indicating that corrosion activity was reduced. This was in good agreement with the corrosion current data. These measurements can be used in the test method to indicate reinforcing bar performance along the length of the bar, so that autopsies need to be conducted only at the completion of testing.

  Figure 6 shows a comparison between a control slab and one treated with silane. The reduction of contours and more positive corrosion potentials in the silane treated slab are indicative of passive behavior, whereas the control slab shows steep contours and highly negative potentials associated with high corrosion rates.

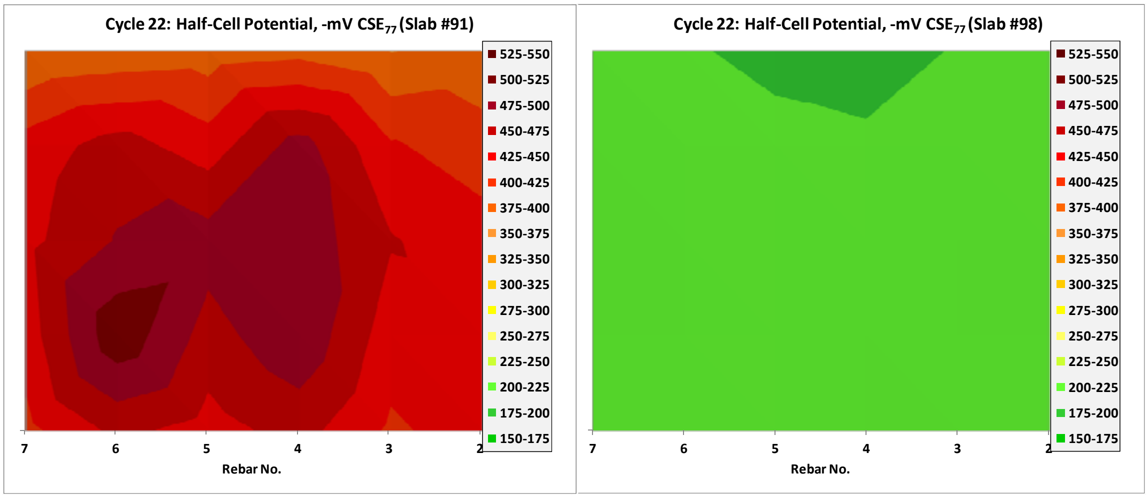


Figure 6 - Corrosion potential maps of slabs. Slab on the left is a control that has a high corrosion rate, and several sharp contours (color gradations). Slab on the right was treated with silane and is passive.

- The corrosion mitigation performance depends on the corrosion rate and level of corrosion at the time of treatment.

- Corrosion Damage at Time of Treatment
  - Corrosion measurements and chloride concentrations corresponded well with visually observed corrosion.
  - The level of corrosion activity observed at just greater than 5000 coulombs was a reasonable level to apply corrosion mitigating technologies with approximately 1000 ppm chlorides on average at the level of rebar.
- Reinforcing Bar End Treatments
  - Two of the three rebar end treatments, H_2SO_4 Pickle/Epoxy and Hot NaOH/Epoxy, provided satisfactory results. The H_2SO_4 Pickle/Epoxy treated rebar were in specimens with the highest levels of corrosion activity.
- Concrete Cracking
  - Concrete cracking was observed in 0.75-inch cover slabs with high levels of corrosion damage, mostly greater than 20,000 Coulombs per rebar.
  - No cracking was observed in 1.5-inch cover slabs. Although, none of the rebar surpassed 20,000 Coulombs, deeper cover is capable of withstanding more corrosion damage on rebar and stress before cracking occurs.

Summary of Test Protocol Recommendations

Based on the findings, several recommendations for the future standard method/procedure can be made. These are stated below, and supported in the report in greater detail.

Concrete Cover, Water-to-Cement Ratio (w/c) and Aggregate Selection

- A depth of concrete cover to reinforcement of 1.0-inch or 1.25-inches would result in acceptable times for corrosion initiation.
- A w/c of 0.5 gave good reproducibility, and will develop a discontinuous capillary system. It is typical of many of the field concretes to which corrosion mitigation techniques would be applied.
- Nominal aggregate size should be ½ the clear cover over the bars to minimize subsidence cracking and chloride ingress at the paste-aggregate interface. Suggested nominal aggregate size should be 0.5-inch, and concrete cover should be 1 inch based on these findings.

Methods to Accelerate Corrosion

For repair specimens, the addition of a localized area to accelerate corrosion (hotspot) was effective. The most effective hotspot configurations, from a performance and ease of production perspective are in order of preference:

1. Slightly reduced cover to accelerate chloride ingress to the bars in the hotspot.
2. Increasing the water-to-cement ratio in the hotspot to increase chloride ingress.

Number of Test Specimens

The reliability of the mean corrosion behavior and statistical differences between controls and mitigation systems is enhanced by increasing the number of specimens tested for each condition. This was analyzed and it is recommended that the number of specimens should be five per condition.

Corrosion Damage at Time of Treatment

The corrosion activity at time of treatment can play a significant role in how effective mitigating technologies perform. The following recommendations were made based on the testing:

- Allow testing of corrosion mitigating technologies at various levels of corrosion damage (separate testing).
- Develop corrosion mitigation classifications based on the desired level of corrosion activity at the time of application.
- As a standard:
    - Topical Treatments should be applied when integrated macrocell current for all the bars combined on the slab meets 5,000 Coulombs, which can be described by a chloride level of approximately 1000 ppm.
    - Repair Treatments should be installed when rebar outside the hotspot have a total of 2500 Coulombs of corrosion.

Additional Recommendations

The following are additional recommendations that should be incorporated into the test method:

- The preferred end treatment for the bars is pickle the ends in sulfuric acid, apply shrink tubing and fill with epoxy.
- Dams on the top of the slabs should be moved in from the edge of the slab, so that the ponded area is located within the limits of the exposed area.
- Detailed corrosion potential maps should be performed periodically to identify localized areas of high corrosion activity.
- Chloride threshold values should be determined when at least one bar goes into corrosion, defined as a corrosion potential greater than -300 mV vs. CSE_{77} and a macrocell current greater than 0.030 mA.
- Trial mixture(s) with the materials to be used in the production of the slabs should be produced prior to producing the concrete for the test specimens to adjust dosage rates of air entrainment, water reducers, as well as the mixture proportions.

Conclusion

Based on the findings of this study, the test protocol can provide the following valuable information:

- Identify corrosion threshold levels for chloride induced corrosion of steel in concrete.
- Differentiate the performance of repair/topical treatment corrosion mitigation technologies for chloride induced corrosion of steel in concrete at various chloride levels. Figures 7 and 8 summarize the mitigation technologies evaluated and their performance.

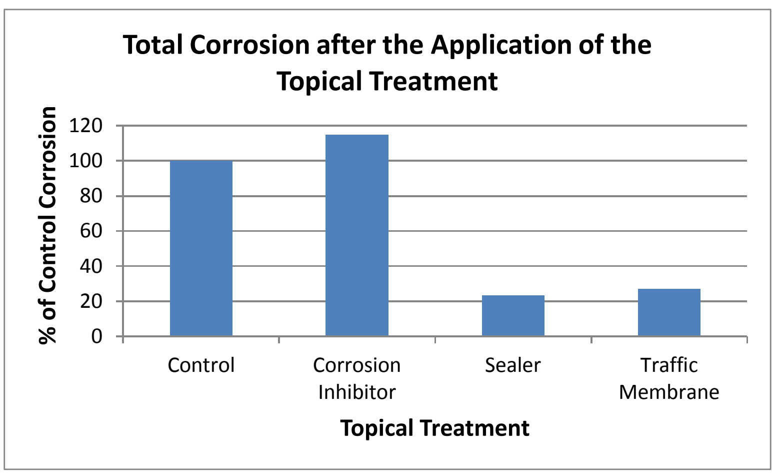


Figure 7 –Comparison of the performance of topical treatments for Batch #4.

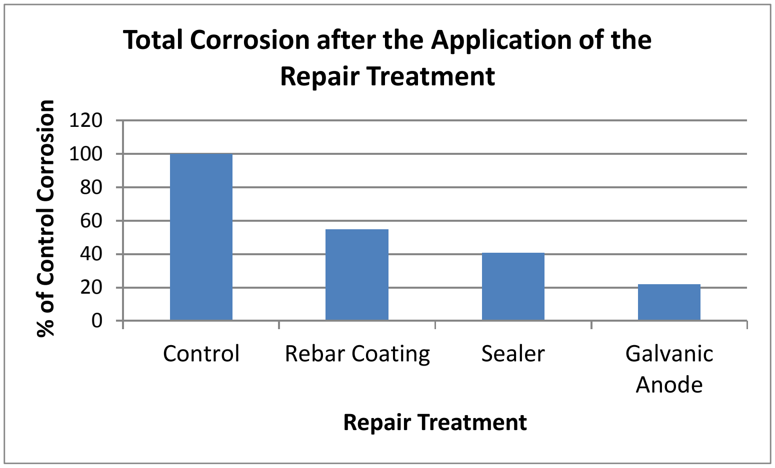


Figure 8 – Comparison of the performance of repair treatments for Batch #1.

Future Studies

Several recommendations for the final procedure have been made. A smaller scale study to determine the within-laboratory precision is suggested.

Additional work to evaluate performance in carbonated concretes with and without chloride exposures would be useful to expand the applicability of the method.

A field to laboratory comparison would be useful. A large reinforced slab could be produced and exposed in a similar manner to the test slabs using the same concretes.

Test extensions can be reviewed to understand the degradation of the corrosion mitigation technology.

Introduction

This project evaluated an industry suggested protocol for measuring the performance of corrosion mitigation technologies for concrete reinforcing steel. The testing protocol was suggested by a group of industry recognized experts and strategic planners in support of goals outlined in Vision 2020: "A Vision for the Concrete Repair, Protection and Strengthening Industry". Vision 2020 is an industry created strategic plan and roadmap; documents were developed over a several year period which began in 2003. Information about these documents is available at the ACI Foundation's Strategic Development Council website.

Background

The purpose of this project was to evaluate a suggested protocol to determine the effectiveness of concrete reinforcing steel corrosion mitigation techniques for reinforced concrete structures undergoing active corrosion.

Corrosion of reinforcing steel in concrete is the most common cause for concrete repair. However, a standard method to evaluate the effectiveness of numerous corrosion mitigation technologies does not exist. This lack of a standard evaluation method makes it very difficult to make engineering decisions on the most appropriate methods or materials to use since data from different corrosion prevention technologies may not be comparable.

The test protocol was suggested with input from a panel of corrosion experts to make the protocol a practical and statistically sound laboratory procedure. In addition, appropriate characterization tests are conducted so the laboratory performance can be related to real-world applications through numerical modeling if desired.

Corrosion mitigation technologies for reinforcing concrete structures can be divided into two general material classes: integral and surface-applied. Integral materials are cast within the repaired material while surface-applied materials are applied to the concrete surface. The test protocol is designed to evaluate the performance of both classes of materials. Test slabs are designed with and without a cavity to contain a "repair material" (repair "hotspot"). Those with a cavity are designed to evaluate integral technologies and those designed without are intended to evaluate surface technologies.

Project Scope

Tourney Consulting Group, LLC was contracted by the Bureau of Reclamation to evaluate an industry suggested testing protocol for measuring the performance of corrosion prevention and mitigation technologies for concrete reinforcing steel. The scope of this project included:

1. Manufacturing a total of 100 pallet-sized, 40-inch by 40-inch by 5.5-inch thick, test slabs using two configurations and five (5) different concrete mixtures (batches).
2. Casting concrete specimens and conduct standard concrete characterization testing on each batch of concrete.

3. Conducting corrosion monitoring and chloride penetration measurements for 24 monthly ponding cycles.
4. Conducting data analysis and document findings after 12 ponding cycles.
5. Applying corrosion mitigation treatment options.
6. Conducting forensic evaluation of specimens upon completion of testing.
7. Compiling all data, photographs, data analysis and test protocol recommendations in a final report.

Project Objectives
The objectives of this project were to evaluate:
- The effect of water-to-cement ratio (w/c) on time to corrosion and mean corrosion rate.
- The effects of concrete cover depth on time to corrosion and mean corrosion rate.
- The effectiveness of different reinforcing bar end treatments on test results.
- Methods to accelerate corrosion in concrete repair specimens.
- The effect of non-proprietary corrosion mitigation treatments on the corrosion rate and the ability of the test protocol to identify corrosion rate reduction mechanisms.

Experimental

Specimen Description
A total of one hundred concrete slab test specimens were fabricated in two configurations:
1. Hotspot Repair Test Specimen (Integral Technologies)
2. Topical Treatment Test Specimen (Surface-Applied Technologies)

Both configurations had overall dimensions of 40-inches wide by 40-inches long by 5.5-inches thick. The one hundred test specimens were constructed from five unique batches numbered 1 thru 5, where each batch produced 20 specimens. Batches 1 and 2 were used for 15 "Hotspot" repair test specimens and five (5) topical treatment test specimens each and batches 3, 4, and 5 were used topical treatment test specimens, 20 in each batch, see Figure 1 for slab configurations and Table 1 for number and type of slabs per batch.

Hotspot Repair Test Specimen
The hotspot repair test specimens were constructed with eight (8) longitudinal #4 reinforcing bars located in six rows with 5–inch spacing and 1.5 inches of concrete cover (unless specified otherwise as determined by the type of hotspot). Two rows of reinforcement contain two half-length rebar to allow construction of the repair hotspot. The group of bars was offset in the specimen to allow an area for measuring internal RH, concrete electrical resistivity, and extracting core samples. Each slab contains W4/W4 6 x 6 welded-wire fabric (WWF) for the bottom layer of steel. All rebar were electrically connected outside the slab to a junction box to facilitate measurements of individual rebar. Each test specimen consists of a 2-inch tall closed cell insulation dam located around the perimeter of the test specimens to facilitate ponding of a 5% NaCl solution.

The 15 hotspot repair test specimens fabricated in batches 1 and 2 were allocated into three groups of five test specimens. Each group was constructed with a different hotspot technique designed to evaluate methods to accelerate corrosion, including:

1. Chloride-spiked concrete
2. High water content concrete (high w/c)
3. Depressed cover, plain concrete (low-cover area)

Each hotspot surrounds two 18-inch long rebar in a 3-inch x 9-inch x 20-inch area located in the front of each slab and centered from right to left.

Topical Treatment Test Specimen

The five (5) topical treatment test specimens in batches 1 and 2 were constructed with 0.75 inches of concrete cover and were used primarily to evaluate the effects of water-to-cement ratio (w/c). These test specimens have a similar rebar configuration as the repair type specimens, i.e. eight (8) longitudinal #4 reinforcing bars located in six rows.

The topical treatment test specimens were constructed with six (6) longitudinal #4 reinforcing bars spanning the entire slab with 5-inch spacing. Again, the group of bars was offset in the specimen to allow an area for measuring internal RH, concrete electrical resistivity, and extracting core samples. Each slab contains W4/W4 6 x 6 welded-wire fabric (WWF) for the bottom layer of steel. All rebar were electrically connected outside the slab to a junction box in order to facilitate measurements of individual reinforcing bars. Each test specimen consists of a 2-inch tall closed cell insulation lip located around the perimeter of the test specimens to facilitate ponding of a 5% NaCl solution.

The 20 topical treatment test specimens in batches 3, 4, and 5 were allocated in groups of 10 slabs each with two different concrete covers, i.e. 0.75-inch and 1.5-inches. Each batch consists of a different type of reinforcing end treatment including:

1. CN Paste/Shrink Tube: Coat end of reinforcement bar with a cement paste having a 30% calcium nitrite admixture and covered with rubber tubing,
2. H_2SO_4 Pickle/Epoxy: Pickle ends of reinforcement bars in 10% sulfuric acid solution, clean with wire wheel, cover with rubber tubing, and inject two part epoxy in cavity between rubber tubing and reinforcement bar, and
3. Hot NaOH/Epoxy: Wire brush end of reinforcement bars, soak in 0.1M NaOH solution, cover with rubber tubing, and inject two part epoxy in cavity between rubber tubing and reinforcement bar.

Table 1 – Type and Number of Test Specimens per Batch

Batch No.	w/c	Quantity of Test Specimens		End Treatment Type	Comment
		¾ inch cover	1 ½ inches of cover		
1	.40	5	15	CN Paste/Shrink Tube	Repair "Hotspot"
2	.60	5	15	CN Paste/Shrink Tube	Repair "Hotspot"
3	.50	10	10	CN Paste/Shrink Tube	Topical
4	.50	10	10	H_2SO_4 Pickle/Epoxy	Topical
5	.50	10	10	Hot NaOH/Epoxy	Topical

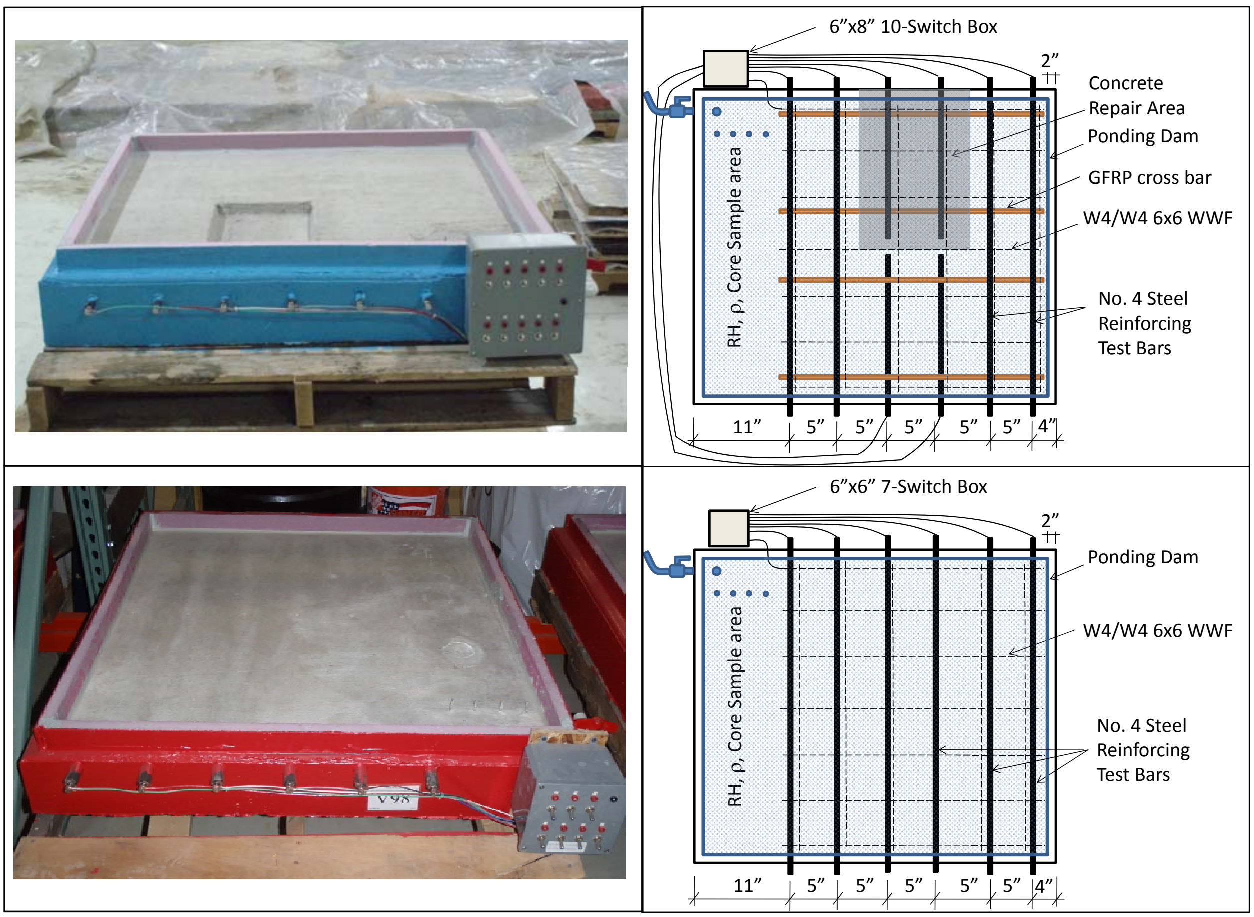


Figure 1 – Repair Test Specimen Configuration with depressed cover hotspot (Top), Topical Treatment Test Specimen Configuration (Bottom)

A full description of the test slab manufacturing can be found in Appendix A.

Materials and Mixtures

The concrete mixture ingredients used in this project included:

- Cement: ASTM C 150 Type I/II, (no supplementary cementitious materials)
- Coarse Aggregate: ASTM C 33 – No. 67 Gradation
- Fine Aggregate: ASTM C 33
- Admixtures:
    - Air Entraining Admixture (AEA): ASTM C 260 – BASF Micro Air®
    - High-Range Water Reducer (HRWR): ASTM C 494 Type F – BASF Glenium® 7500
    - Mid-Range Water Reducer (MRWR): ASTM C 494 Type A – BASF Polyheed® FC 100

The mixture designs for each batch are provided in Table 2.

Table 2 – Concrete Mixture Designs

Concrete Mixture Designs, lbs./yd^3									
Batch No.	w/c	Cement	Water	Coarse Aggregate	Fine Aggregate	Design Air Content, %	AEA, oz./cwt	MRWR, oz./cwt	HRWR, oz./cwt
1	.40	564	225	1200	1947	6%	0.5	-	6
2	.60	564	338	1440	1412	6%	1.25	-	-
3	.50	564	284	1750	1251	6%	1	3	-
4	.50	564	284	1750	1251	6%	1	3	-
5	.50	564	284	1750	1251	6%	1	3	-

Test Procedures

Concrete Characterization

TCG tested each concrete batch for fresh concrete properties according to the following standard test methods:

- ASTM C 138 "Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete"
- ASTM C 143 "Slump of Hydraulic Cement Concrete"
- ASTM C 231 "Air Content of Freshly Mixed Concrete by the Pressure Method"
- ASTM C 1064 "Temperature of Freshly Mixed Concrete"

TCG tested each concrete batch for hardened concrete properties according to the following standard test methods:

- ASTM C 39 "Compressive Strength of Cylindrical Concrete Specimens". The compressive strength was tested at 3, 7, 28, 56, 90, 180, and 365 days on 4-inch diameter x 8-inch tall cylinders in replicates of three specimens.

- ASTM C 1202 "Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration." The resistivity was tested at 28, 90, 180, and 365 days on samples taken from 4-inch diameter x 8-inch tall cylinders in replicates of three specimens.
- "ASTM C 1152 "Acid-Soluble Chloride Content Determination in Concrete." The background chloride content was tested at 28 days on bottom portions of three cylinders removed for testing in the ASTM C 1202 procedure.

Test Slab Conditioning

The slabs underwent 7 days of moist-curing and 21 days of air drying in a heated warehouse environment. At an age of 28 days, the slabs began the initial ponding cycle with 14 days wetting with 5% NaCl solution followed by 14 days of air drying. The ponding cycle is then repeated every 28 days.

Corrosion Monitoring and Chloride penetration measurements

TCG conducted periodic corrosion monitoring including:

- Corrosion potential (ASTM C 876), (After every ponding cycle),
    - Time-to-Corrosion Initiation
    - Half-cell potential mapping
- Macrocell Corrosion Current Monitoring, (After every ponding cycle),
- Mat-to-Mat Resistance Monitoring, (Before and after initial ponding cycle and after 6th, 12th, 18th, and 24th ponding cycle or end of testing),
- Electrical Resistivity (Wenner 4-Pin Method), (Before and after initial ponding cycle and after 6th, 12th, 18th, and 24th ponding cycle or end of testing)
- Chloride Profiles (At corrosion initiation (Topical slabs only), and after 6th, 12th, 18th, and 24th ponding cycle or end of testing)
- Internal Relative Humidity (After installation of 0.75-inch cover topical treatment slabs)

A full description of each procedure can be found in Appendix C.

Results and Analysis

The results and analysis are subdivided into the following eight sections:

1. Concrete Characterization
2. Corrosion Initiation
3. Corrosion Rate
4. Methods to Accelerate Corrosion
5. Corrosion Mitigation
6. Corrosion Damage at Time of Treatment
7. Concrete Cracking
8. Number of Test Specimen

Concrete Characterization

TCG tested each concrete batch for fresh concrete properties and recorded the following:

Table 3 – Summary of Fresh Concrete Properties

Concrete Description						
Batch No.	1	1A*	2	3	4	5
Date Cast	10/05/10	11/02/10	10/19/10	11/02/10	11/19/10	11/30/10
Design w/c	0.40	0.40	0.60	0.50	0.50	0.50
Concrete Test Results						
Unit Weight, lbs./ft^3 (ASTM C138)						
Unit Weight	139.1	137.7	144.1	139.1	142.3	143.9
Yield	28.29	28.58	26.05	27.67	27.04	26.74
Slump, inches (ASTM C143)						
Slump	6.75	5.00	5.50	7.50	6.50	4.00
Air Content, % (ASTM C231)						
Air Content	8.5	9.1	5.3	8.0	6.9	6.9
Temperature, °F (ASTM C1064)						
Temp.	59.5	52.3	60.0	59.7	61.2	61.9

*5 test specimens in Batch #1 (Slabs 1-5) were recast with Batch #1A to correct the hotspot mixture

TCG tested each concrete batch for hardened concrete properties and recorded the following:

Table 4 – Summary of Hardened Concrete Properties

Concrete Description						
Batch No.	1	1A*	2	3	4	5
Date Cast	10/05/10	11/02/10	10/19/10	11/02/10	11/19/10	11/30/10
Design w/c	0.40	0.40	0.60	0.50	0.50	0.50
Test Age, days	**Concrete Test Results**					
Compressive Strength, psi (ASTM C39)						
3	2440	3030	2850	2090	2670	2760
7	3010	3340	3680	2690	3440	3360
28	3790	4240	4810	3360	4570	4630
56	4220	4500	5470	3930	5060	5060
90	4380	4830	6010	4090	5460	5620
180	4680	4970	6260	4290	5770	5930
365	4770	5120	6460	4420	6090	6360
Background Chloride Content, ppm (ASTM C1152)						
-	256	239	225	267	299	325
Rapid Chloride Permeability, Coulombs (ASTM C1202)						
28	6425	5135	6299	6200	5065	5319
90	3476	2901	3590	3791	2965	3157
180	2737	2250	2903	2040	1751	1880
365	2850	2352	3157	2956	2350	2188

*5 test specimens in Batch #1 (Slabs 1-5) were recast with Batch #1A to correct the hotspot mixture

Plots showing compressive strength and rapid chloride permeability as a function of time are provided in Figure 2 and Figure 3 respectively.

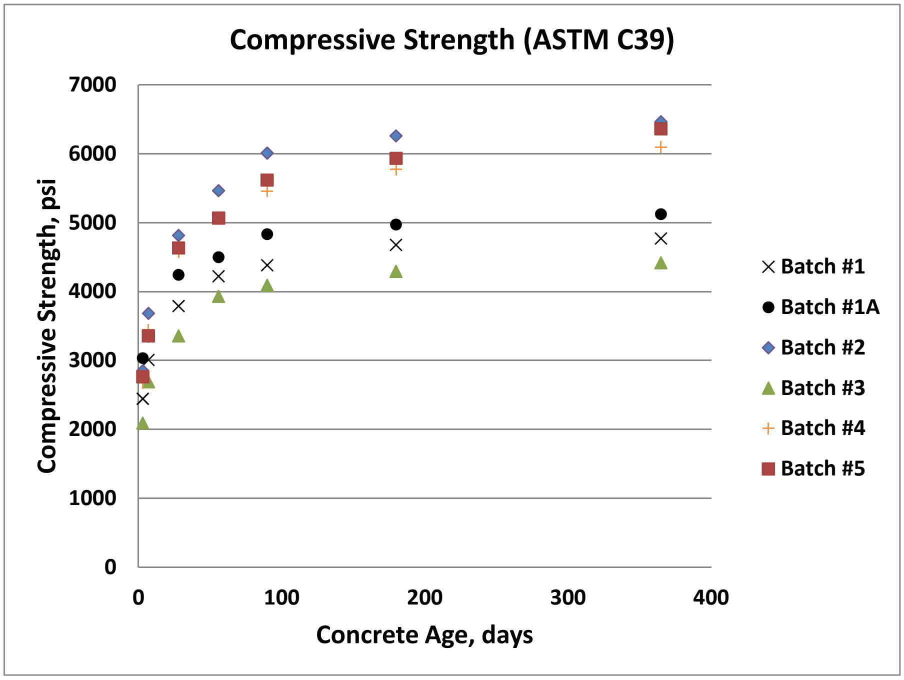


Figure 2 – Concrete compressive strength as a function of time

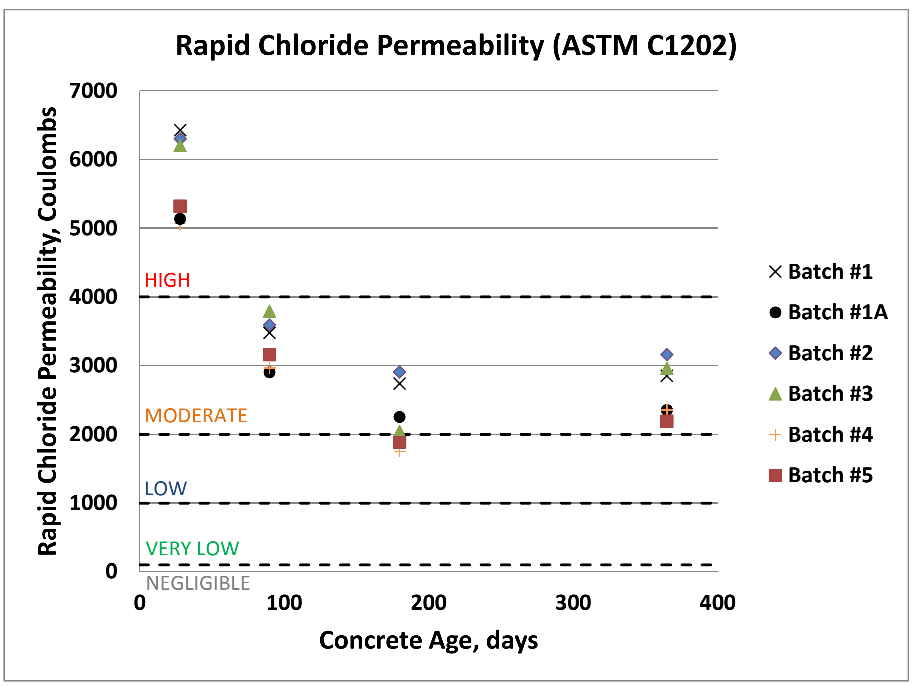
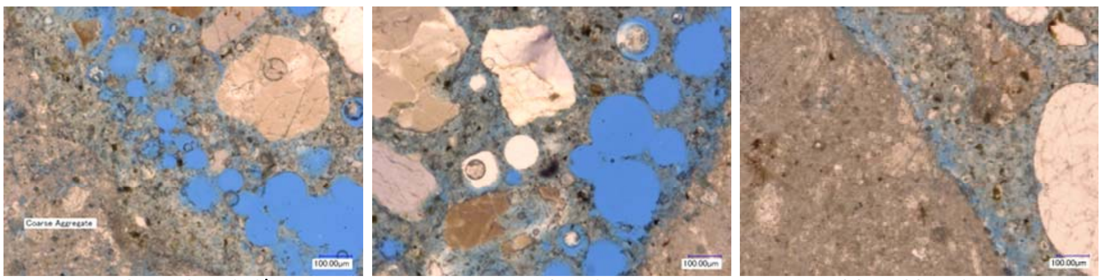


Figure 3 – Rapid chloride permeability as a function of time

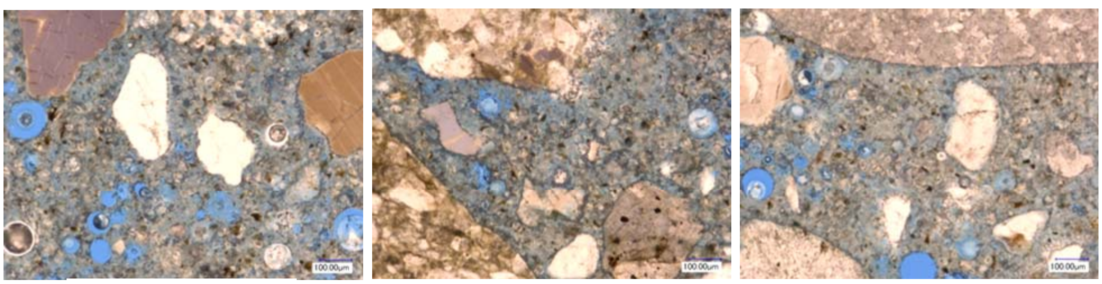
The 0.60 w/c concrete showed better concrete characteristic performance than the 0.40 w/c concrete and was comparable to the 0.50 w/c concretes. Concrete thin sections were analyzed to evaluate the mixture designs. This unexpected behavior is due to coalescence of air voids at the paste/aggregate interface for the 0.40 w/c concrete as can be seen in Figure 4. The 0.60

w/c mixture had the lowest porosity at the paste/aggregate interface as it had the lowest air content.

The reduced times to corrosion and more porous structure found are in agreement with the rapid chloride permeability results for Batch 1 versus the other mixtures. Though Batch 1 can't be used to represent a low permeability concrete, it can be used to show the effect of a higher permeable concrete. As expected increasing the permeability of the concrete does reduce the time to corrosion initiation, as discussed in the following section.



V3 – .40 WC-Cl V11 – .40 WC-RM V29 – .60 WC



V50 – .50 WC-RM V70 – .50 WC-RM V89 – .50 WC-RM

Figure 4 – Thin section analysis of concrete batches, where blue represents porous areas, the w/c=0.40 concrete the air void shapes are clearly visible. Slab 50 is from Batch #3, Slab 70 from Batch #4 and Slab 89 from Batch #5

Further analysis of the concrete batches are provided in Figure 5 and Figure 6 where the chloride content at the level of the rebar was plotted as a function of time. The data consists of the chloride content measured from cores extracted periodically over time. Background chlorides were mathematically removed to show external chloride ingress only. Each data point is the average of 2 or more slabs during a given time period. In 0.75-inch cover slabs, Batch #1 had the highest chloride levels at the depth of rebar over time. Batch #4 had the lowest amount of chloride at 0.75-inches deep and 1.5-inches, where chloride had not reached the level of the rebar at 1.5-inches deep at completion of testing.

Note: subsidence in 0.75-inch cover slabs may have resulted in higher chloride concentrations at the rebar than that measured in the corresponding depths of extracted cores shown in Figure 5. See Figure 1 for core locations.

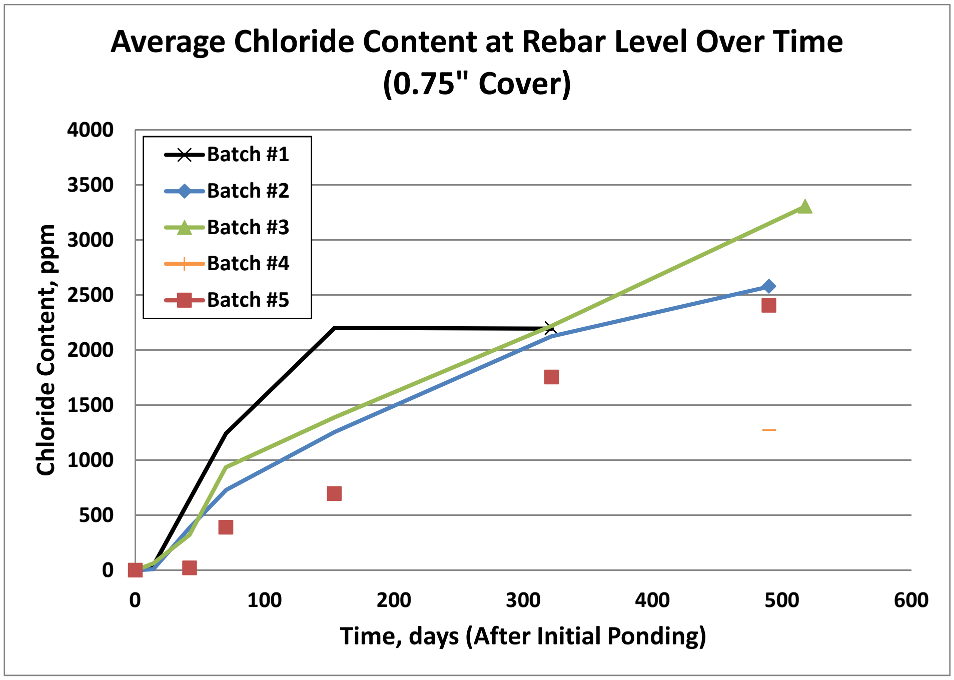


Figure 5 – Chloride content vs. time at 0.75-inch concrete cover (Background chlorides removed)

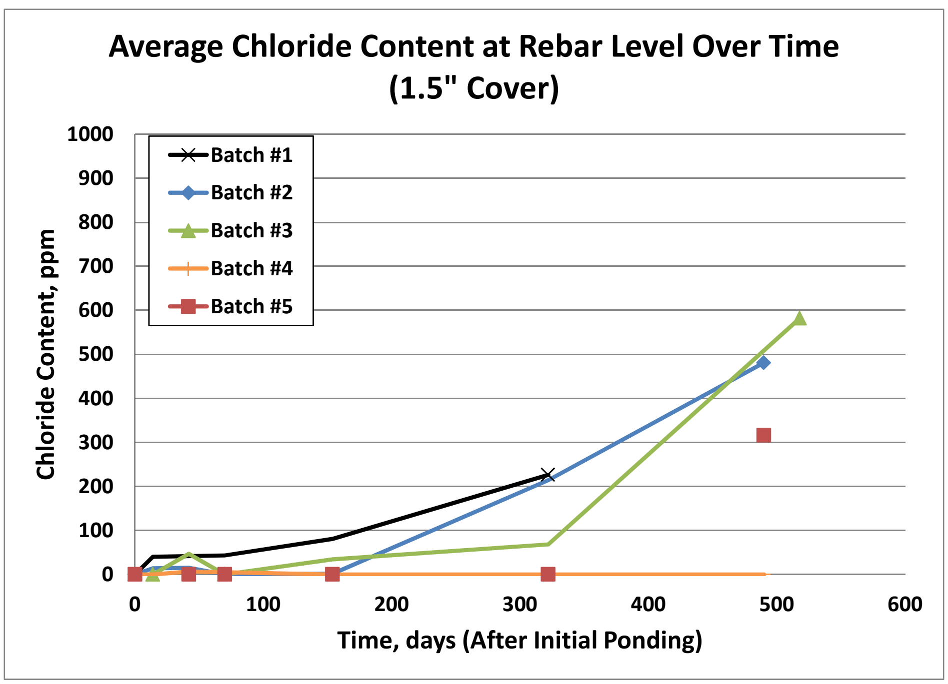


Figure 6 - Chloride content vs. time at 1.5-inch concrete cover (Background chlorides removed)

Corrosion Initiation

The suggested protocol was intended to initiate corrosion within approximately one year followed by a six to twelve month treatment phase to evaluate the efficacy of mitigation technology. When environmental conditions remain unchanged, time to corrosion initiation depends on:

- Concrete cover depth
- Chloride diffusion rate
- Chloride threshold

In this study, the time to corrosion initiation was evaluated for two concrete covers, i.e. 0.75-inches and 1.5-inches. Within the group of 0.75-inch cover slabs, three different concrete mixture designs were tested, conceptually having three various chloride diffusion rates, i.e. 0.40, 0.50, and 0.60 w/c (Note, since concrete characterization results revealed coalesced air bubbles surrounding aggregates in the 0.40 w/c, it will be described as a high permeability concrete). One reinforced concrete system type exists, i.e. plain cement concrete, conventional black rebar reinforcement, for determining the chloride threshold at corrosion initiation.

Therefore, four data sets exist and were analyzed in this program:

1. 0.75-inch cover, 0.40 w/c (Batch 1) N = 40 rebar, 5 slabs
2. 0.75-inch cover, 0.60 w/c (Batch 2) N = 40 rebar, 5 slabs
3. 0.75-inch cover, 0.50 w/c (Batches 3, 4, and 5) N = 180 rebar, 30 slabs
4. 1.5-inch cover, 0.50 w/c (Batches 3, 4, and 5) N = 180 rebar, 30 slabs

Corrosion Initiation Definition

For this analysis, corrosion initiation was defined when measurements on an individual rebar meet the following criteria:

3. **Half-cell potential**, $E_{corr} \leq$ -350 mV CSE_{77}; **AND**
4. **Macrocell current**, $I_m \geq$ 0.036 mA (short rebars $I_m \geq$ 0.018 mA).

Since rebar within the same slab can have an effect on one another, the time to corrosion initiation was analyzed according to both individual rebar and total slab in the following ways:

1. **Rebar** – Time when the rebar meets the criteria stated above
2. **Slab –** Time when the slab initiates corrosion as defined in two ways by:
    a. Time when at least any one rebar (first rebar) in a slab meets the corrosion initiation criteria stated above.
    b. Time when at least any three rebars (third rebar) in a slab meet the corrosion initiation criteria stated above.

Rebar and slab corrosion initiation times were excluded from the statistical analysis when:

- Rebar corrosion initiation occurred after corrosion mitigating treatments were installed. Treatments can delay the time to corrosion initiation or prevent it all together. Each batch was treated as shown in Table 5.

Table 5 – Time treatments were applied in days (After initial ponding)

Batch No.	0.75-inch Cover	1.5-inch Cover
1	217	-
2	217	-
3	189	≥ 518
4	189	≥ 742
5	161	≥ 630

- Testing completed prior to rebar corrosion initiation as shown in Table 6.

Table 6 – Time testing completed in days (After initial ponding)

Batch No.	0.75-inch Cover	1.5-inch Cover
1	490	-
2	490	-
3	630	770
4	630	742
5	602	742

<u>Time to Rebar Corrosion Initiation</u>

Table 7 lists the statistical data for the time to corrosion of individual rebar for each of the four data sets. Frequency and cumulative distribution plots are provided in Figure 7 through Figure 9. The data indicate that nearly 20% of all 0.75-inch cover rebars initiated corrosion after just the first ponding cycle and more than 80% within the first 3 ponding cycles or 70 days after the initial ponding.

For 1.5-inch cover slabs only 16%, or 28 of 180 rebars initiated corrosion prior to treatment or test completion. However, the slabs typically met the treatment criteria when just two of six rebar were corroding which is part of the reason for the limited data set. Of the 28 rebars that initiated corrosion, the average time to corrosion was over one year at 427 days. Note “other” in Figure 9 includes both rebar that did not corrode and rebar that initiated corrosion after treatment applications, which may be prior to 602 days.

Table 7 – Rebar Corrosion Initiation Statistics

Rebar Corrosion Initiation Statistics, days (After Initial Ponding)							
	N	Mean	Std. Dev.	COV (%)	Std. Error	Minimum	Maximum
0.75-inch Concrete Cover							
0.40 w/c (Batch #1)	40/40	32.9	24.9	76	3.9	14	126
0.60 w/c (Batch #2)	37/40	69.2	35.2	51	5.8	14	182
0.50 w/c (Batches #3-5)	161/180	55.0	33.1	60	2.6	14	182
1.5-inch Concrete Cover							
0.50 w/c (Batches #3-5)	28/180	427	93.2	22	17.6	210	602

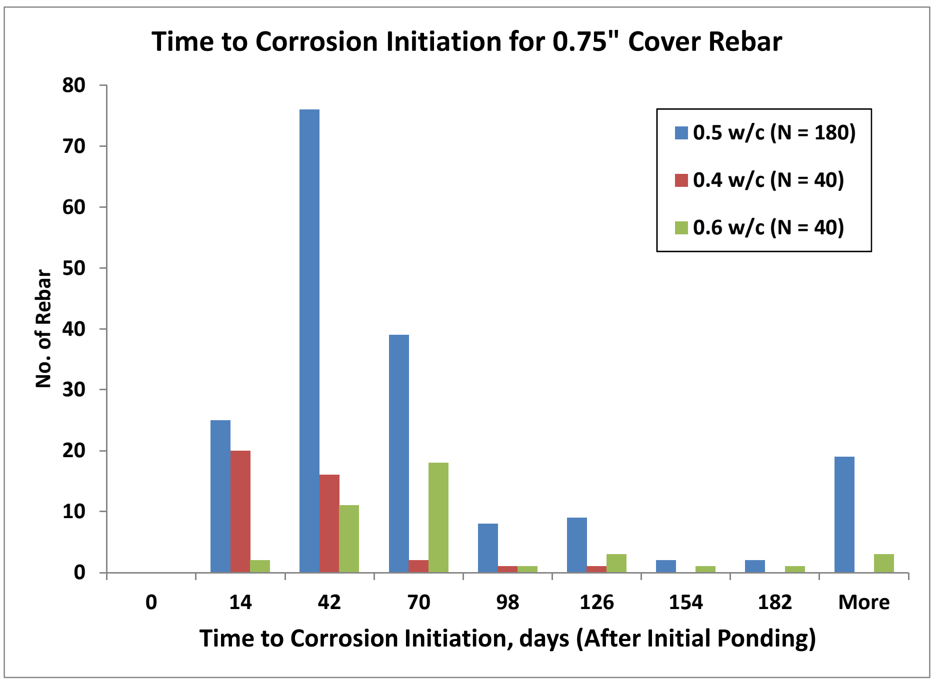


Figure 7 – Histogram of Time to Corrosion Initiation for 0.75-inch Cover Rebar

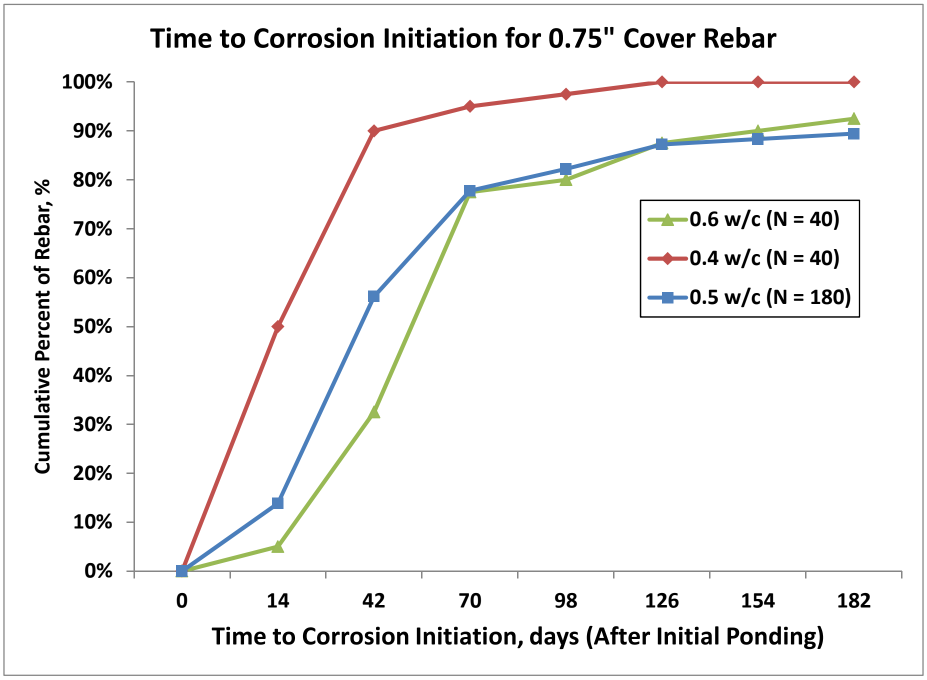


Figure 8 – Cumulative Distribution of Time to Corrosion Initiation for 0.75-inch Cover Rebar

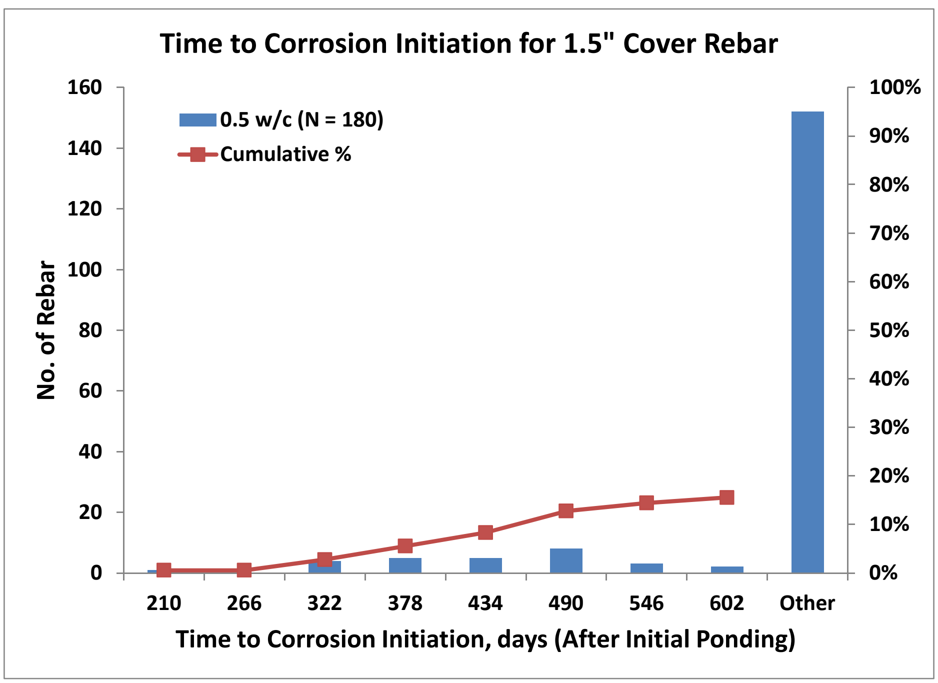


Figure 9 – Histogram and Cumulative Distribution of Time to Corrosion Initiation for 1.5-inch Cover Rebar

Time to Slab Corrosion Initiation

Table 8 shows the mean and standard deviation for the initiation time for the first rebar in each slab to corrode for the four data sets. Frequency and cumulative distribution plots are provided in Figure 10 through Figure 12. 100% of all slabs with 0.75-inch cover had at least one rebar corroding by the end of the 2nd ponding cycle or 42 days. Approximately 57% or 17 of 30 slabs with 1.5-inch cover had at least one rebar corroding by the end of the 23rd ponding cycle or 658 days. This means many of the 28 individual 1.5-inch cover rebar shown in Figure 9 were the first rebar to initiate corrosion within each slab.

Table 8 – Corrosion Initiation Statistical Data per Slab (First Rebar in each Slab)

Rebar Corrosion Initiation Statistics, days (After Initial Ponding)							
	N	Mean	Std. Dev.	COV (%)	Std. Error	Minimum	Maximum
0.75-inch Concrete Cover							
0.40 w/c (Batch #1)	5/5	14.0	0.0	0	0.0	14	14
0.60 w/c (Batch #2)	5/5	30.8	15.3	50	6.9	14	42
0.50 w/c (Batches #3-5)	30/30	28.9	14.2	49	2.6	14	42
1.5-inch Concrete Cover							
0.50 w/c (Batches #3-5)	17/30	N/A	N/A	N/A	N/A	N/A	N/A

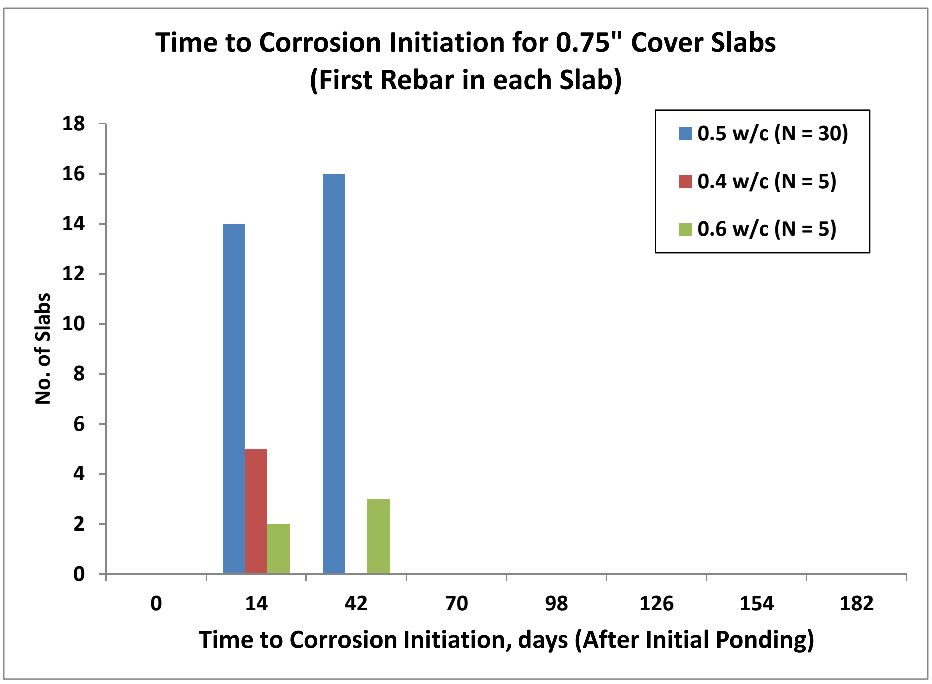


Figure 10 – Distribution of time to corrosion initiation for first rebar in 0.75-inch cover slabs

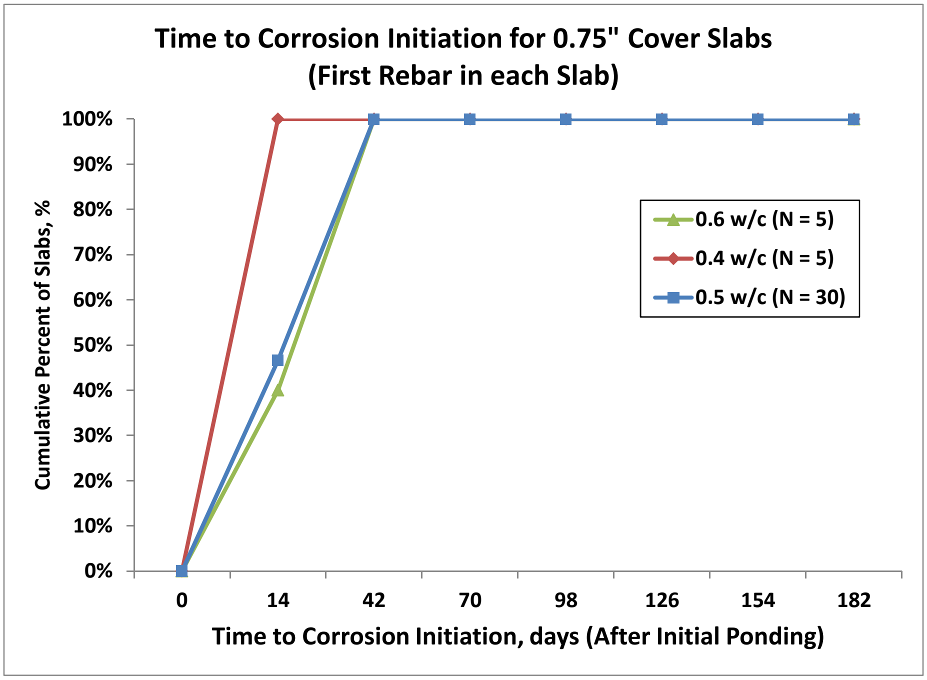


Figure 11 – Cumulative distribution of time to corrosion initiation for first rebar in 0.75-inch cover slabs

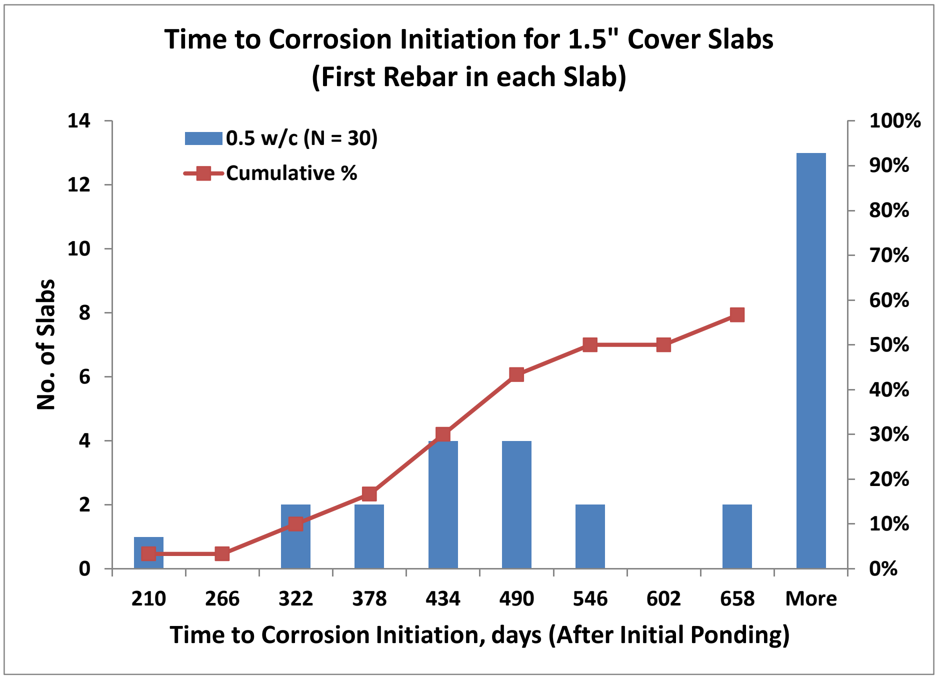


Figure 12 – Distribution of time to corrosion initiation for first rebar in 1.5-inch cover slabs

Since only 17 of the 30 slabs had at least one bar meeting the corrosion criteria a reliability analysis was conducted to estimate the mean time for a slab to have at least one bar corroding.

In this case three distributions, Weibull, Lognormal, and Normal, all had distributions with a high correlation coefficient as shown in Table 9 and Figure 13.

Table 9 – Estimation of mean time to corrosion initiation for first rebar for 1.5-inch cover slabs

Distribution	N	Time to Corrosion Initiation, days (After Initial Ponding)						R
		Mean	Std. Error	Std. Dev.**	CoV (%)	Lower 95% CL	Upper 95% CL	
Weibull	17	569.53	38.21	157.54	27.66	499.35	649.56	0.98
Lognormal	17	660.03	68.64	283.00	42.88	538.33	809.25	0.98
Normal	17	572.34	37.12	153.03	26.74	499.59	645.08	0.96

*Note only 17 of 30 slabs had at least one corroding bar
**Note Std. Dev. = Std. Error x Sq. Rt(N)

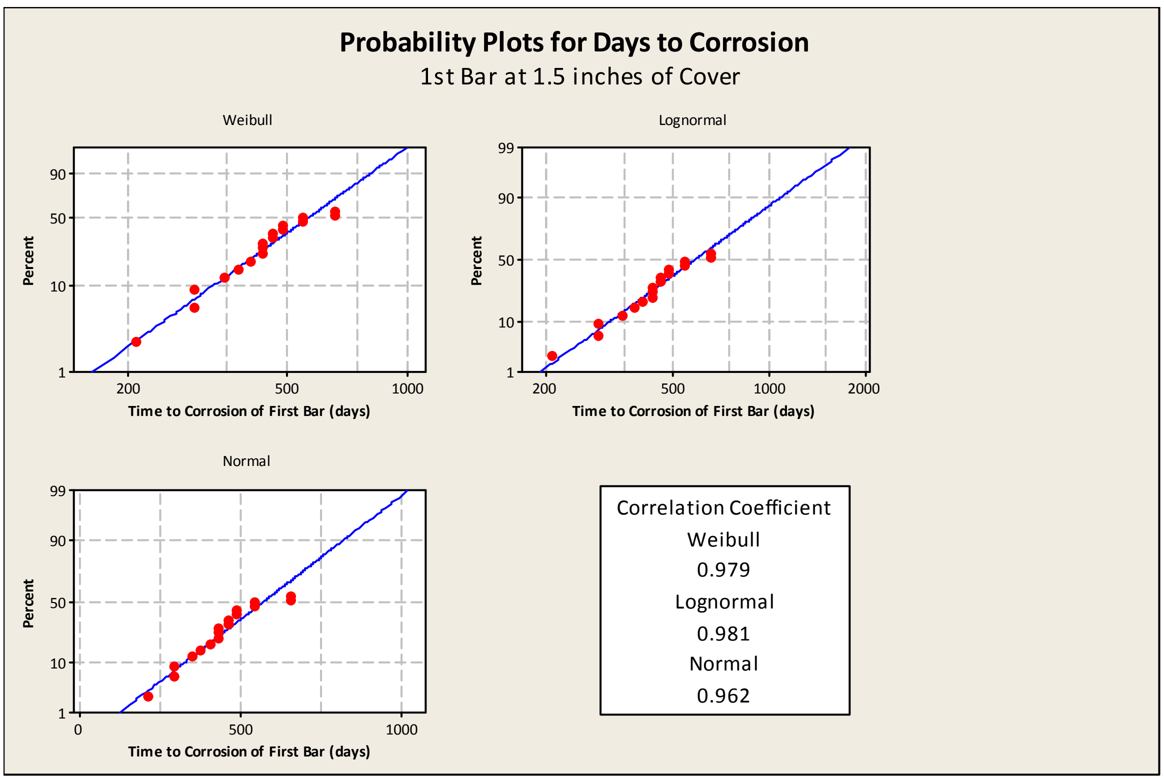


Figure 13 – Estimate of time to corrosion initiation distributions for first rebar in 1.5-inch cover slabs

Given the equally, good fits for the distributions, the Normal distribution is recommended for the mean time to corrosion for the first bar. Note that the confidence levels shown are for the mean value and the actual distribution curves will have data outside of the confidence limits.

Table 10 shows the mean and standard deviation for the initiation time for the third rebar in each slab to initiate corrosion for cover equal to 0.75-inch. Frequency and cumulative distribution plots are provided in Figure 14 and Figure 15. This data set represents the time when the chloride threshold was measured by extracting cores from each topical slab. Only three of the thirty 1.5-inch cover slabs had at least three rebars corroding prior to treatment or test completion. The statistical analysis for the 1.5-inch cover is not shown since it is such a small data set and many slabs were treated prior to three rebars initiated corrosion.

The data indicates slabs with deeper cover may exhibit a greater difference between the corrosion initiation times of individual rebars within the slab. Furthermore, since individual rebars in a slab are connected to each other through the bottom mat, except at the time of measurement, some rebars could be, and were found to be, cathodes to other rebars on the top mat. Highly corroding rebar can have a macrocell with adjacent rebars and delay corrosion initiation for the rebar acting as a cathode. Thus, the time between the first rebar and the remaining rebars in a slab to initiate corrosion can even be further delayed depending on the initial corrosion behavior of the slab.

Table 10 - Corrosion Initiation Statistical Data per Slab (Third Rebar in each Slab)

Rebar Corrosion Initiation Statistics, days (After Initial Ponding)							
	N	Mean	Std. Dev.	COV (%)	Std. Error	Minimum	Maximum
0.75-inch Concrete Cover							
0.40 w/c (Batch #1)	5/5	25.2	15.3	61	6.9	14	42
0.60 w/c (Batch #2)	5/5	53.2	15.3	29	6.9	42	70
0.50 w/c (Batches #3-5)	30/30	47.6	18.6	39	3.4	14	98

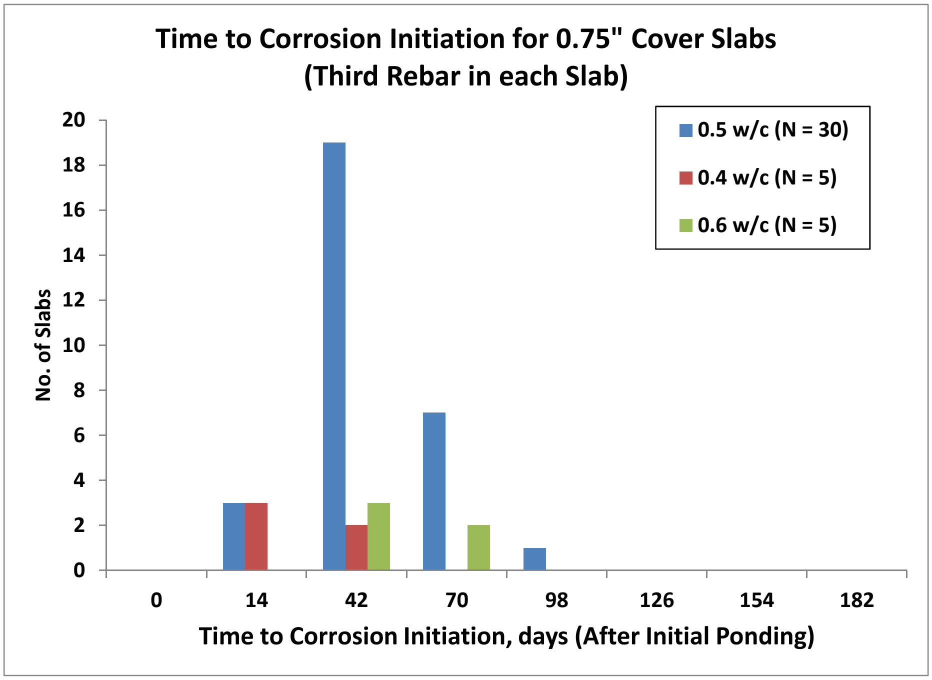


Figure 14 – Distribution of time to corrosion initiation for third rebar in 0.75-inch cover slabs

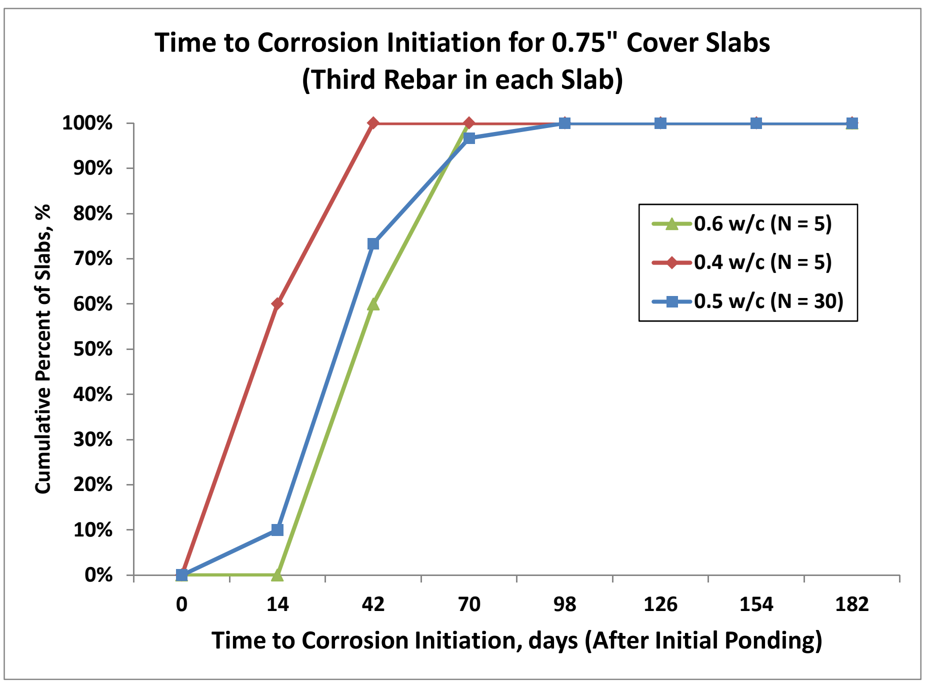


Figure 15 - Cumulative distribution of time to corrosion initiation for third rebar in 0.75-inch cover slabs

Although the half-cell potential and macrocell current criteria was not met for some rebar, it does not necessarily indicate the rebar was not corroding. Microcell corrosion can occur without resulting in macrocell current.

Repeatability of Time-to-Corrosion

The batch-to-batch repeatability was evaluated by comparing the time to corrosion initiation for batches #3-5 at both concrete covers.

0.75-inch Cover Slabs

The mean times to corrosion, and statistical data for Batches 3, 4, and 5 are given in Table 11. It appears that Batch 5 has a longer time to corrosion initiation for the first bars; however, all the specimens had bars initiating corrosion by the end of the third ponding cycle, due to the low cover. The times for 3 bars going into corrosion are shown in Table 12. Even though the mean time for three bars to initiate corrosion is lower for Batch 4, the 95% confidence limits will overlap. The mean time (days) for corrosion initiation, and standard deviation for batch numbers 3, 4, and 5 indicate that the three sets of samples statistically represent the same population.

Table 11 – Time to Corrosion Initiation of first rebar within a slab for Batches 3, 4, and 5 at w/c = 0.5 and 0.75-inch cover

		Time from first day of Ponding (days)					
Batch	N	Mean	Std. Dev.	COV (%)	Std. Error	Minimum	Maximum
3	10	28	14.76	52.7	4.67	14	42
4	10	16.8	2.8	16.7	2.8	14	42
5	10	42	0	-	0	42	42

Table 12 - Time to Corrosion Initiation of first three rebar within a slab for Batches 3, 4, and 5 at w/c = 0.5 and 0.75-inch cover

		Time from first day of Ponding (days)					
Batch	N	Mean	Std. Dev.	COV (%)	Std. Error	Minimum	Maximum
3	10	53.2	19.58	36.8	6.19	14	70
4	10	36.4	11.81	32.4	3.73	14	42
5	10	53.2	19..58	36.8	6.19	42	98

1.5-inch Cover Slabs

At 1.5-inches of cover there were no rebars corroding in the Batch 4 slabs at 742 days when testing ended. There was at least one rebar corroding in each slab for Batch 3, and Batch 5 had 7 slabs with at least one rebar corroding. A normal distribution was a good representation for the data for Batch 3 and a reliability analysis resulted in the best fit for the normal distribution for Batch 5 with an R value of 0.95. Table 13 compares Batch 3 and Batch 5. Statistics for the time of corrosion for the third rebar in each slab can't be determined, as there are not enough data points.

Table 13 - Time to Corrosion Initiation of first rebar within a slab for Batches 3, 4, and 5 at w/c = 0.5 and 1.5-inch cover

		Time from first day of Ponding (days)					
Batch	N	Mean	Std. Dev.	COV (%)	Std. Error	Minimum	Maximum
3	10	397.6	67.4	17.0	21.3	294	490
4	0	>742	-	-	-	>742	>742
5	7	609.5	195.9	32.1	74.04	210	>742

Notes: Values for Batch #5 were determined using reliability statistics for a normal distribution.

Chloride Threshold for Corrosion Initiation

The chloride threshold values for corrosion initiation were determined from cores extracted when at least 3 rebars in a slab initiated corrosion as defined previously (topical slabs only). The total (acid soluble) chloride concentration at the reinforcing bar level was determined from the core and chloride levels expressed as ppm on the concrete mass, which includes background chlorides.

The chloride threshold values were screened through Minitab to determine the best-fit distribution for the data. The distribution data for the chloride threshold values at 0.75 inch and 1.5-inch cover are given in Table 14.

The data from 0.75-inch cover consists of 30 slabs and fits a lognormal distribution as shown in Figure 16. Even though the lognormal is a better fit than the normal distribution, the values of the mean are statistically the same.

Data from 1.5-inch cover consists of seven slabs and the three major distributions were all good fits to the smaller data set. The chloride thresholds are significantly higher at 1.5-inches of cover as the 95% confidence limits do not overlap those at 0.75-inch of cover. Figure 16 shows the distribution curves.

Table 14 – Chloride threshold statistics, ppm

Chloride Threshold Statistics, ppm							
	N	Mean	Std. Dev.	COV (%)	Std. Error	Minimum	Maximum
0.75-inch Concrete Cover							
0.40 w/c (Batch #1)	3*	305	2	1	1.3	302	306
0.60 w/c (Batch #2)	4*	896	484	54	241.9	542	1575
0.50 w/c (Batches 3-5)	30	564	388	69	70.9	222	1889
All 0.75 inch Cover	37	579	398	69	65.4	222	1889
1.5-inch Concrete Cover							
0.5 w/c (Batches 3-5)	7	922	236	26	89.4	586	1216

*The chloride threshold of the remaining slabs (N = 5) was taken when 1 rebar initiated corrosion and is not included in this data set

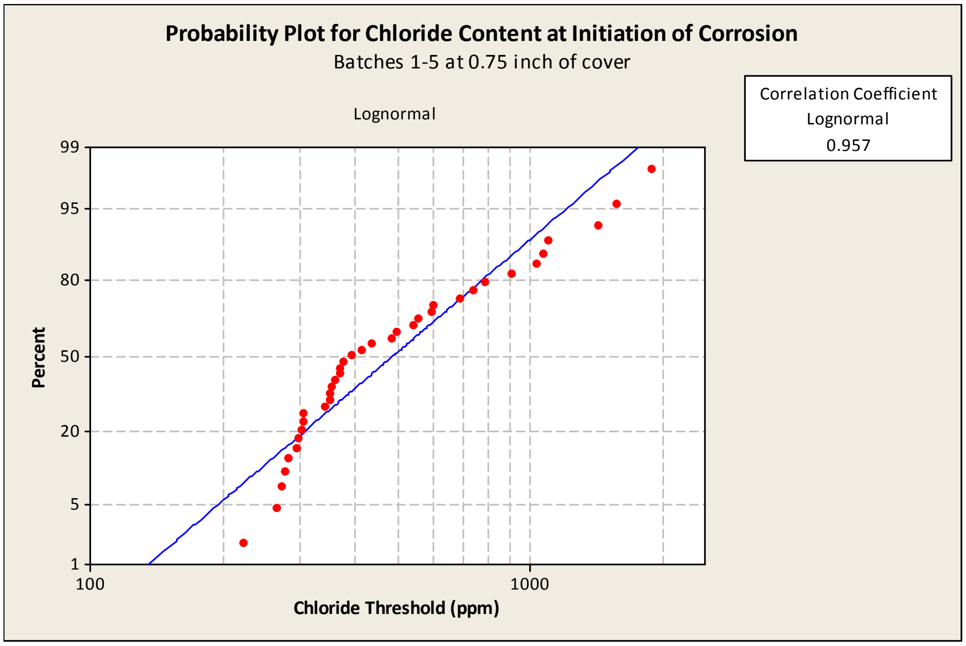


Figure 16 – Chloride threshold distribution (Batches 1-5, 0.40-0.60 w/c, 0.75-inch cover)

Evaluation of Corrosion Initiation Definition

The corrosion initiation definition for this project was evaluated by plotting the half-cell potential as a function of current on a semi-log scale for all measurements. Figure 17 through Figure 19 provide the plots for Batches #3-5 for 1.5-inch cover slabs. In all batches the data becomes linear once active corrosion starts, typically around a half-cell potential of -300 mV CSE_{77} and macrocell current above 0.030 mA.

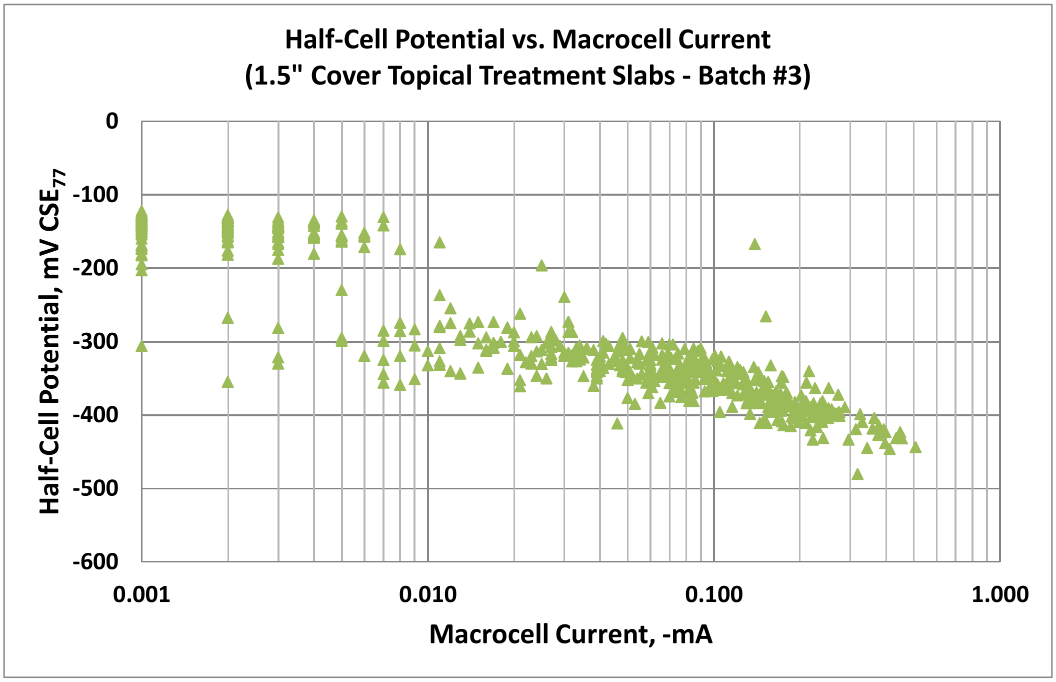


Figure 17 – Semi-Log plot of macrocell current vs. half-cell potential as a function of time (1.5-inch cover, Batch #3)

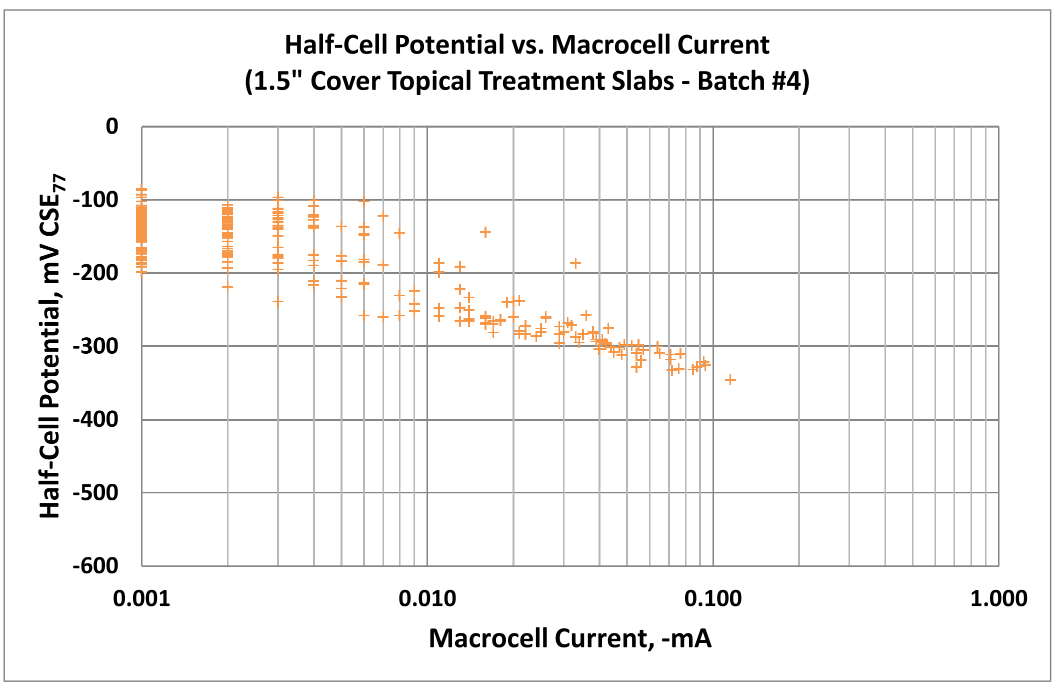


Figure 18 - Semi-Log plot of macrocell current vs. half-cell potential as a function of time (1.5-inch cover, Batch #4)

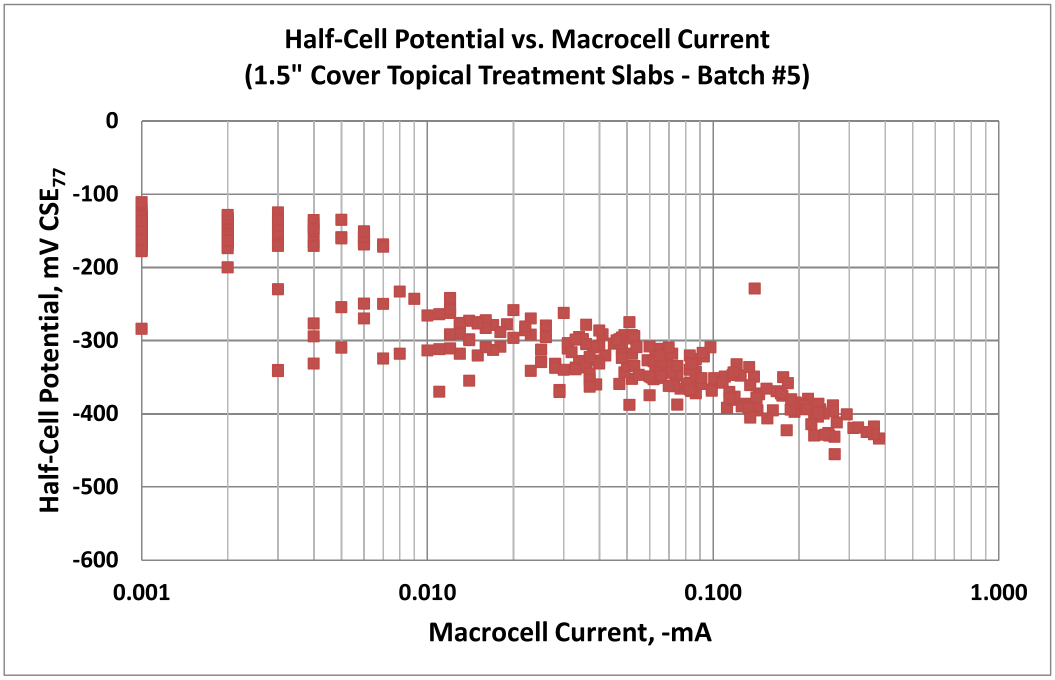


Figure 19 - Semi-Log plot of macrocell current vs. half-cell potential as a function of time (1.5-inch cover, Batch #5)

Time to Corrosion Initiation and Chloride Threshold Key Findings

The key findings of the time to corrosion initiation and chloride threshold analysis are:

- 0.75-inch cover test specimens began to corrode essentially immediately with more than 18% of all rebar and 53% of all slabs corroding after the first ponding cycle including:
  - o 20 of 40 rebar and 5 of 5 slabs in Batch #1, 0.40 w/c
  - o 25 of 180 rebar and 14 of 30 slabs in Batches #3-5, 0.50 w/c
  - o 2 of 40 rebar and 2 of 5 slabs in Batch #2, 0.60 w/c
- More than 80% of all bars in 0.75-inch cover slabs had initiated corrosion by 70 days, i.e. the end of the wetting period of the third ponding cycle
- 1.5-inch cover test specimens took significantly longer to initiate corrosion. Many either began corroding after 1-year or did not corrode within the test duration.
  - o 10 of 180 rebar and 5 of 30 slabs had initiated corrosion at 378 days or just over 1 year
  - o Only 28 of 180 rebar and 17 of 30 slabs initiated corrosion prior to treatment or test completion
- The time to corrosion initiation between batches provided consistent and repeatable results for 0.75-inch cover slabs with the 95% confidence interval overlapping in batches #3-5. The time to corrosion initiation in 1.5-inch cover slabs had more scatter between batches. No slabs in batch #4 had initiated corrosion within the project duration.
- Individual bars may delay the time for corrosion initiation for other bars within the same slab by becoming the recipient of macrocell cathodic current

- Further analysis of the corrosion initiation definition used in this study revealed corrosion activity actually begins at approximately -300 mV CSE[77] and 0.030 mA.
- The chloride threshold for 0.75-inch cover slabs was 579 ppm, on average, which is typical for conventional reinforcement. The chloride threshold for 1.5-inch cover slabs was higher at 922 ppm. The higher chloride threshold was likely a result of chloride accumulation from additional ponding cycles in the time between one rebar corroding and three rebars corroding when cores were extracted. Measuring the chloride threshold when one rebar corrodes may be more appropriate.

Test Protocol Recommendations Related to Time to Corrosion Initiation

For use in the test protocol TCG recommends:

- Using a depth of concrete cover to reinforcement of 1.0-inch or 1.25-inches would result in acceptable times for corrosion initiation.
- Use nominal maximum size aggregate no greater than ½ times the concrete cover in order to minimize settlement cracking and crazing, e.g. 0.5-inch nominal maximum size aggregate for 1.0-inch cover.

Corrosion Rate

The corrosion rate was analyzed for each concrete cover and w/c. This helps to predict the amount of corrosion expected after a defined number of ponding cycles and the desired duration of testing. The slab repeatability and batch-to-batch repeatability was also evaluated by analyzing the variability of corrosion rates. Furthermore, the corrosion rates of both concrete covers were compared for Batch #3 slabs. Batch #3 was selected since it has the most data available.

The corrosion rates are expressed in the form of charge passed per time or integrated macrocell current per time (ponding cycle) in Coulombs (Amps x Seconds). For 0.75-inch cover, the data is evaluated from the initial measurements up to the time of treatment application. The average and standard deviation of the slab total integrated current as a function of days and ponding cycle is provided in Table 16. The data is compared by batch in Figure 20 and by w/c in Figure 21. The data consists of an average of individual slabs as shown by the solid lines and plus or minus one standard deviation as shown by the dashed lines. Plots for individual slabs showing each rebar are provided in Appendix F.

Some of the integrated current variation can be attributed to the deviation in which corrosion initiates on individual rebars.

Table 15 – Corrosion Rate Conversion for One Ponding Cycle

Corrosion Rate Conversion		
Passed Charge, Coulombs	Measured Current per Cycle, mA (28 days)	Rate per Slab, mA/m^2 ($0.219\ m^2$)
10	0.004	0.019
100	0.041	0.189
1000	0.413	1.89
10000	4.134	18.9

Table 16 – Integrated Macrocell Current Statistics with Time (Prior to Treatment Application)

Integrated Macrocell Current, C									
Cycle	0	1	2	3	4	5	6	7	8
Age, d	0	14	42	70	98	126	154	182	210
0.5 w/c, Batches 3-5, N = 30									
Average	0	147	1648	5098	10123	16300	23068	-	-
St. Dev.	0	197	1278	2887	4682	6757	9108	-	-
Δ/Cycle	0	147	1501	3450	5025	6177	6768	-	-
0.40 w/c, Batch #1, N = 5									
Average	0	795	7746	20075	35385	51265	66211	80996	96352
St. Dev.	0	782	3703	5658	7059	8257	9472	11080	12846
Δ/Cycle	0	795	6951	12329	15310	15880	14946	14785	15356
0.60 w/c, Batch #2, N = 5									
Average	0	43	1110	5004	12005	21012	31394	42699	55755
St. Dev.	0	63	360	931	1747	2624	3760	5172	7029
Δ/Cycle	0	43	1067	3894	7001	9007	10382	11305	13056
0.50 w/c, Batch #3, N = 10									
Average	0	122	1279	4503	9797	16591	24429	33445	
St. Dev.	0	145	969	2686	4836	7047	9284	11439	
Δ/Cycle	0	122	1157	3224	5294	6794	7838	9016	
0.50 w/c, Batch #4, N = 10									
Average	0	318	2896	7668	13750	20974	28764	37118	
St. Dev.	0	217	1169	2312	3559	5279	7030	8362	
Δ/Cycle	0	318	2578	4772	6082	7224	7790	8354	
0.50 w/c, Batch #5, N = 10									
Average	0	2	770	3122	6823	11334	16011	-	-
St. Dev.	0	3	467	1492	2782	4220	6182	-	-
Δ/Cycle	0	2	768	2352	3701	4511	4677		-

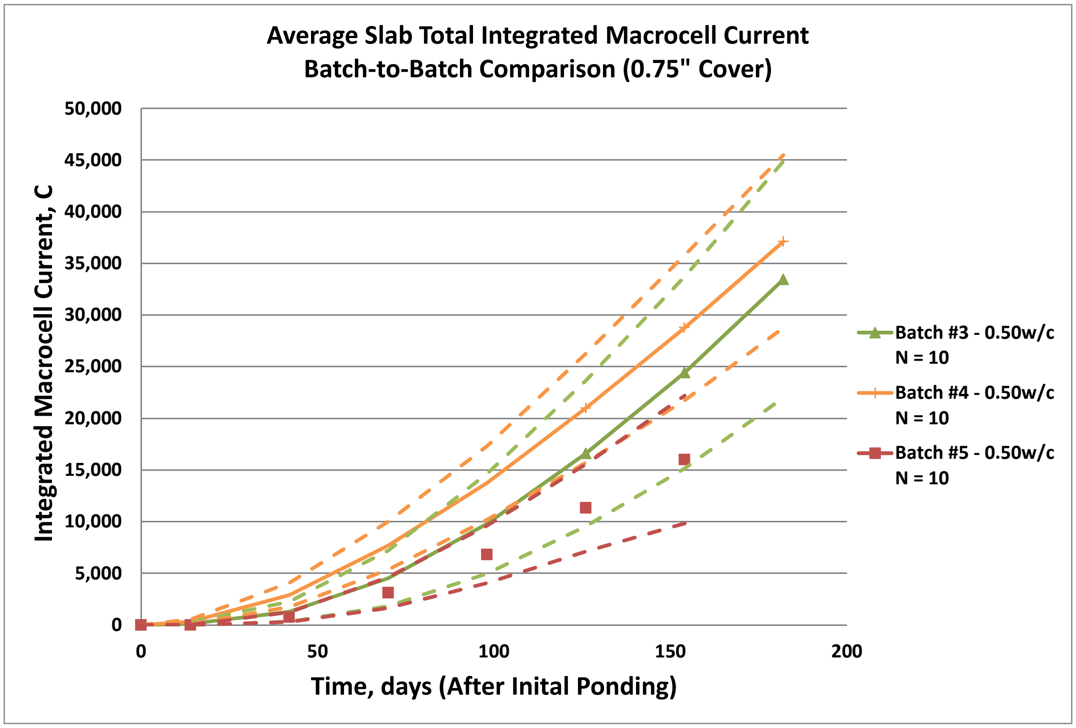


Figure 20 – Average Slab total integrated current as a function of time, batch-to-batch comparison

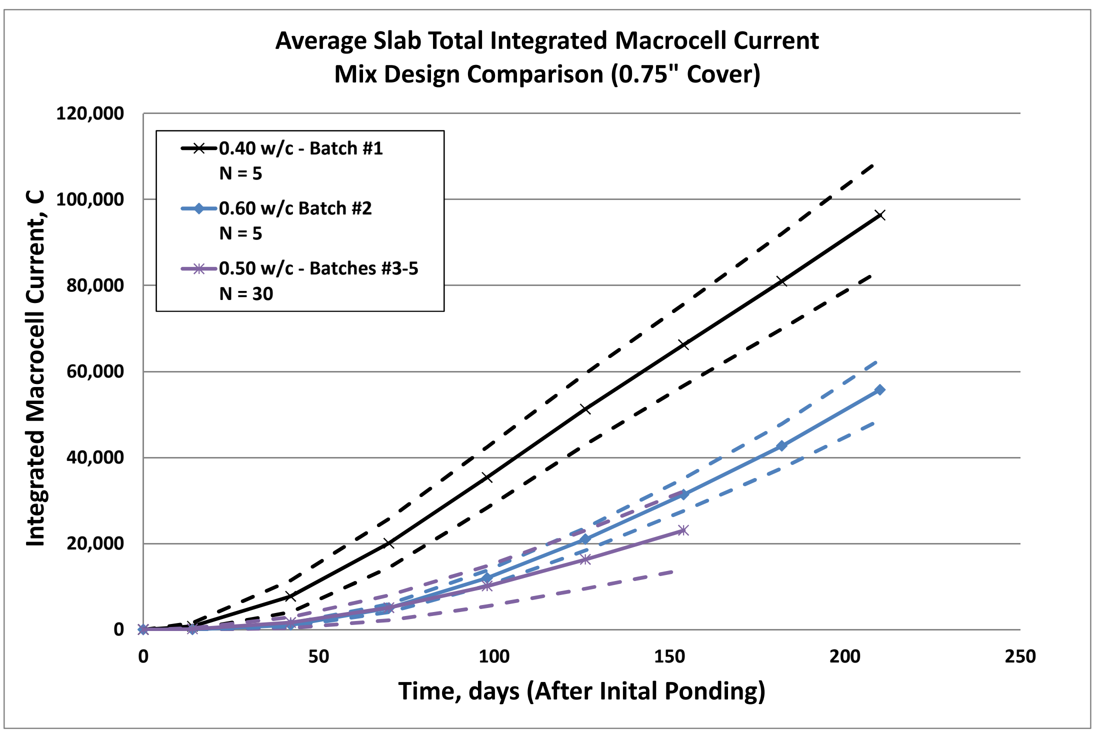


Figure 21 – Average Slab total integrated current as function of time, w/c comparison

The rate of corrosion for both depths of concrete cover is listed in Table 17 and shown in Figure 22. For a simpler comparision, the time zero was set to be 2 cycles prior to corrosion initiation of any rebar in the slab. This way, only the corrosion rate after corrosion initiation is compared. The data indicates 1.5-inch cover rebars corrode at a slower rate after corrosion has initiated.

Table 17 - Integrated Macrocell Current Statistics with Time – Concrete Cover Comparison (Prior to Treatment Application)

Integrated Macrocell Current, C										
Cycle*	0	1	2	3	4	5	6	7	8	9
Age, d	0	14	42	70	98	126	154	182	210	238
0.75-inch Cover, 0.5 w/c, Batch #3, N = 10										
Average	0	122	1279	4503	9797	16591	24429	33445	-	-
St. Dev.	0	145	969	2686	4836	7047	9284	11439	-	-
Δ/Cycle	0	122	1157	3224	5294	6794	7838	9016	-	-
1.5-inch Cover, 0.5 w/c, Batch #3, N = 10										
Average	0	152	271	485	854	1368	1981	2708	3519	4427
St. Dev.	0	147	242	342	418	455	505	603	847	1150
Δ/Cycle	0	152	119	214	369	514	613	727	811	909

*Cycle “0” is set as two cycles prior to corrosion initiation of the first rebar in each slab

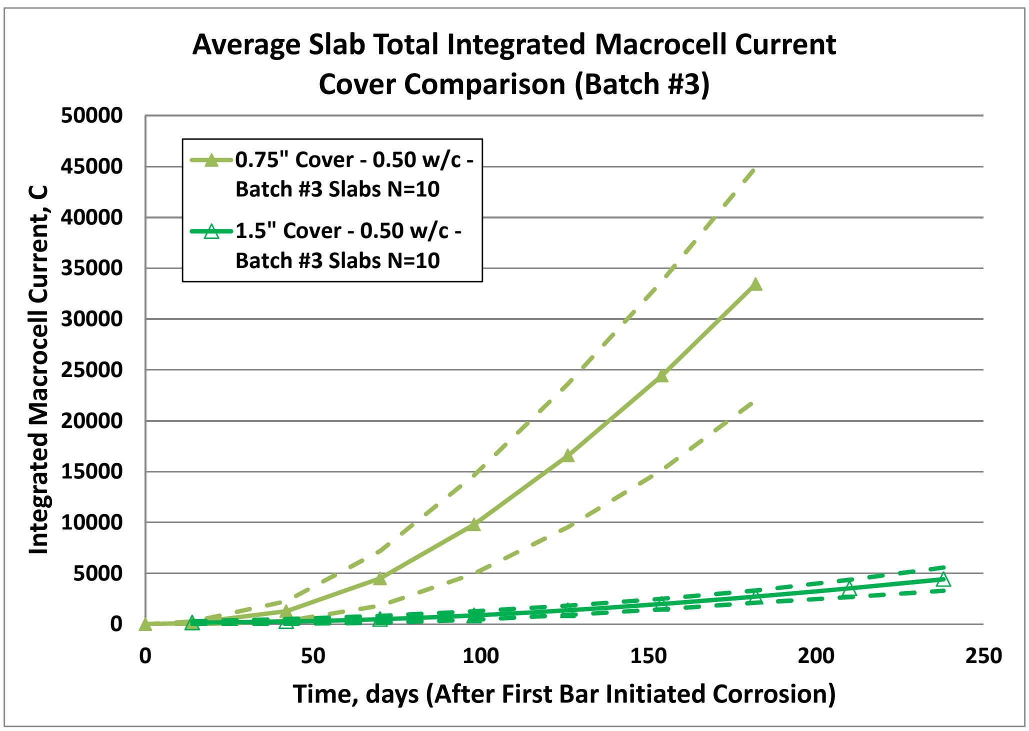


Figure 22 – Corrosion rate as a function of time for both concrete covers in Batch #3 (data shown is after corrosion has initiated)

The slower corrosion rates measured in slabs with deeper cover can be attributed to a slower buildup of chloride at the rebar. Figure 23 displays the average number of rebar that have initiated corrosion per slab is much less in 1.5-inch cover slabs.

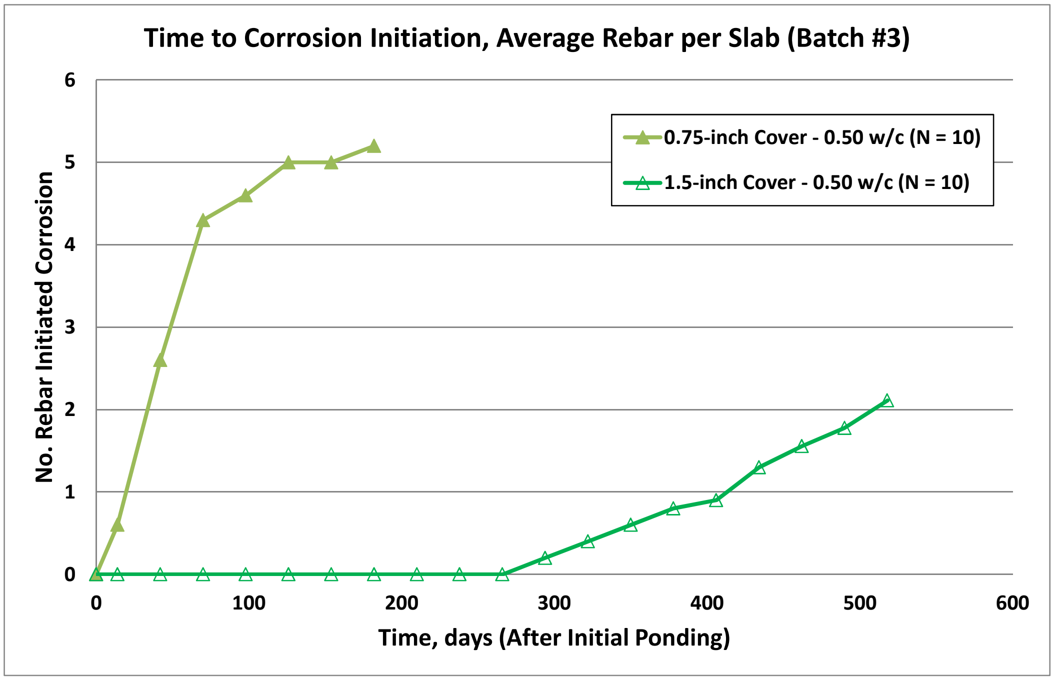


Figure 23 - Average number of rebar corroding (initiated) per slab as a function of time comparing cover depth in Batch #3 slabs

Summary of Corrosion Rate Findings

The key findings of slab corrosion rates are:

- The corrosion rate of 0.75-inch cover slabs was very rapid.
  - Batch #1 slabs corrosion rate was nearly 15,000 coulombs per ponding cycle by the 4th cycle.
  - Batch #5 slabs corrosion rate was slower, but still reaching nearly 5,000 Coulombs per ponding cycle by the 6th cycle.
- The corrosion rates between batches are similar as shown by comparing batches #3 through batch #5 in Figure 20 and Table 16. The main discrepancy between the batches is that rebar in batch #5 initiated corrosion on average nearly one ponding cycle after batch #4 (refer to Table 11 and Table 12). The batch-to-batch corrosion rates become much closer if the corrosion rates of Batch #5 slabs are compared to the corrosion rates in Batch #3 and #4 at one cycle earlier.
- Slabs constructed with the higher permeability batch #1 concrete corroded at the fastest rate suggesting the quality of concrete also plays a role in the rate of corrosion.

- Concrete cover had a significant effect on the rate of corrosion, i.e. after corrosion initiation, 0.75-inch cover slabs corroded at a much faster rate than 1.5-inch cover slabs. This behavior is likely caused by the faster continual build-up of chlorides at the rebar level.

Methods to Accelerate Corrosion

Hotspot Techniques

Three hot-spot techniques designed to accelerate corrosion were evaluated in repair slabs:

1. Chloride spiked: Admixtured flake calcium chloride to the base concrete mixture at a rate of 20 lbs./yd^3.
2. High-water content: High water to cement ratio concrete (>0.70) located in repair area.
3. Depressed cover: 8-inch wide by 15-inch long by 1-inch deep depression centered over the half-length reinforcing steel bars.

A more detailed description of the construction methods of each hotspot is located in Appendix A.

The effectiveness of hotspot techniques were evaluated based on:

- The ability to accelerate corrosion of rebar within the hotspot
- The ability to influence rebar outside of the hotspot

The following plots provide the average half-cell potential (Figure 24) and integrated current (Figure 25) for individual rebar as a function of time. Each plot is the average of 20 bars, i.e. 2 per slab, 5 slabs per batch. Data is shown up to approximately 400 days of testing (~15 ponding cycles). At this time the hotspots were disconnected when it became apparent that the hotspots may be cathodically protecting rebar outside the hotspot by throwing positive current to the main rebar.

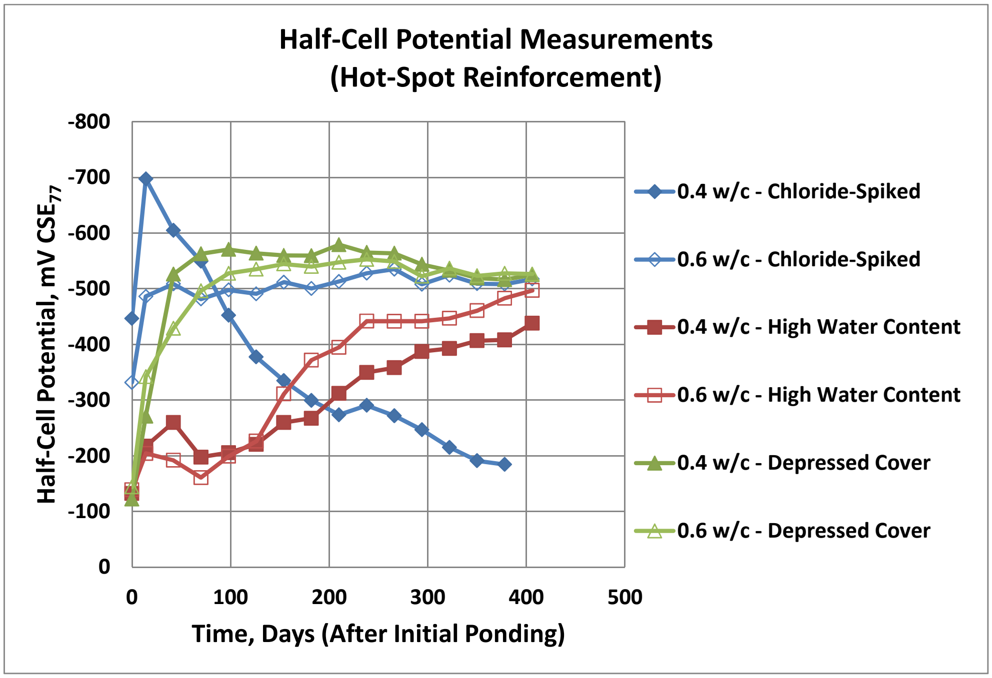


Figure 24 - Average half-cell potential as a function of time (hotspot rebar, 1.5-inch cover)

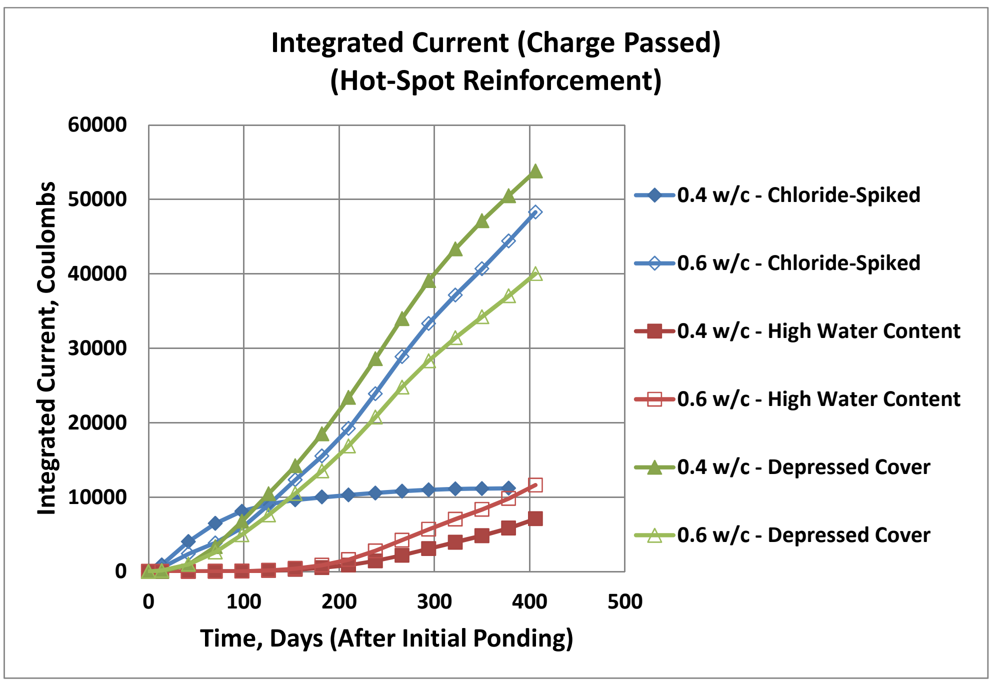


Figure 25 - Average integrated current as a function of time (hotspot rebar, 1.5-inch cover)

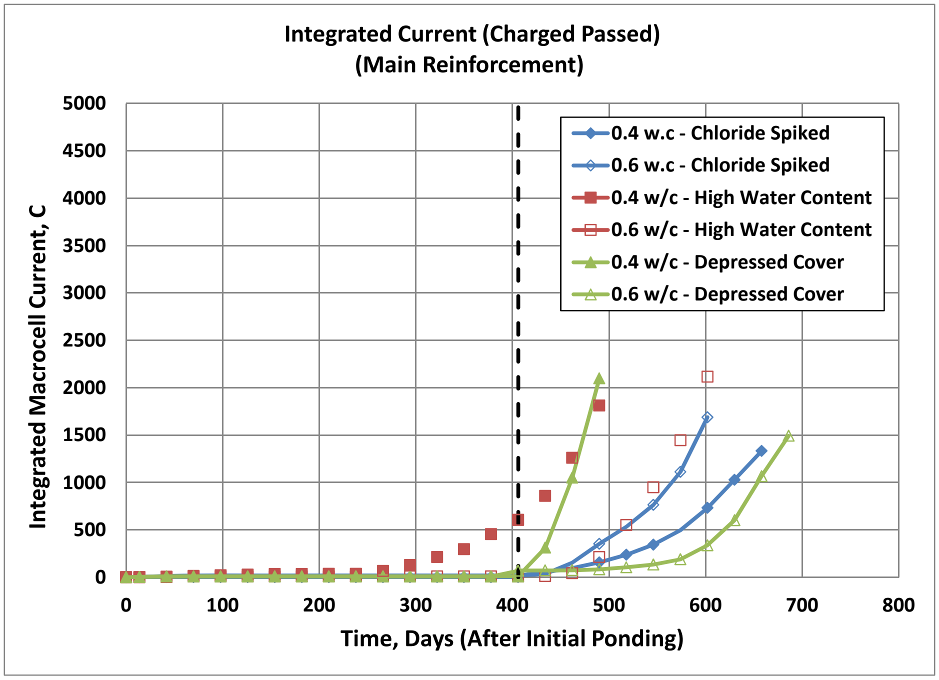


Figure 26 – Average integrated current as a function of time (main rebar, 1.5-inch cover)

Figure 27 and Figure 28 show photographs of chloride-spiked and depressed cover hotspots where severe corrosion damage has occurred with visual damage on the slab surface.

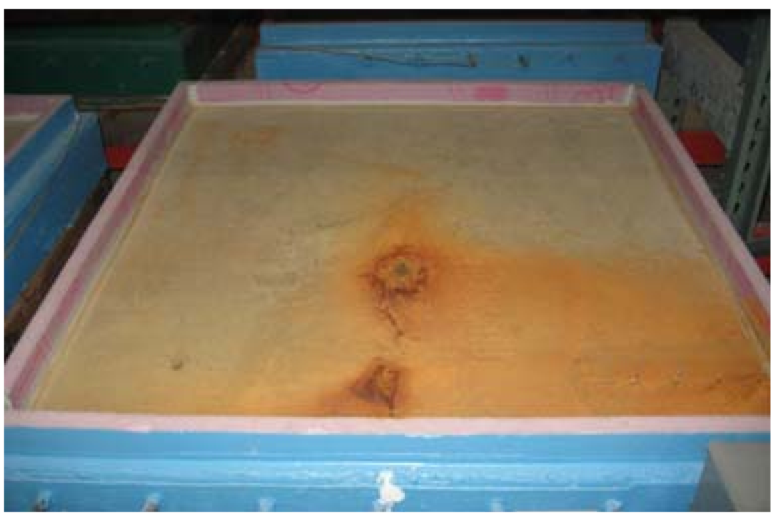


Figure 27 – Photograph of chloride-spiked hotspot (Batch #2, Slab 23)

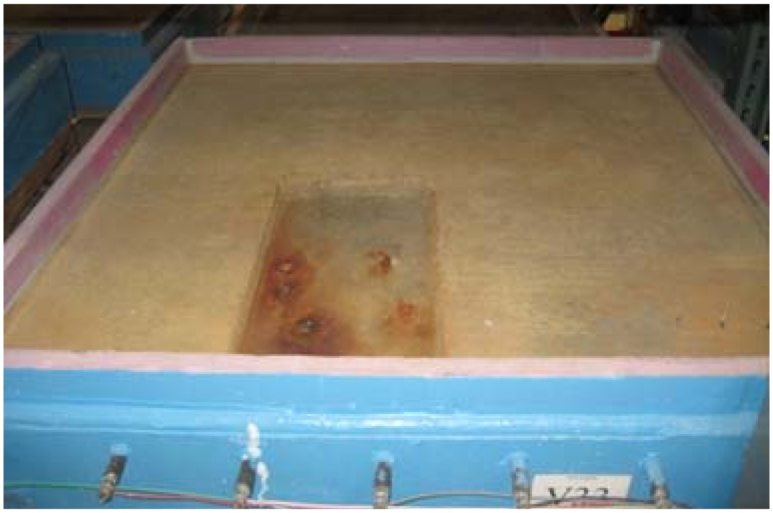


Figure 28 – Photograph of depressed cover hotspot (Batch #2, Slab 33)

<u>Summary of Findings of Methods to Accelerate Corrosion</u>

The key findings are:

- All hotspot techniques accelerated corrosion in rebars within the hotspot compared to rebar outside the hotspots.
    - Chloride-spiked hotspot rebars in batch #1 did not sustain macrocell corrosion activity and gradually reduced after the initial ponding cycle. Microcell corrosion may have continued on these rebars.
    - High-water content hotspot technique gradually increased the corrosion activity over time rather than reach a high level of corrosion activity after the first ponding cycle as seen by the chloride-spiked and depressed cover hotspot techniques.
    - Depressed cover hotspot technique resulted in severe cracking in a short period of time. The cracking lead to direct pathways for the ponding solution and in some cases even allowed enough chlorides to reach the wire mesh and turn it anodic.
- Most hotspot techniques setup active corrosion cells between rebar inside the hotspot and rebar outside the hotspot.
    - The chloride-spiked and depressed cover hotspot rebar provided galvanic current to the main bars
    - The high-water content hotspot rebar with lower corrosion activity did not create strong active corrosion cells between hotspot and main rebars in the 0.40 w/c concrete slabs.

Note the hot-spot rebar tended to prevent corrosion from initiating in rebar surrounding the hot-spot and effectively provided cathodic protection as shown by positive macrocell current. It was only after the hot-spot rebar was disconnected from the system that corrosion began in rebar outside the hot-spots.

Additional findings related to constructability and testing include:

- Depressed cover hotspots were the easiest and most efficient to construct as they did not require any additional concrete mixing.
- Depressed cover hotspots require additional means of drainage after each ponding cycle such as a vacuum.

Corrosion Mitigation

Topical Treatments

Three topical corrosion mitigation treatments were selected by the expert panel:

Topical Treatments

A. Calcium Nitrite Inhibitor (CNI)
B. 40% Silane Sealer (Sealer)
C. Epoxy/Urethane Traffic Membrane (Epoxy)

The 0.75-inch cover slabs were the first to initiate corrosion and were treated according to Table 18. The slabs were treated in two groups:

1. May 2011 treatments
   a. Batch #1 – 217 days after initial ponding, 8th ponding cycle
   b. Batch #3 – 189 days after initial ponding, 7th ponding cycle
   c. Batch #5 – 161 days after initial ponding, 6th ponding cycle
2. June 2011 treatments
   a. Batch #2 – 217 days after initial ponding, 8th ponding cycle
   b. Batch #4 – 189 days after initial ponding, 7th ponding cycle

The 0.75-inch topical treatment slabs were treated during the same time period resulting in treatment applications at various levels of corrosion activity by batch. Certain technologies may not provide the same level of performance at different levels of corrosion activity. Therefore, the comparison of technologies was limited to within each batch. Within each batch, the results vary as each slab was treated at the same time, but having different levels of corrosion damage. A treatment criteria for the amount of corrosion damage at time of treatment was developed and fine-tuned during this project which is discussed later on page 67.

Table 18 – 0.75-inch cover topical slab treatment list

Batch #	Control	0.75" Cover Topical Treatments			TOTAL Slabs
		A	B	C	
1 (0.40 w/c)	3	2	-	-	5
2 (0.60 w/c)	3	2	-	-	5
3 (0.50 w/c)	4	2	2	2	10
4 (0.50 w/c)	4	2	2	2	10
5 (0.50 w/c)	4	2	2	2	10
Total	**18**	**10**	**6**	**6**	**40**

A full description of the treatments and application procedures can be found in Appendix D.

The effectiveness of corrosion mitigation topical treatments was evaluated by statistical differences between control and treated test specimens in the following performance categories:

- Half-cell potential measurements
    - Half-cell potential mapping
- Macrocell current measurements
    - Integrated Current (Passed Charge)
- Mat-to-Mat resistance
- Concrete resistivity (Wenner 4-Pin Method)
- Chloride profile
- Internal relative humidity
- Destructive analysis

The following plots are a sample of the results showing the performance of the corrosion mitigating technologies. The results focus on Batches #4 and #5 where each slab within each batch was treated at approximately the same level of corrosion. In some cases, the same data is presented in several ways. The complete results organized by slab type, cover, and batch are provided in Appendix H.

Table 19 – Batch #4, 0.50 w/c, 0.75-inch cover topical slabs

Slab No.	Treatment	Days (After Initial Ponding)	Completed Ponding Cycles Prior to Treatment	Number of Rebar Initiated Corrosion	Total Slab Integrated Current, Coulombs	Average Half-Cell Potential, mV CSE_{77}
71	Control	(189)	(7)	4	28967	-467
72	Control	(189)	(7)	6	55457	-536
73	CNI	189	7	6	41313	-525
74	Control	(189)	(7)	3	29428	-462
75	Sealer	189	7	6	40461	-517
76	Sealer	189	7	6	38492	-497
77	Control	(189)	(7)	6	30027	-500
78	Epoxy	189	7	6	33121	-490
79	CNI	189	7	6	31025	-490
80	Epoxy	189	7	6	42894	-515

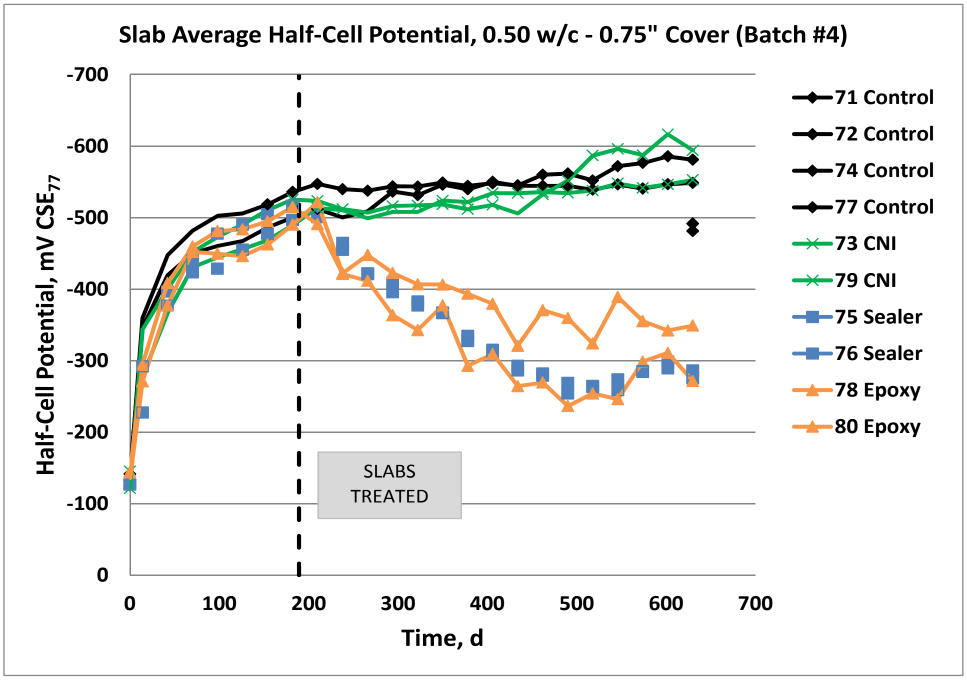


Figure 29 - Slab average half-cell potential as a function of time (Individual slabs, Batch #4, 0.50 w/c, 0.75-inch cover)

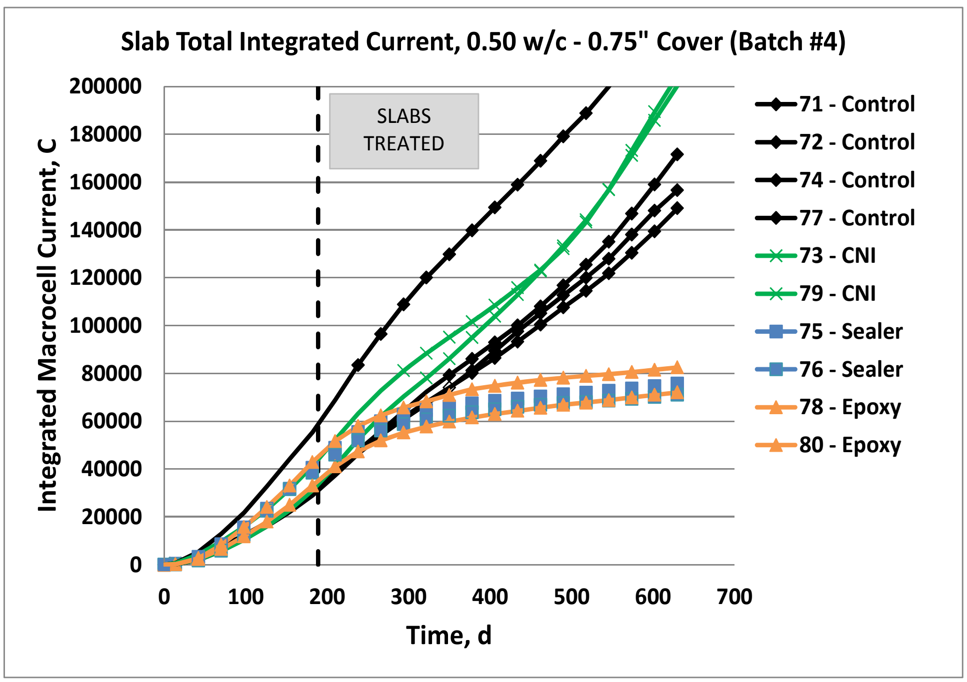


Figure 30 - Slab total integrated current as a function of time (Individual slabs, Batch #4, 0.50 w/c, 0.75-inch cover)

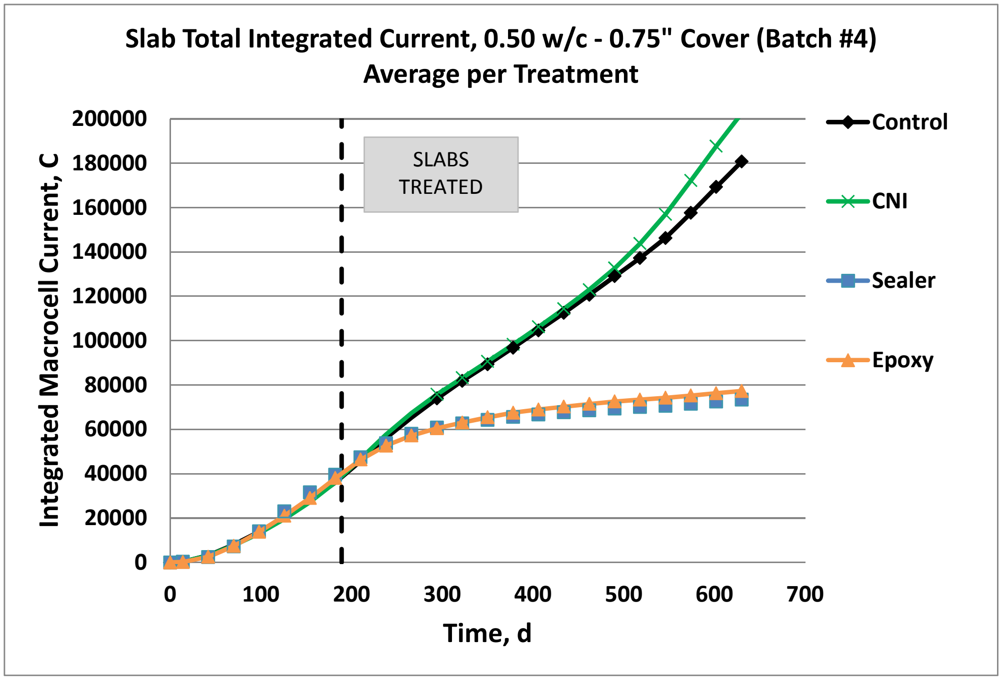


Figure 31 – Slab total integrated current as a function of time (Average per treatment, Batch #4, 0.50 w/c, 0.75-inch cover)

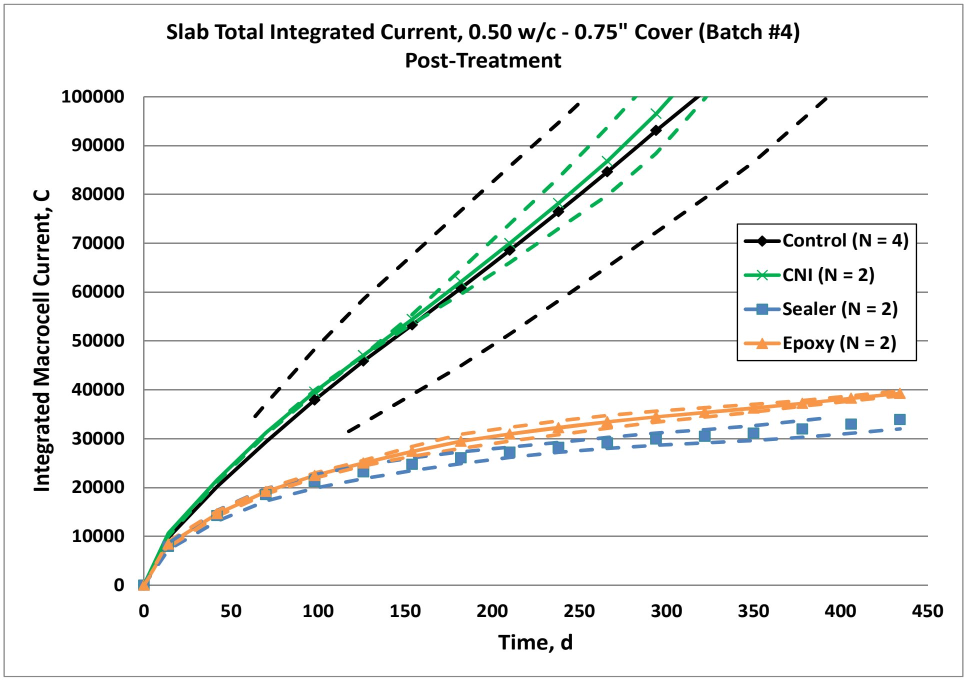


Figure 32 – Slab total integrated current post-treatment as a function of time (Average per treatment, 0.50 w/c, 0.75-inch cover)

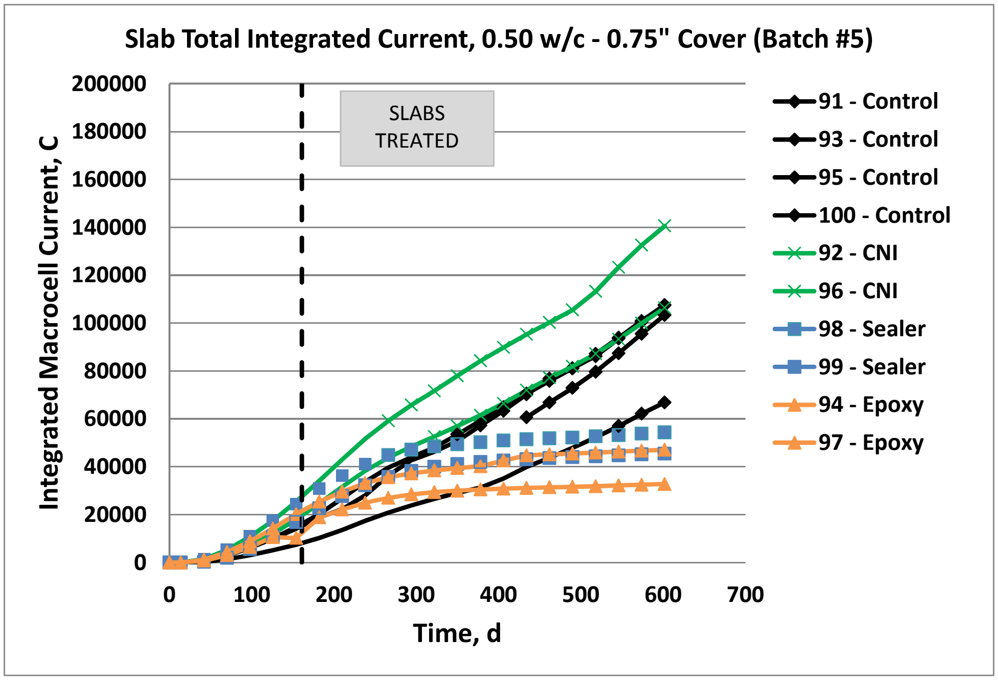


Figure 33 - Slab total integrated current as a function of time (Individual slabs, Batch #5, 0.50 w/c, 0.75-inch cover)

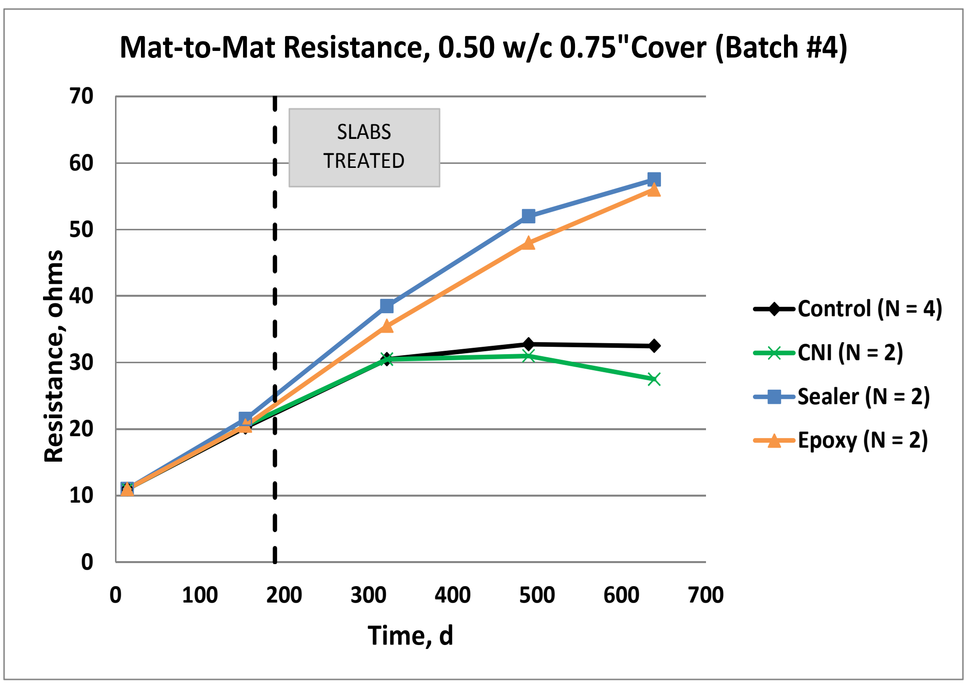


Figure 34 - Average mat-to-mat resistance as a function of time (Batch #4, 0.50 w/c, 0.75-inch cover)

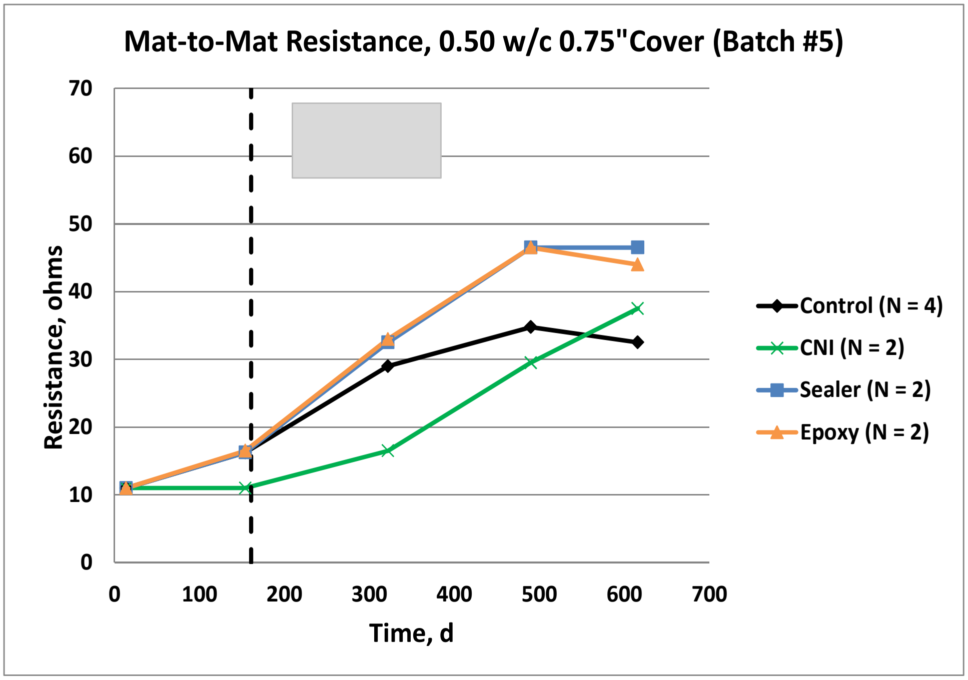


Figure 35 - Average mat-to-mat resistance as a function of time (Batch #5, 0.50 w/c, 0.75-inch cover)

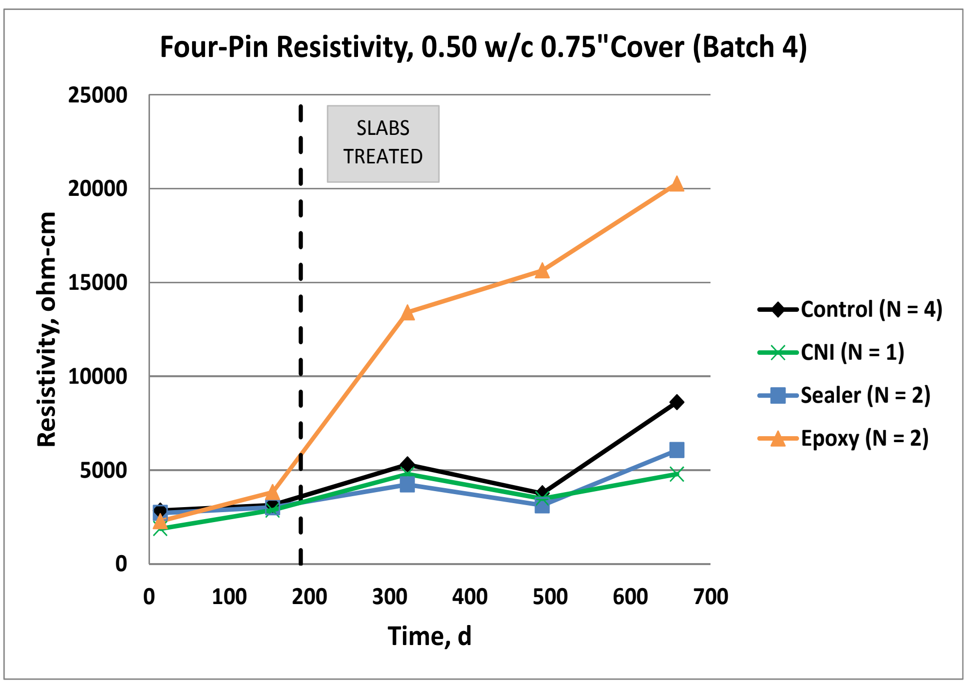


Figure 36 - Average 4-pin resistivity as a function of time (Batch #4, 0.50 w/c, 0.75-inch cover)

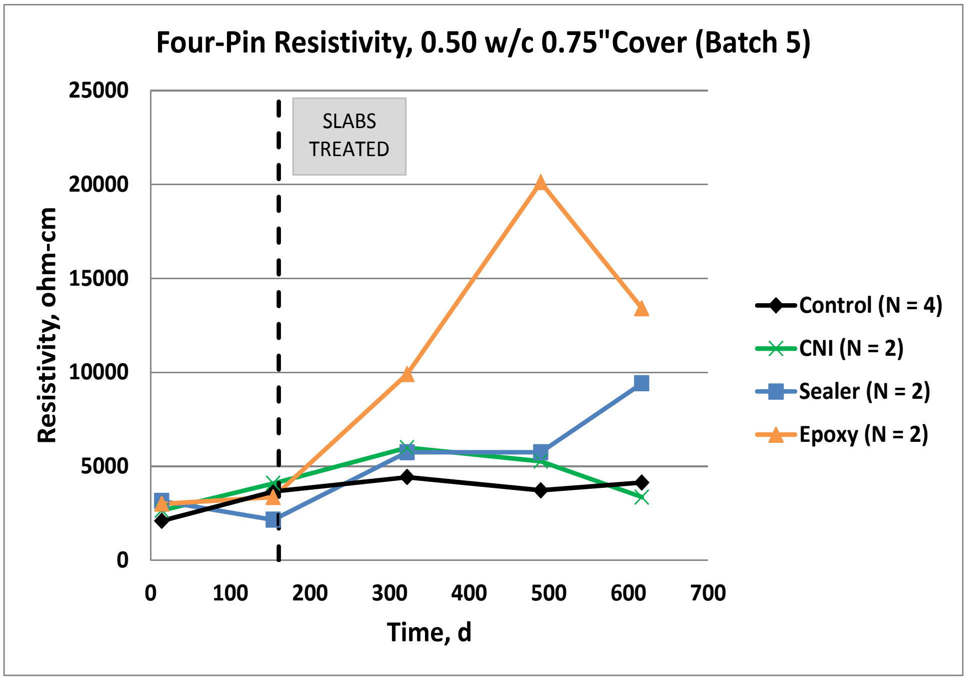


Figure 37 - Average 4-pin resistivity as a function of time (Batch #5, 0.50 w/c, 0.75-inch cover)

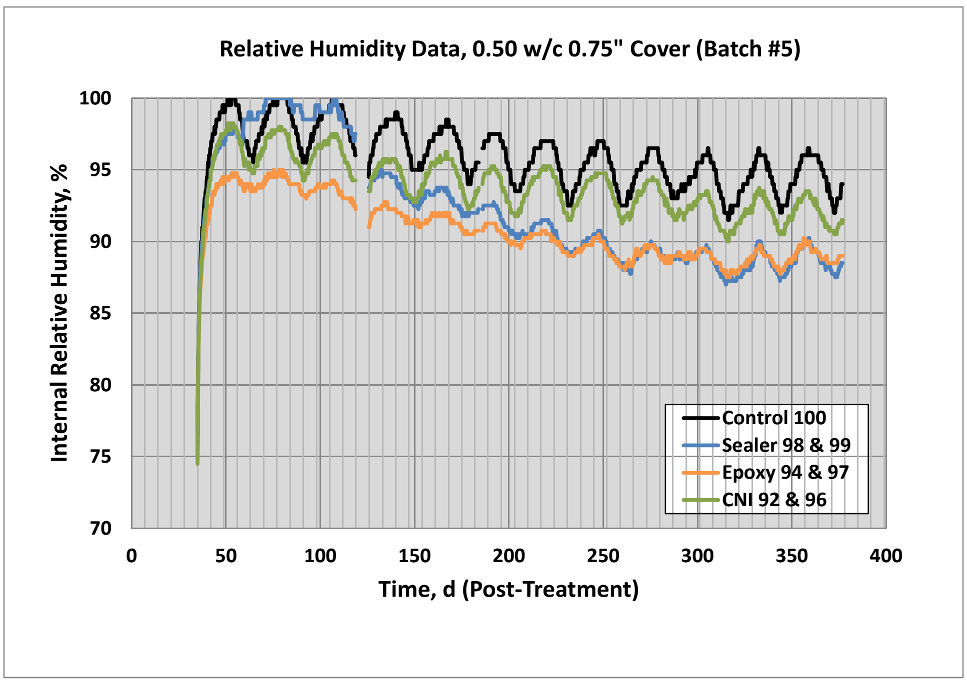


Figure 38 - Relative humidity as a function of time (Batch #5, 0.50 w/c, 0.75-inch cover)

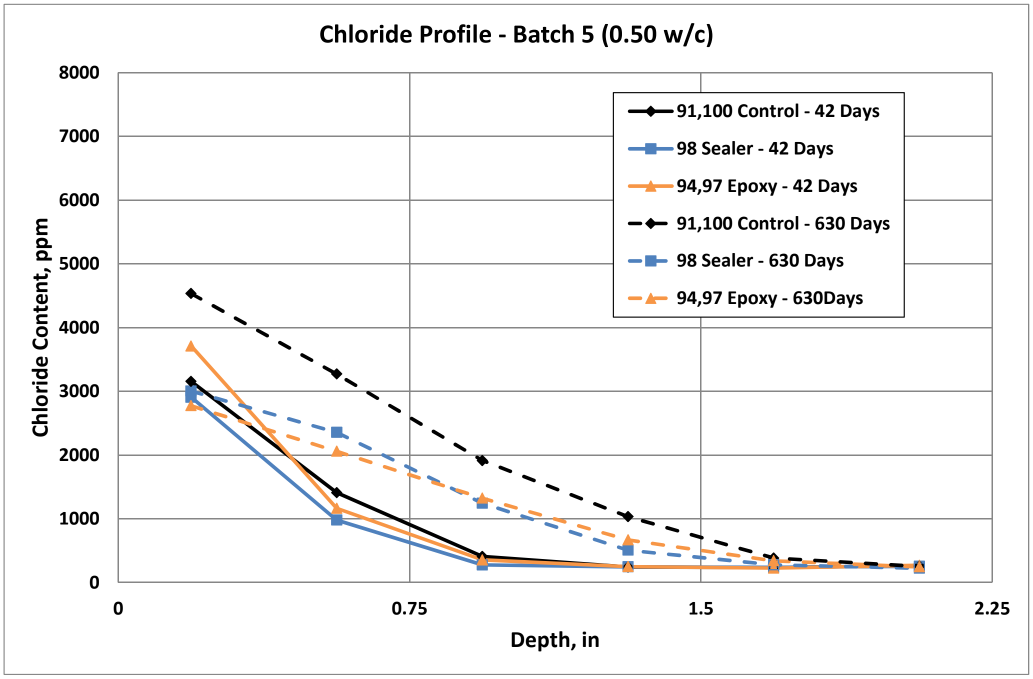


Figure 39 – Chloride profiles at two time periods, 42 days (prior to treatment) and 630 days (end of testing) for selected Batch #5 control, sealer, and epoxy treated slabs

Table 20 – Destructive Analysis Results and Treatment Evaluation for Batch #3 Slabs

Batch #3											
Slab ID		Pre-Treatment		Final Measurements		Difference		Visually Examined Corrosion			
Treatment	Slab #	Integrated Current (Coulombs)	Average Half-Cell Potential (mV CSE_{77})	Integrated Current (Coulombs)	Average Half-Cell Potential (mV CSE_{77})	Integrated Current (Coulombs)	Average Half-Cell Potential (mV CSE_{77})	Light	Moderate	Heavy	Total
Control	54	22257	-508	128882	-504	106625	4	0.0%	4.1%	28.1%	32.2%
CNI	51	55164	-566	293549	-546	238385	20	0.3%	1.7%	44.2%	46.2%
Sealer	52	50282	-577	110622	-291	60340	286	0.0%	4.2%	40.4%	44.6%
Epoxy	58	36950	-522	89121	-371	52171	151	0.1%	7.7%	32.4%	40.4%

Table 21 – Destructive Analysis Results and Treatment Evaluation for Batch #4 Slabs

Batch #4											
Slab ID		Pre-Treatment		Final Measurements		Difference		Visually Examined Corrosion			
Treatment	Slab #	Integrated Current (Coulombs)	Average Half-Cell Potential (mV CSE_{77})	Integrated Current (Coulombs)	Average Half-Cell Potential (mV CSE_{77})	Integrated Current (Coulombs)	Average Half-Cell Potential (mV CSE_{77})	Light	Moderate	Heavy	Total
Control	72	55457	-536	245564	-581	190107	-45	0.3%	5.3%	34.0%	39.6%
Control	77	30027	-500	149062	-548	119035	-48	0.9%	7.1%	27.8%	35.9%
CNI	79	31025	-490	200431	-552	169406	-62	1.0%	7.9%	28.6%	37.5%
Sealer	76	38492	-497	71065	-286	32573	211	3.4%	13.0%	9.3%	25.6%
Epoxy	78	33121	-490	72050	-349	38929	142	3.8%	12.3%	13.2%	29.4%

Table 22 - Destructive Analysis Results and Treatment Evaluation for Batch #5 Slabs

Batch #5												
Slab ID		Pre-Treatment		Final Measurements		Difference		Visually Examined Corrosion			
Treatment	Slab #	Integrated Current (Coulombs)	Average Half-Cell Potential (mV CSE_{77})	Integrated Current (Coulombs)	Average Half-Cell Potential (mV CSE_{77})	Integrated Current (Coulombs)	Average Half-Cell Potential (mV CSE_{77})	Light	Moderate	Heavy	Total
Control	91	14744	-477	107508	-477	92764	0	0.7%	1.9%	14.5%	17.1%
Control	93	7455	-393	66868	-442	59413	-49	0.6%	3.2%	8.5%	12.2%
CNI	92	25400	-513	140576	-450	115176	63	0.9%	4.5%	15.4%	20.7%
Sealer	98	24344	-553	54311	-292	29967	262	0.2%	4.3%	12.5%	16.9%
Epoxy	94	20193	-506	47109	-327	26916	180	0.6%	1.9%	9.4%	11.8%

Key Findings of Topical Treatment Results

The key findings from topical treatment results are:

- Corrosion mitigation was quantifiably measured for two of the three technologies by increased half-cell potentials, reduced magnitude of macrocell current (slowed rate of passed charge), increased concrete resistivity, reduced internal relative humidity, reduced chloride ingress, and decreased area and severity of visual corrosion.
- The effectiveness of corrosion mitigation is difficult to evaluate when slabs have various levels of corrosion damage at the time of treatment.
- In retrospect, it appears that in some cases, the topical treatments were not applied soon enough and significant corrosion damage had already occurred.
    - Visual corrosion damage could not be differentiated in some cases because too much corrosion occurred prior to treatment application and microcell corrosion may have remained active after treatment applications.
- The corrosion mitigation performance depends on the corrosion rate and level of corrosion at the time of treatment.

Recommendations for Topical Treatment Applications

- Treatments should be applied earlier and at equivalent levels of corrosion activity/damage to have a better comparison of performance and differentiation of visual corrosion damage.
- Half-cell potential mapping should be used to evaluate microcell corrosion by measuring the contour differences.

Repair Treatments

One aspect of integral technologies that was evaluated is the ability of a product to arrest Anodic Ring Corrosion which occurs along the perimeter of the repair area. Anodic ring corrosion occurs when repairs result in newly cathodic repaired rebar adjacent to rebar in chloride contaminated concrete. Corrosion initiation of the existing rebar is supported by the addition of newly cathodic adjacent rebar, thus resulting in an increased corrosion rate.

The anodic ring effect was evaluated by comparing statistical differences in the corrosion parameters of the rebar located outside the hotspot between control (repair mixture) and repair treatment test specimens. The effectiveness of corrosion mitigation repair treatments was evaluated by the following performance categories:

- Half-cell potential measurements
    - Half-cell potential mapping
- Macrocell current measurements
    - Integrated Current (Passed Charge)

Additional performance measures of corrosion mitigation not evaluated here, but may be considered:

- Resistance between repaired rebar and main rebar
- Concrete resistivity (Wenner 4-Pin Method)
- Chloride profile
- Internal relative humidity
- Destructive analysis

Four repair corrosion mitigation treatments were selected by the expert panel including:

Repair Treatments

A. Repair mixture, 0.40 w/c, 6.5 SK, Type I/II Cement (Repair)
B. Repair mixture with rebar coating (Rebar Coating)
C. Repair mixture with galvanic anode (Anode)
D. Repair mixture with 40% silane sealer (Sealer)

A detailed description of each repair installation can be found in Appendix D.

Repair treatments were applied when slabs met the following criteria:

- Total integrated current greater than 2500 Coulombs for rebar outside the hotspot (Summation of integrated current of six rebars, i.e. four full length rebars and two half-length rebars)

Table 23 summarizes the repair type, time of repair, and level of corrosion at the time of repair. Examples of half-cell potential, half-cell potential mapping, and integrated current results for

Batch #1 are provided in Figure 42 through Figure 44. The complete results obtained from repair test specimens are provided in Appendix H.

Table 23 - Batch #1, 0.40 w/c, 1.5-inch cover repairs

Slab No.	Treatment	Days (After Initial Ponding)	Completed Ponding Cycles Prior to Treatment	Number of Rebar Initiated Corrosion	Total Slab Integrated Current, Coulombs	Average Half-Cell Potential, mV CSE[77]
1	-	-	-	-	-	-
2	-	-	-	-	-	-
3	Rebar Coating	658	24	4	2748	-311
4	Repair	658	24	1	2764	-262
5	-	-	-			
6	Rebar Coating	518	19	3	3108	-299
7	Destructive Analysis	-	-	-	-	-
8	Repair	518	19	4	2938	-346
9	Anode	518	19	2	2823	-273
10	Repair	490	18	3	4780	-302
11	Anode	490	18	2	3593	-309
12	Sealer	546	20	3	3722	-362
13	Sealer	490	18	3	2949	-293
14	Destructive Analysis	-	-	-	-	-
15	Rebar Coating	546	20	2	3063	-271

Note: The integrated current results provided in Figure 40 and Figure 41 for test specimens containing galvanic anodes are comprised of data from four rebars, instead of six (two half-length rebars excluded). The half-cell potential measurements provided in Figure 42 through Figure 44 were measured with the galvanic anode disconnected, typically for 4 to 24 hours, allowing the rebar to depolarize prior to measuring.

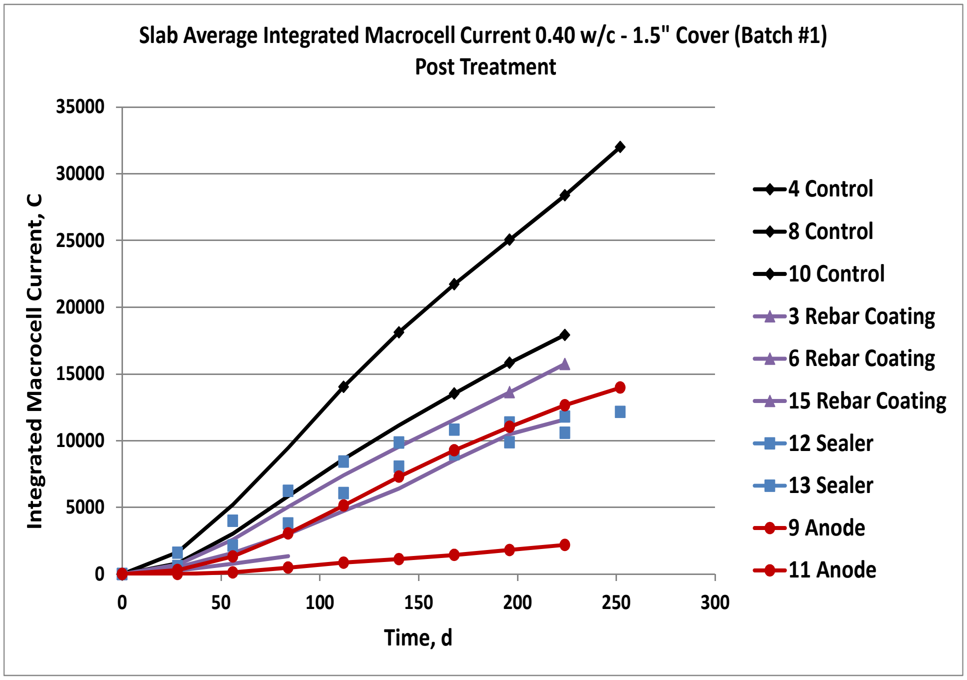


Figure 40 - Slab total integrated current as a function of time (Individual slabs, Batch #1, 0.40 w/c, 1.5-inch cover)

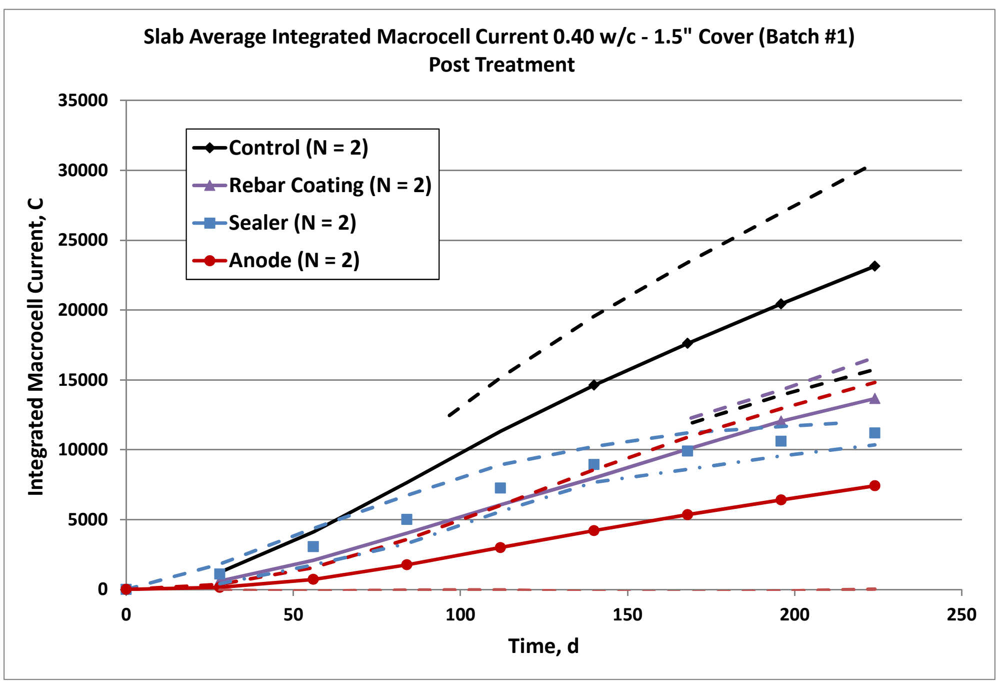


Figure 41 - Slab total integrated current as a function of time (Slab average, Batch #1, 0.40 w/c, 1.5-inch cover)

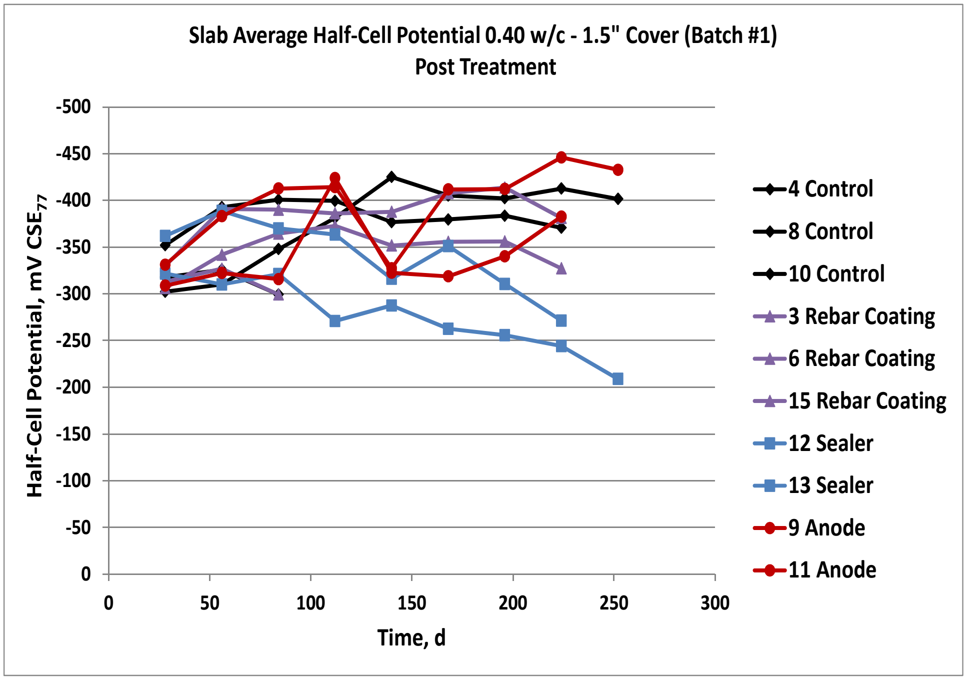


Figure 42 - Slab average half-cell potential as a function of time (Individual slabs, Batch #1, 0.40 w/c, 1.5-inch cover)

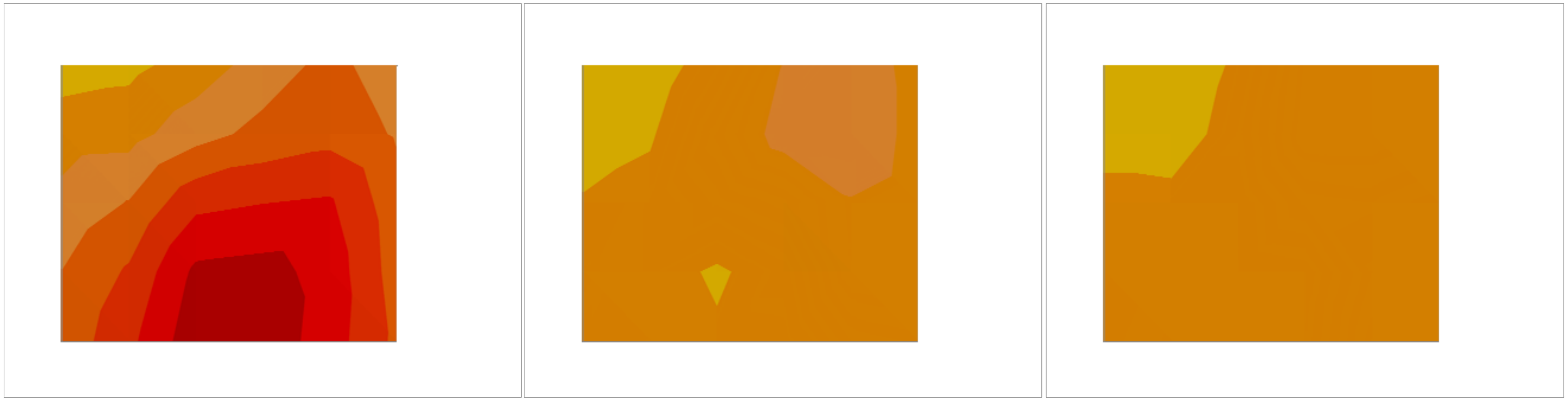


Figure 43 - Half-cell potential mapping over time, prior to repair, after 5 ponding cycles, and after 8 ponding cycles (Rebar Coating)

Figure 44 – Half-cell potential mapping over time, prior to repair, after 5 ponding cycles, and after 8 ponding cycles (Sealer)

Key Findings of Corrosion Mitigating Repair Treatments

The key findings of corrosion mitigating repair treatments are:

- Integral repairs may require a longer time to evaluate the corrosion mitigation performance than surface repairs since some time is needed to establish the anodic ring effect.
- Some corrosion mitigation was observed on rebar adjacent to the hotspots by a reduction in half-cell potentials (sealer), and reduced magnitude of macrocell current (slowed rate of passed charge) when compared to control slabs.
- Half-cell potential mapping was useful to create contour maps to highlight areas of severe corrosion. The equipotential lines are perpendicular to the corrosion currents.

Recommendations for Corrosion Mitigating Repair Treatments

The recommendations of corrosion mitigating repair treatments related to constructability and testing are:

- Repair treatments that require connecting additional components to the existing wiring circuit, e.g. galvanic anodes, should be wired in such a way that all measurements and result s can be directly and easily compared to other repair treatments. It is preferred to have one connection terminal for each component, i.e. rebar and galvanic anode, for both repair treatments and control specimens.

Corrosion Damage at Time of Treatment

To properly evaluate corrosion mitigation treatments all slabs should begin with generally the same level of corrosion damage and ongoing corrosion activity. Thus, criteria are needed to determine when treatments should be applied to each slab. This issue was clearly shown by 0.75-inch cover test results. The criteria should include a minimum level of sustained corrosion activity prior to treatment application. However, too much corrosion activity may impact the ability of some technologies to provide acceptable corrosion mitigation and may vary depending on the technology.

Treatment Criteria

Several variations of treatment criteria have been suggested. Ideally, for experimental purposes, all or most rebar should be corroding at the same level. However, the time to corrosion initiation analysis shows that the time from the first rebar to begin corroding in a slab to all rebars corroding can be over a year. In this time, significant corrosion damage can occur. Thus, it is impractical to wait for all the bars to begin corroding before applying treatments.

The simplified treatment criteria for this study have become:

- Topical Treatments – Slab combined passed charge greater than 5000 coulombs
- Repair Treatments – Slab combined passed charge greater than 2500 coulombs (rebar outside the hotspot only)

By not specifying a minimum number of rebar corroding within a given slab, it prevents any single rebar from reaching high levels of corrosion activity and cracking from occurring, which is discussed later.

The level of corrosion at the time of treatment was quantified by destructively analyzing several slabs with various levels of corrosion damage. The intent was to quantify the amount of corrosion on slabs meeting the criteria above and to provide a bench mark for other levels of corrosion damage, should different criteria be tested for certain technologies.

The destructive analysis includes removing from the concrete and visually examining each rebar to determine the amount and severity of corrosion. Each rebar was assessed in 3" long sections on both the top and bottom surfaces. Each section was then tallied for comparison. A full description of the destructive analysis can be found in Appendix E.

A list of the slabs destructively analyzed is provided in Table 24. As an example, the comparison between measured corrosion and observed corrosion for slab 46 is provided in Figure 45 and Table 25. Two chloride profiles were extracted from slab 46, one at a location with high corrosion activity (more anodic) and one at a location with less corrosion activity (more cathodic). The complete results from other destructively analyzed slabs 7, 14, and 28 are provided in Appendix G.

Table 24 – Slabs destructively analyzed to quantify corrosion condition at time of treatment

Slab No.	Slab Type	Batch No.	Cover, inches	w/c
46	Topical	3	1.5	0.50
7	Repair	1	1.5	0.40
14	Repair	1	1.5	0.40
28	Repair	2	1.5	0.60

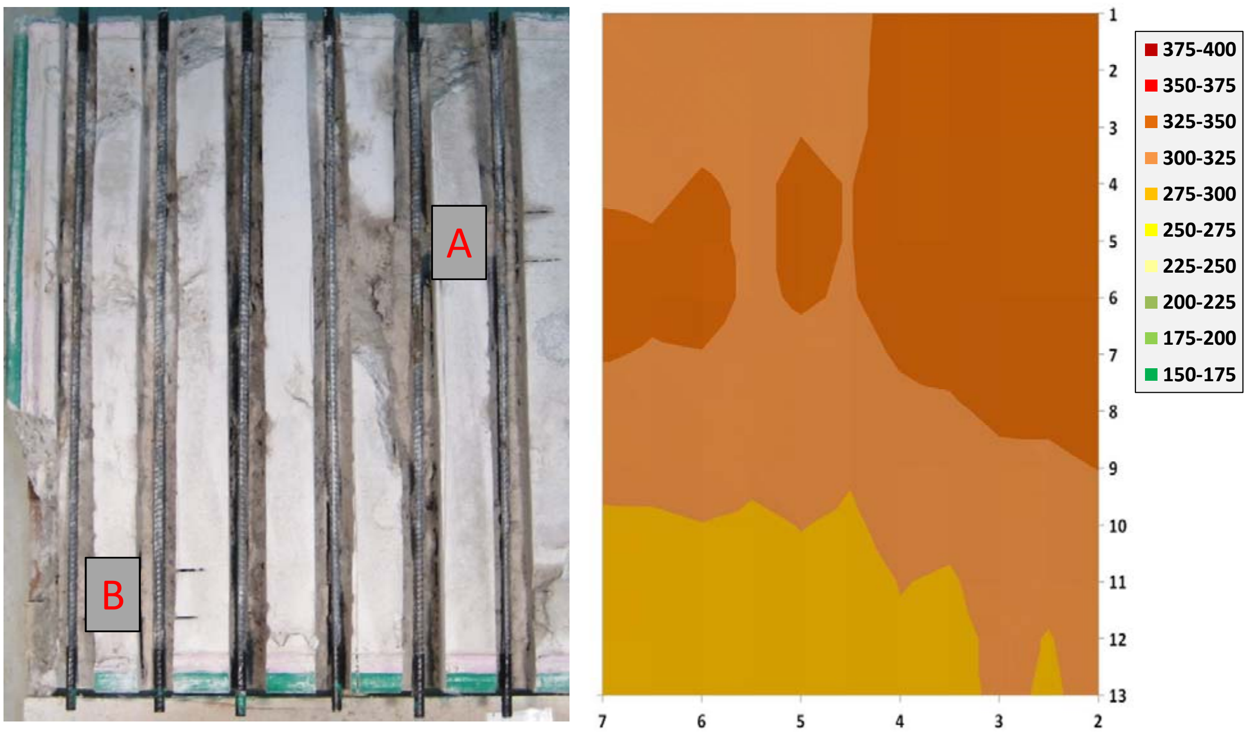


Figure 45 – Slab 46 plan view with exposed rebar (left) compared to half-cell potential mapping (right)

Table 25 – Corrosion activity of Slab #46 at time of destructive analysis

Slab 46	Final Measurements		Visually Examined Corrosion			
Rebar No.	Integrated Current, Coulombs	Half-Cell Potential, mV CSE[77] (Disconnected)	Light	Moderate	Heavy	Total
2	2295	-411	0.2%	1.3%	0.8%	2.2%
3	2797	-445	0.4%	0.8%	7.6%	8.8%
4	15	-202	0.3%	0.0%	0.0%	0.3%
5	10	-206	0.1%	0.0%	0.0%	0.1%
6	158	-325	0.3%	0.2%	0.0%	0.5%
7	931	-381	0.1%	0.1%	4.1%	4.3%
Total	**6205**	-	-	-	-	-

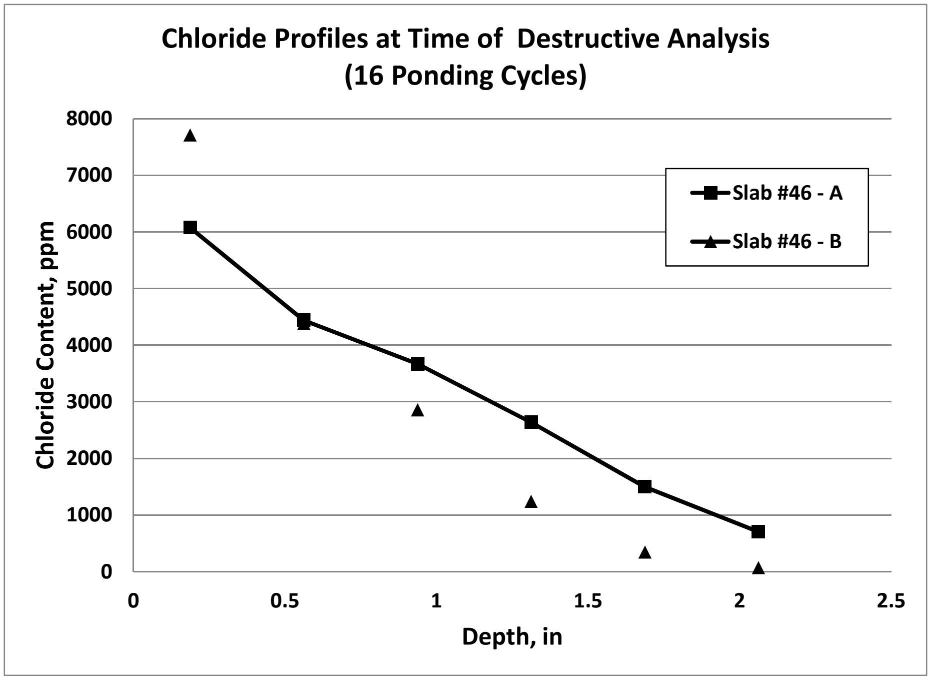


Figure 46 – Chloride profiles at "A" anodic location and "B" cathodic locations (Based on slab measurements)

Key Findings of Corrosion Damage at Time of Treatment

The key findings are:

- Corrosion measurements and chloride concentrations corresponded well with visually observed corrosion.
    - Half-cell potential mapping was a good way of nondestructively determining areas with higher corrosion activity.
- The level of corrosion activity observed at just greater than 5000 coulombs was a reasonable level to apply corrosion mitigating technologies with approximately 900 ppm chlorides on average at the level of rebar.

Recommendations based on Corrosion Damage at Time of Treatment Results

Recommendations for the protocol include:

- Allow testing of corrosion mitigating technologies at various levels of corrosion damage or chloride content (separate testing).
- Develop corrosion mitigation classifications based on the desired level of corrosion activity, corrosion damage, chloride content, etc. at the time of application.

Reinforcing Bar End Treatments

Three different reinforcing bar end treatments are commonly used to minimize erroneous edge effects (corrosion at the ends of reinforcing bars not related to the treatment). Batches 3, 4, and 5 each use different end treatments. The performance of rebar end protection was evaluated in two ways: 1) Determining whether corrosion initiated near or underneath end coatings by measuring half-cell potentials along the reinforcing bar at the onset of corrosion, and 2) Destructive forensic sampling at the completion of the testing program to visually observe whether corrosion was prevented underneath treatments. The three different reinforcing bar end treatments were:

1. Calcium nitrite cement paste with heat shrink tubing (CN paste/Shrink Tube) (Batch #3);
2. Sulfuric acid pickling with epoxy coating (H_2SO_4 Pickle/Epoxy), similar to ASTM G109 procedure (Batch #4);
3. Hot soak NaOH solution with epoxy coating (Hot NaOH/Epoxy) (Batch #5).

__Corrosion Potentials (ASTM C876)__

At the onset of corrosion, five corrosion potentials were recorded on the concrete surface over each bar. The corrosion potential measurements along the reinforcing bar were intended to identify the location where corrosion activity initiated, as indicated by the most negative potential measurement. The measurement locations for each reinforcing bar are shown in Figure 47. The measurements are equally spaced 6” apart and 6” from the front and back edge of the ponding dam. The results are provided in Table 26 and compared to the visual observations of corrosion in the following section.

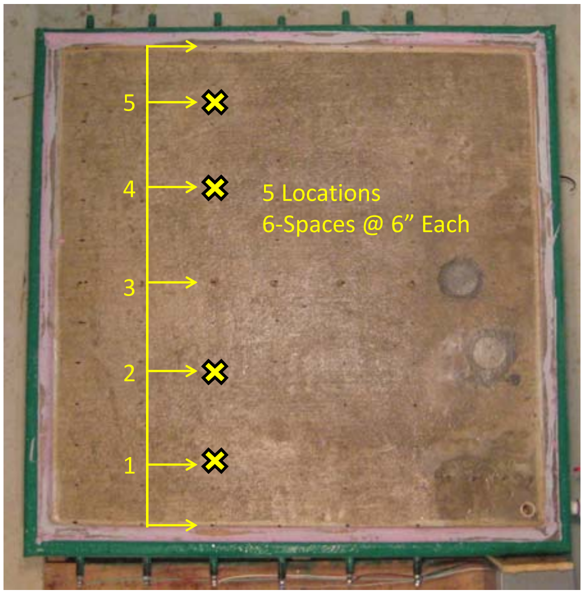


Figure 47 – Corrosion Potential Locations for Corrosion Initiation Measurements

Table 26 – Summary of Corrosion Initiation Location (Most Negative Corrosion Potential, ASTM C876)

End Treatment	CN Paste/Shrink Tube	H_2SO_4 Pickle/Epoxy	Hot NaOH/Epoxy
Batch No.	3	4	5
No. of Bars Measured	57	56	58
Minimum Potential @ Corrosion Initiation Near End Locations (Positions 1 or 5)	24 (42%)	31 (55%)	14 (24%)

Note: The minimum corrosion potential located in positions 1 or 5 does not necessarily indicate the corrosion initiated underneath the treatments. A random distribution would result in corrosion initiation at end locations 40% of the time (2/5).

Destructive Analysis

The end coatings were destructively sampled from 4 slabs in Batch #3 and 5 slabs in Batches #4 and #5. The rebar treatments were removed to visually observe any corrosion underneath the coatings. The results are provided in Table 27. CN Paste/Shrink Tube end treatments had the highest percentage of rebar ends with visual corrosion at 21%. Only 6% (maximum of any end treatment) of corroded ends also had the minimum corrosion potential when corrosion initiated. This suggests in most cases the corrosion initiated along the bar, then spread underneath the coating over time.

Slabs in batch #3 generally had higher corrosion levels at the time of destructive sampling, which may result in greater chances corrosion spreads underneath the coatings. Figure 48 compares the number of corroded and non-corroded rebar to total charge passed per rebar. The results show the median charge passed for reinforcing bars with corroded ends is more than 30,000 coulombs for the CN Paste/Shrink Tube end treatments and 75% of all reinforcing bars with corroded ends had greater than 24,000 coulombs.

Table 27 – Results of end treatment visual observation by destructive analysis (0.75" cover slabs, Batches 3, 4, and 5)

End Treatment	CN Paste/Shrink Tube	H_2SO_4 Pickle/Epoxy	Hot NaOH/Epoxy
Slabs Observed	46, 51, 52, 53, 54, 58	72, 76, 77, 78, 79	91, 92, 93, 94, 98
No. of Slabs Observed	6	5	5
No. of Bars Observed	36	30	30
No. of Bars Observed with Corrosion	12 (33%)	5 (17%)	5 (17%)
No. of Ends Observed	72	60	60
No. of Ends with Corrosion	15 (21%)	5* (8%)	5* (8%)
No. of Ends with Corrosion and Minimum Potential @ Corrosion Initiation	4 of 72 (6%)	1 of 60 (2%)	1 of 60 (2%)

*In 4 of 5 ends in Batch #4 and 5 of 5 ends in Batch #5, the corrosion was observed in a void in the epoxy.

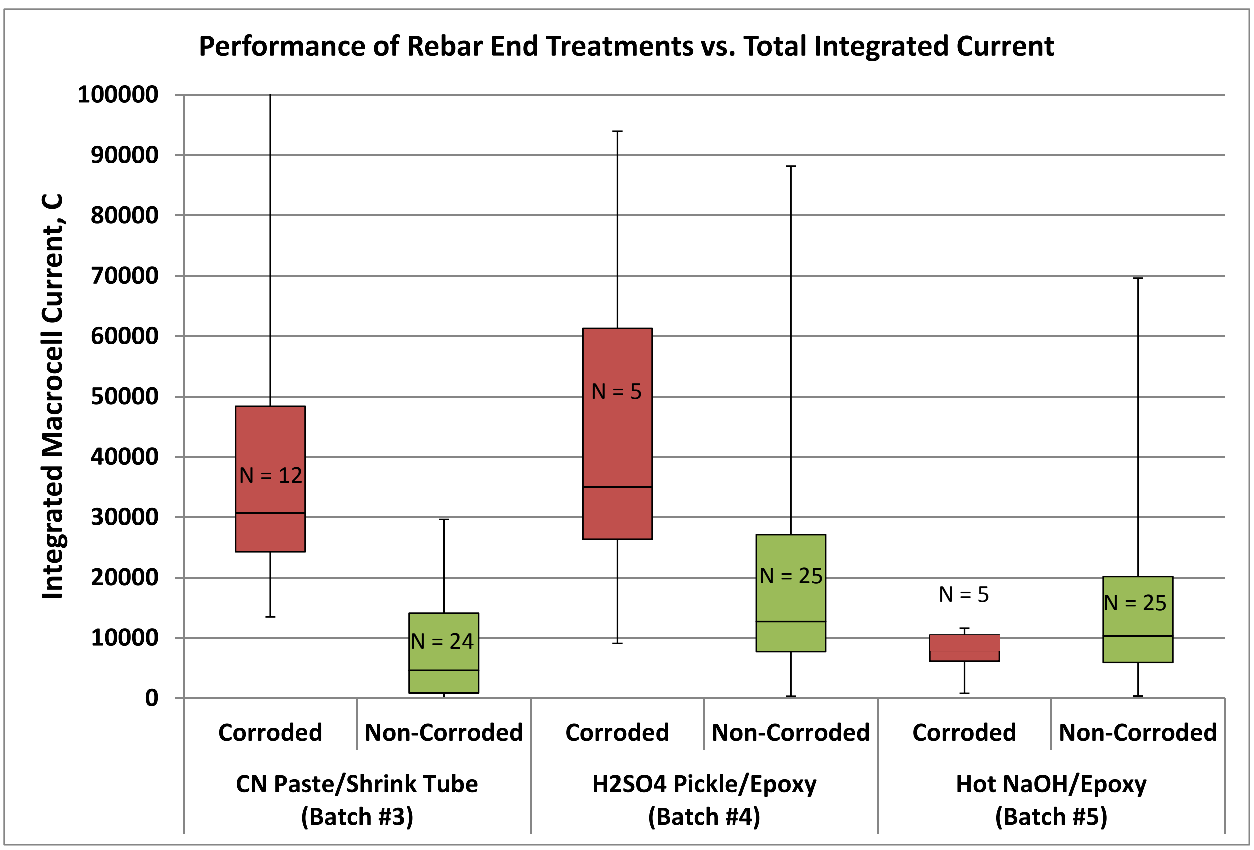


Figure 48 – Performance of Rebar End Treatments vs. Total Integrated Current

CN Paste/Shrinktube Batch #3	H_2SO_4 Pickle/Epoxy Batch #4	Hot NaOH/Epoxy Batch #5

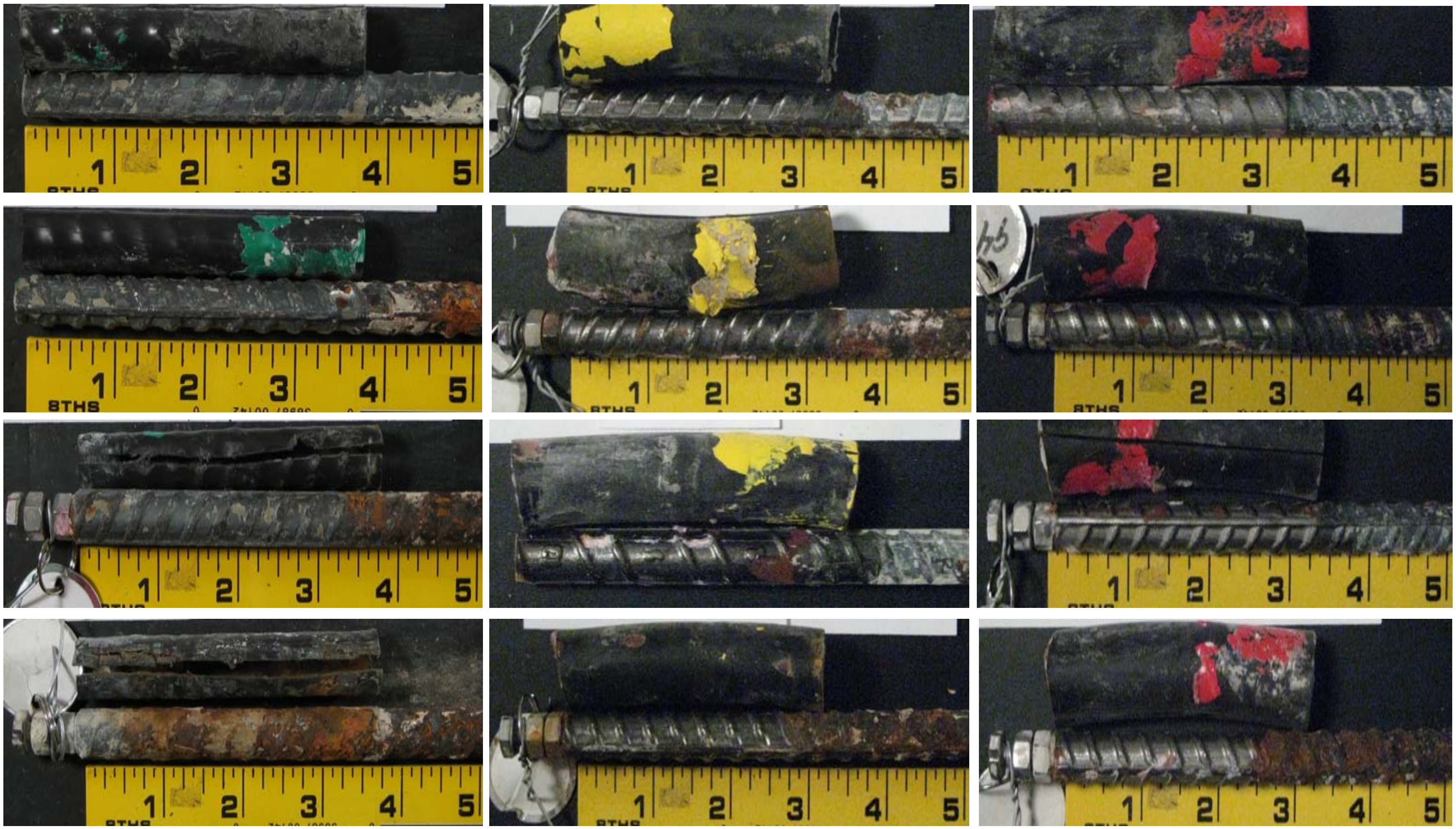


Figure 49 – Reinforcing bar end treatment photos

Summary of Findings of Reinforcing Bar End Treatments

The key findings are:

- Corrosion more commonly spread underneath end coatings rather than initiated within end coatings.
- Rebar ends with CN Paste/Shrink Tube (Batch #3) were more likely to have corrosion than ends with H_2SO_4 Pickle/Epoxy (Batch #4) and with Hot NaOH/Epoxy (Batch #5); however, rebar in batch #3 tended to have higher levels of corrosion and charge passed at the time of destructive sampling.
- End corrosion was less frequent and less severe when treated with H_2SO_4 Pickle/Epoxy (Batch #4) and Hot NaOH/Epoxy (Batch #5);
- 75% of rebar observed to have corrosion with CN Paste/Shrink Tube (Batch #3) or H_2SO_4 Pickle/Epoxy (Batch #4) end treatments had greater than 25,000 coulombs of charge passed, while corroded rebar with Hot NaOH/Epoxy (Batch #5) end treatments all had less than 12,000 coulombs of charge passed.

Other findings related to constructability are:

- CN Paste/Shrink Tube end treatments were the easiest and most expeditious to apply.

Recommended Reinforcing Bar End Treatments

For use in the test protocol TCG recommends:

- Using H_2SO_4 Pickle/Epoxy (Batch #4) end treatments since high levels of corrosion, i.e. >25,000 coulombs can occur on rebar through the duration of testing. Hot NaOH/Epoxy (Batch #5) end treatments may work just as well, however have not been tested at as high of corrosion levels as the H_2SO_4 Pickle/Epoxy (Batch #4) end treatments.
- Placing ponding dams further from the edge of the slab to limit moisture and the susceptibility of corrosion near rebar ends.

Concrete Cracking

Corrosion products have a greater volume than the original steel which results in expansive forces and consequently stress buildup at the concrete interface. When the stress exceeds the concrete strength cracking may occur.

During the experiment concrete cracking induced by high levels of corrosion activity was observed in the surface and on the sides of slabs. Corrosion induced cracking can further increase the rate of chloride ingress by providing a direct pathway for chlorides to the reinforcing steel. Therefore cracking should be minimized in the test protocol and corrosion mitigation technologies should be applied prior to cracking, depending on the objective of the corrosion mitigation technology.

The total amount of corrosion activity or total charge passed at the time of cracking is shown in Figure 50. Here, cracking is described by a range between small openings cracks spreading to the outer surface of slabs. Several photographs are provided in Figure 51 and Figure 52.

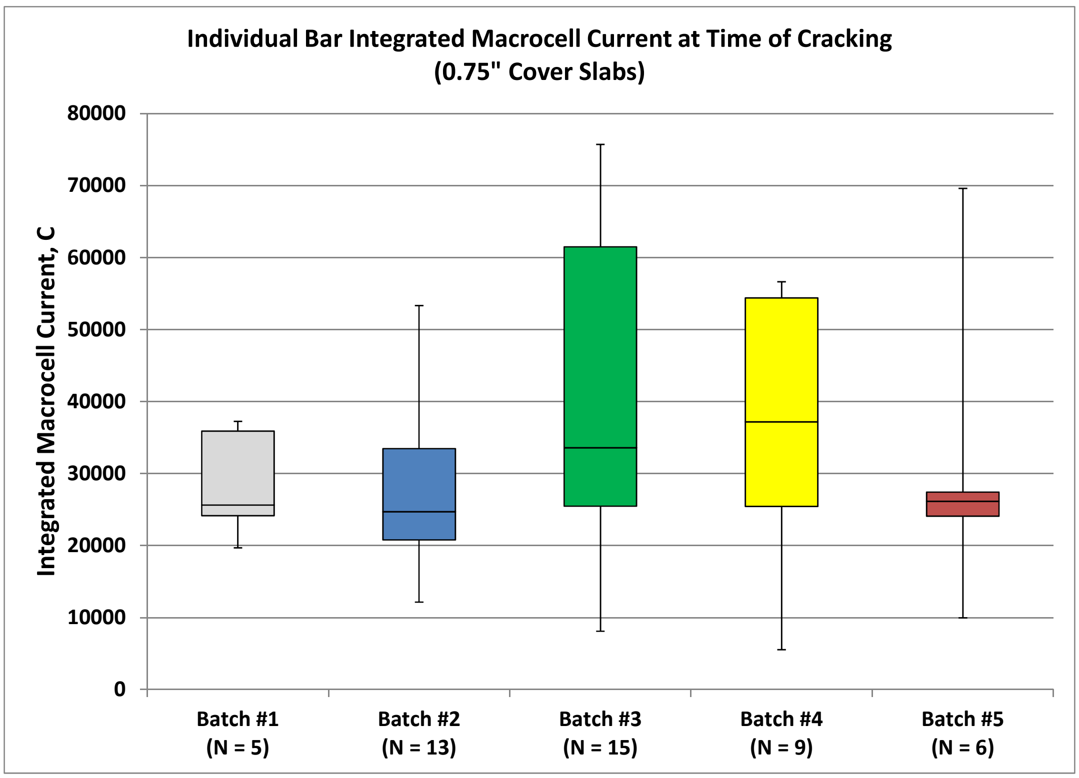


Figure 50 – Individual Bar Integrated Macrocell Current at Time of Cracking

Figure 51 – Slab with cracked surface and small corrosion stained openings (0.75-inch cover, Batch #2, Slab 39)

Figure 52 – Slab with visual corrosion damage on surface (0.75-inch cover, Batch #4, Slab 77)

<u>Key Findings for Concrete Cracking</u>

The key findings are:

- Concrete cracking was observed in 0.75-inch cover slabs with high levels of corrosion damage, mostly greater than 20,000 Coulombs per rebar.
- No cracking was observed in 1.5-inch cover slabs. Although, none of the rebar surpassed 20,000 Coulombs, deeper cover is capable of withstanding more corrosion damage on rebar and stress before cracking occurs.

Number of Test Specimen

The sample size needs to show that two data sets (control and treated) have different means. The mean value (μ) for the results will fall in a confidence limit about the sample data mean ($\bar{x}$), according to equation 1.

Confidence Limits = $\bar{x}$ + (t_{np}/sqrt(n))•s_x **Equation 1**

Where:

t_{np} = Is the double sided t-distribution value for a probability of p (typically 90 or 95%), and sample size n. Note that t_{np} drops in value as n increases or p decreases.

$\bar{x}$ = Mean of sample data (estimate of the population mean, μ)

s_x – Standard deviation of sample data (estimate of population variance)

The data sets will have different mean values, μ, when the confidence limits on the two sample means, $\bar{x}$ do not overlap. The minimum sample size should be chosen at the point where for a given confidence level there is not a significant decrease in t_{np}/sqrt(n), as shown in Figure 53. The last sharp decrease in the confidence limits occurs at n=5, so that should be the minimum number of specimens needed.

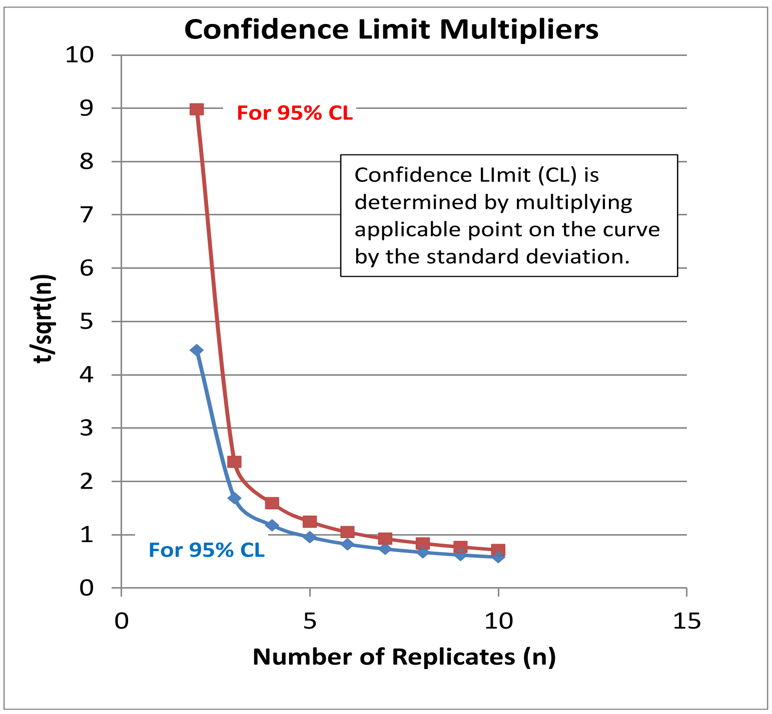


Figure 53 – Graph for Double-Sided t_{np} distributions to differentiate two data sets.

Summary of Findings

The key findings from this evaluation are summarized as follows:

- Corrosion Initiation
    - Concrete cover played a significant role in the time to corrosion initiation where the majority of 0.75-inch cover slabs initiated corrosion within the first few cycles and 1.5-inch cover slabs remained passive beyond one year of testing or longer.
    - In 0.75-inch cover, slabs constructed with higher permeable concrete resulted in slightly reduced times to corrosion initiation. However, the shallow concrete cover already produced early corrosion initiation times making it harder to distinguish between the effects of concrete quality.
    - The first rebar in the slab to corrode best defines the time of corrosion initiation.
- Corrosion Rate
    - Corrosion rate was inversely related to concrete cover. After corrosion initiation, slabs with 0.75-inch concrete cover exhibited high corrosion rates resulting from the rapid ingress of chlorides beyond the chloride threshold at the level of the rebar. 1.5-inch cover slabs corroded at slower rates as chlorides ingress at a slower rate.
    - Concrete with higher permeability corroded at higher rates. As chloride contents at corrosion initiation were statistically the same for the 0.75-inch cover slabs, the main role of increasing permeability was the more rapid ingress of chlorides.
- Methods to Accelerate Corrosion
    - Chloride-spiked hotspots all successfully initiated corrosion quickly, however in some cases did not sustain active corrosion.
    - High-water content hotspots produced a more gradual increase in corrosion activity, however in some cases did not result in a significant acceleration compared to rebar outside the hotspot.
    - Depressed cover hotspots accelerated corrosion in all cases, however resulted in concrete cracking in the hotspot before the time of repair.
- Corrosion Mitigation
    - The effectiveness of the treatments was quantitatively measured by reductions in corrosion activity after application of the treatments.
    - Two topical treatments, 40% silane sealer and epoxy/urethane traffic membrane, were able to show a reduction in corrosion activity, while a third treatment, calcium nitrite inhibitor, was shown to be not effective. It is possible that another topically-applied inhibitor could have better performance.
    - The three repair treatments, coating the rebars in the patch, installing a galvanic anode in the patch, and treating the slab with a 40% silane sealer showed an improvement over the control treatment of just patching the repair with the same concrete.
    - Detailed surface maps of corrosion potentials and integrated corrosion currents compared to visual reinforcing bar corrosion determined by destructive analysis

were in good agreement with each other. In repaired/surface treated specimens, the potential maps showed a decrease in potential gradients and more positive potentials indicating that corrosion activity was reduced. This was in good agreement with the corrosion current data. These measurements can be used in the test method to indicate reinforcing bar performance along the length of the bar, so that autopsies need to be conducted only at the completion of testing.
    - The corrosion mitigation performance depends on the corrosion rate and level of corrosion at the time of treatment.
- Corrosion Damage at Time of Treatment
    - Corrosion measurements and chloride concentrations corresponded well with visually observed corrosion.
    - The level of corrosion activity observed at just greater than 5000 coulombs was a reasonable level to apply corrosion mitigating technologies with approximately 1000 ppm chlorides on average at the level of rebar.
- Reinforcing Bar End Treatments
    - Two of the three rebar end treatments, H_2SO_4 Pickle/Epoxy and Hot NaOH/Epoxy, provided satisfactory results. The H_2SO_4 Pickle/Epoxy treated rebar were in specimens with the highest levels of corrosion activity.
- Concrete Cracking
    - Concrete cracking was observed in 0.75-inch cover slabs with high levels of corrosion damage, mostly greater than 20,000 Coulombs per rebar.
    - No cracking was observed in 1.5-inch cover slabs. Although, none of the rebar surpassed 20,000 Coulombs, deeper cover is capable of withstanding more corrosion damage on rebar and stress before cracking occurs.

Summary of Recommendations

Based on the findings, several recommendations for the future standard method/procedure can be made.

<u>Concrete Cover, Water-to-Cement Ratio (w/c) and Aggregate Selection</u>

- A depth of concrete cover to reinforcement of 1.0-inch or 1.25-inches would result in acceptable times for corrosion initiation.
- A w/c of 0.5 gave good reproducibility, and will develop a discontinuous capillary system. It is typical of many of the field concretes to which corrosion mitigation techniques would be applied.
- Nominal aggregate size should be ½ the clear cover over the bars to minimize subsidence cracking and chloride ingress at the paste-aggregate interface. Suggested nominal aggregate size should be 0.5-inch, and concrete cover should be 1 inch based on these findings.

Methods to Accelerate Corrosion

For repair specimens, the addition of a localized area to accelerate corrosion (hotspot) was effective. The most effective hotspot configurations, from a performance and ease of production perspective are in order of preference:

1. Slightly reduced cover to accelerate chloride ingress to the bars in the hotspot.
2. Increasing the water-to-cement ratio in the hotspot to increase chloride ingress.

Number of Test Specimens

The reliability of the mean corrosion behavior and statistical differences between controls and mitigation systems is enhanced by increasing the number of specimens tested for each condition. This was analyzed and it is recommended that the number of specimens should be five per condition.

Corrosion Damage at Time of Treatment

The corrosion activity at time of treatment can play a significant role in how effective mitigating technologies perform. The following recommendations were made based on the testing:

- Allow testing of corrosion mitigating technologies at various levels of corrosion damage (separate testing).
- Develop corrosion mitigation classifications based on the desired level of corrosion activity at the time of application.
- As a standard:
    - Topical Treatments should be applied when integrated macrocell current for all the bars combined on the slab meets 5,000 Coulombs, which can be described by a chloride level of approximately 1000 ppm.
    - Repair Treatments should be installed when rebar outside the hotspot have a total of 2500 Coulombs of corrosion.

Additional Recommendations

The following are additional recommendations that should be incorporated into the test method:

- The preferred end treatment for the bars is pickle the ends in sulfuric acid, apply shrink tubing and fill with epoxy.
- Dams on the top of the slabs should be moved in from the edge of the slab, so that the ponded area is located within the limits of the exposed area.
- Detailed corrosion potential maps should be performed periodically to identify localized areas of high corrosion activity.
- Chloride threshold values should be determined when at least one bar goes into corrosion, defined as a corrosion potential greater than -300 mV vs. CSE[77] and a macrocell current greater than 0.030 mA.
- Trial mixture(s) with the materials to be used in the production of the slabs should be produced prior to producing the concrete for the test specimens to adjust dosage rates of air entrainment, water reducers, as well as the mixture proportions.

Limitations

This report contains professional opinions and judgments based on the results obtained during experimental testing. This report is believed to be accurate within the limitations of the information obtained. TCG reserves the right to modify our recommendations should additional data or information become available.

APPENDIX

Appendix A - Slab Manufacturing and Conditioning

This section describes the fabrication of 100 – 40-inch x 40-inch x 5.5-inch thick concrete test slabs including all necessary labor, materials, equipment, and facilities to cast, cure, and store all specimens by TCG during the course of this project.

Test Slab Configuration

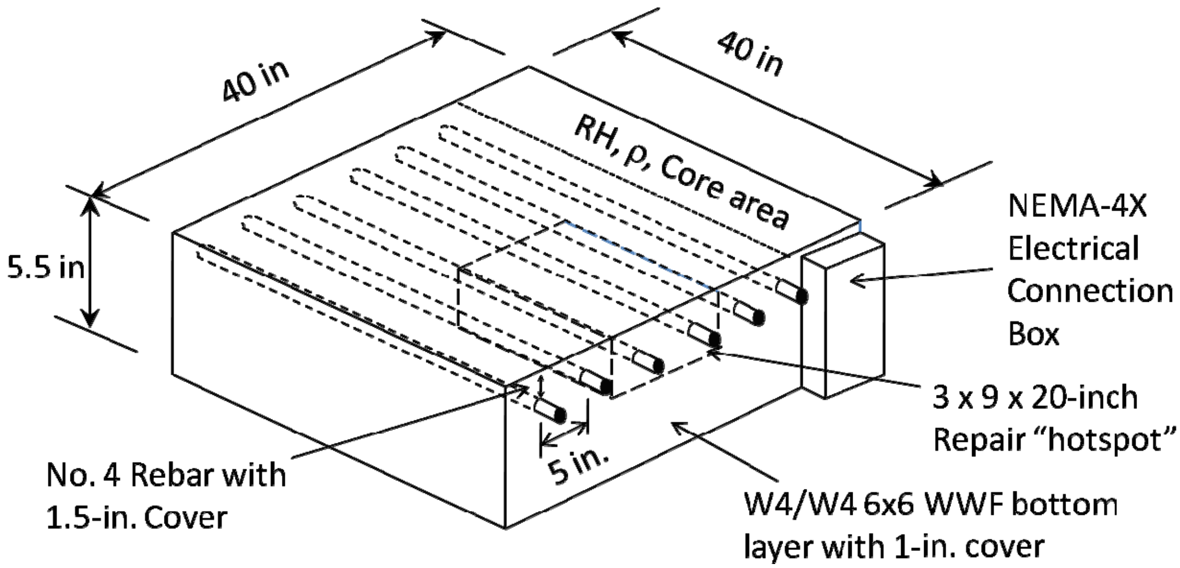


Figure 54 – Repair Test Slab Configuration
(WWF – Welded Wire Fabric, NEMA – National Electrical Manufacturers Association)

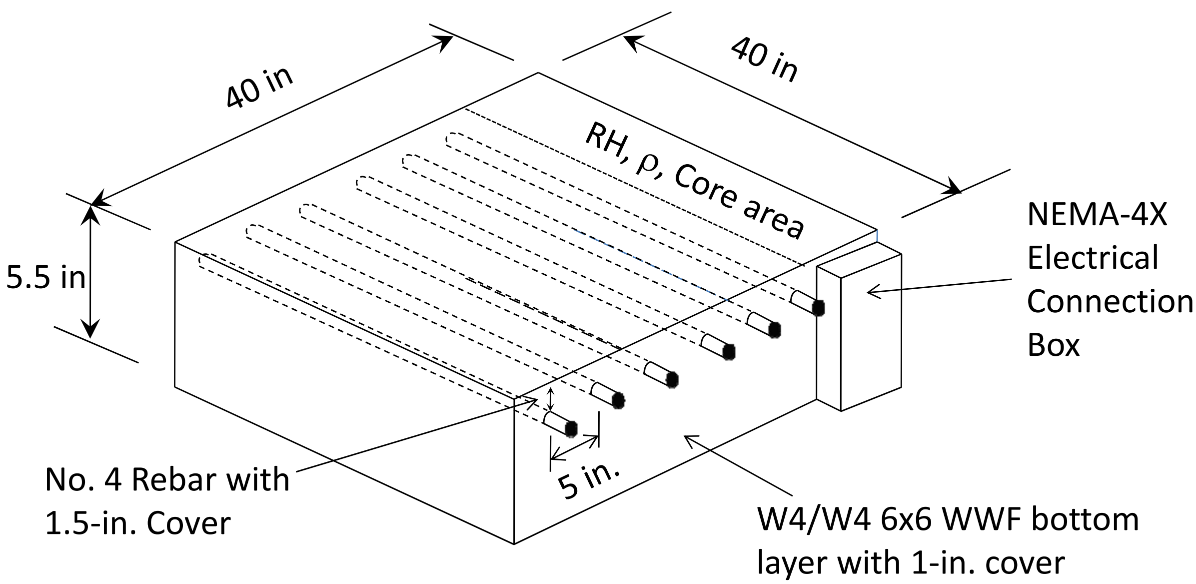


Figure 55 – Topical Treatment Test Slab Configuration

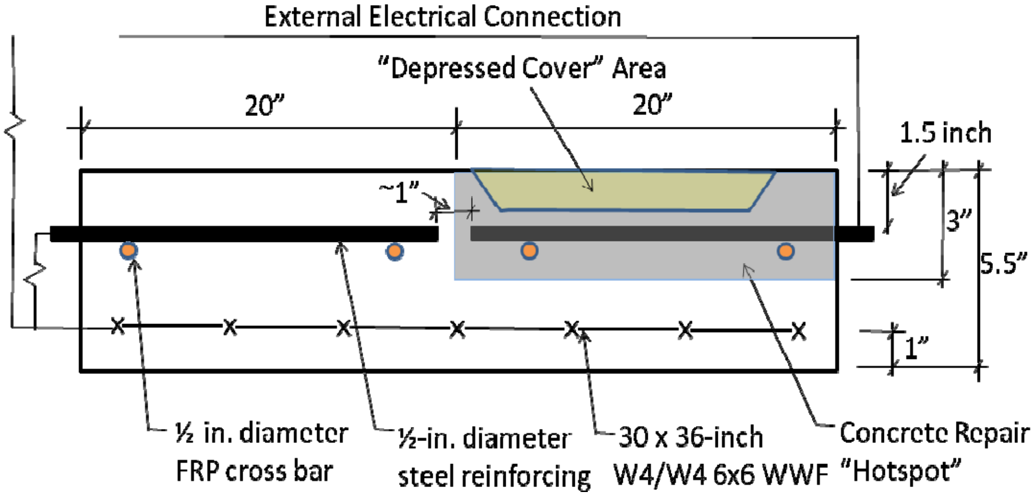


Figure 56 – Section through concrete repair test slab (FRP – Fiber reinforced polymer)

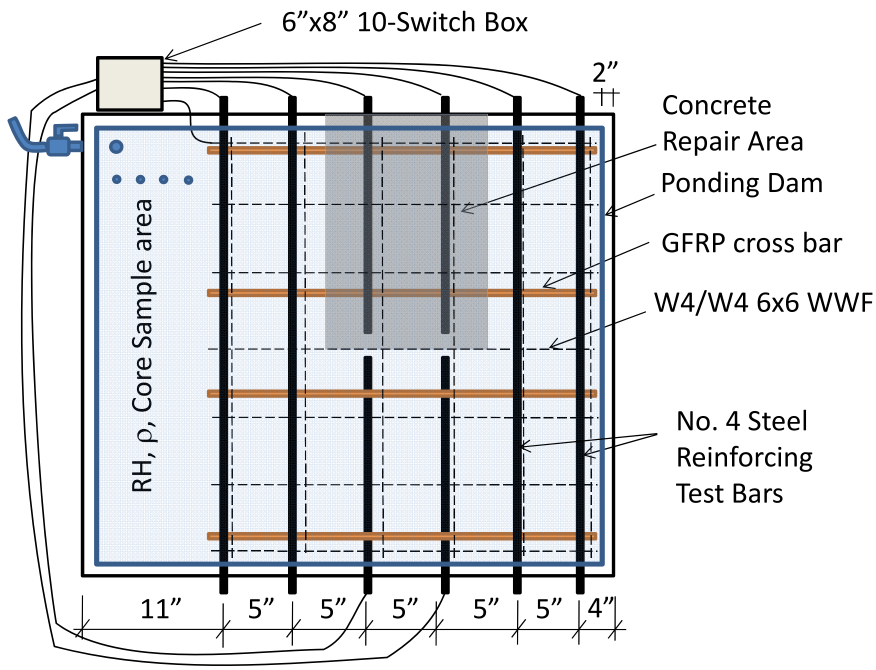


Figure 57 – Test slab reinforcing configuration plan view for concrete repair test slab

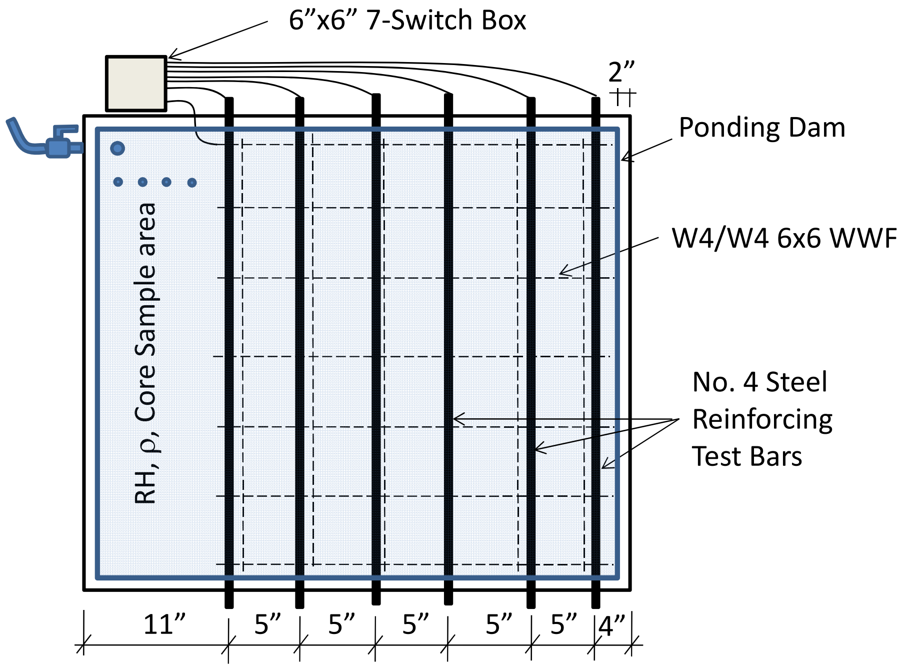


Figure 58 - Test slab reinforcing configuration plan view for concrete topical treatment test slab

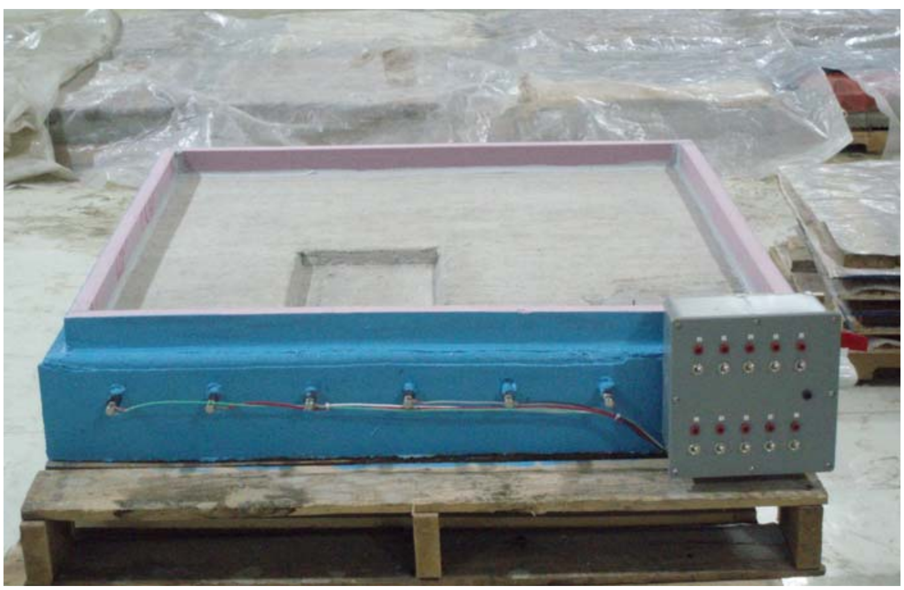


Figure 59 - Completed Batch #2 Repair Test Specimen with Depressed Cover Hotspot

Figure 60 – Completed Batch #5 Topical Treatment Test Specimen

Concrete Batches

Five batches of concrete were produced by a local ready mix supplier and delivered to TCG on the following dates:

1. Batch 1 – October 5, 2010,
2. Batch 2 – October 19, 2010,
3. Batch 3 – November 2, 2010,
4. Batch 4 – November 16, 2010,
5. Batch 5 – November 30, 2010.

Three different water-cement ratios were produced, i.e. 0.40, 0.50, and 0.60. Concrete batches 1 and 2 are for repair (hotspot) testing. Batches 3, 4, and 5 are for replication testing and topical treatments. Two concrete covers were produced with 0.75-inch and 1.5-inch clear cover.

Table 28 – Concrete Mixture Designs

Concrete Mixture Designs, lbs./yd^3									
Batch No.	w/c	Cement	Water	Coarse Aggregate	Fine Aggregate	Design Air Content, %	AEA, oz./cwt	MRWR, oz./cwt	HRWR, oz./cwt
1	.40	564	225	1200	1947	6%	0.5	-	6
2	.60	564	338	1440	1412	6%	1.25	-	-
3	.50	564	284	1750	1251	6%	1	3	-
4	.50	564	284	1750	1251	6%	1	3	-
5	.50	564	284	1750	1251	6%	1	3	-

Table 29 – Concrete batch and specimen quantity summary table

		Quantity of Specimens		
Batch No.	w/c	0.75” Cover	1.5” Cover	Type (Comment)
1	0.4	5	15	Repair (15 hotspot + 5 plain)
2	0.6	5	15	Repair (15 hotspot + 5 plain)
3	0.5	10	10	Topical
4	0.5	10	10	Topical
5	0.5	10	10	Topical

Notes:

1. Batch 1 and 2 “hotspot” specimens are subdivided into three groups of 5 specimens to evaluate three techniques to initiate early corrosion in the repair area shown in Figure 54. See detailed descriptions in Concrete Repair “Hotspot”.
2. Batch 1 and 2 “plain” specimen groups contain discontinuous reinforcing, but were cast without special “hotspot” treatment.

Table 30 - Test slab summary table including rebar end treatment and hotspot

Batch No.	1		2		3		4		5	
Specimen Type	Repair		Repair		Topical		Topical		Topical	
Bar End Treatment	CN paste/Shrinktube		CN paste/Shrinktube		CN paste/Shrinktube		H_2SO_4 Pickle/Epoxy		Hot NaOH/Epoxy	
w/c	0.4		0.6		0.5		0.5		0.5	
Cover Depth, in.	0.75	1.5	0.75	1.5	0.75	1.5	0.75	1.5	0.75	1.5
Quantity of Specimens per Treatment										
No Hotspot	5		5		10	10	10	10	10	10
Depressed Cover		5		5						
Admixed Chloride		5		5						
High w/c		5		5						

Test Slab Manufacturing

Each test slab is approximately 5.1 cubic feet of concrete. The test slabs were constructed in the following manner.

Reinforcement

Six pieces of # 4 reinforcing bars with a length of 44 inches were located in the top of each test specimen with 0.75-inch or 1.5-inch clear cover, see Table 29. The six #4 reinforcing bars were spaced at 5 inches on center and were offset, as a group, in the specimen, as shown in Figure 57 and Figure 58. The offset produced a "clear" area for the RH, resistivity, and core sample area. All reinforcement for this project was procured from the same source and lot (heat).

Surface rust, if present, was removed with a wire brush in accordance with SSPC SP3. The #4 reinforcing bars were manufactured in accordance with ASTM A 615 Grade 60. 1/4 – 20 Grade 304 stainless steel machine screws with two nuts were installed into the tapped end of each #4 reinforcing bar for the purposes of making an electrical connection. One nut is tightened against the end of the reinforcing bar to secure the machine screw.

Figure 61 – Wire brushed reinforcing bars

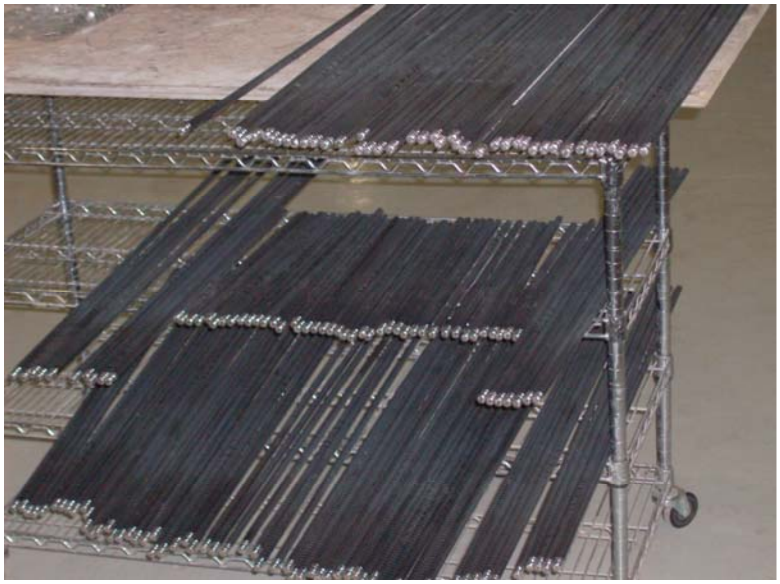


Figure 62 – Reinforcing bars with ends drilled and tapped with screws and two nuts each

Reinforcing Bar End Preparation

Three different treatments were used at the ends of the #4 reinforcement bars to study the effectiveness of minimizing erroneous time to corrosion measurement caused by crevice corrosion under the coated ends of the reinforcement bars extending past the face of the concrete test specimen. The three treatment techniques that were considered are:

4. CN Paste/Shrink Tube: Coat end of reinforcement bar with a cement paste having a 30% calcium nitrite admixture and covered with rubber tubing,
5. H_2SO_4 Pickle/Epoxy: Pickle ends of reinforcement bars in 10% sulfuric acid solution, clean with wire wheel, cover with rubber tubing, and inject two part epoxy in cavity between rubber tubing and reinforcement bar, and
6. Hot NaOH/Epoxy: Wire brush end of reinforcement bars, soak in 0.1M NaOH solution, cover with rubber tubing, and inject two part epoxy in cavity between rubber tubing and reinforcement bar.

See Table 30 for a list of reinforcing bar end treatments for each batch.

Reinforcing Bar End Preparation for Batches 1, 2, and 3 – The ends of the reinforcement for batches 1, 2, and 3 were cleaned of any loose mill scale by wire brush in accordance with SSPC SP15 and then coated with a cement paste containing calcium nitrite. Each end of the reinforcement bars were coated with a cement paste having a w/c ratio of 0.50 with 25% of the mixing water comprised of a 30% solution of calcium nitrite corrosion inhibitor. The cement paste was then covered immediately with electrical connection grade heat shrink tubing. After wiring is complete the ends are coated with 2-part epoxy paint.

Figure 63 – Rubber Tubing Shrink Wrapped on to End of Reinforcement Bar

Figure 64 – Photograph of batch #3 reinforcing bar end treatment

Reinforcing Bar End Preparation for Batch 4 – Four inches of each end of the reinforcing bars was pickled in a 10% sulfuric acid solution for 15 minutes to remove mill scale. The adjacent four inches (4 to 8 inches from each end) was covered with electroplaters tape. The ends of the reinforcing bars were then rinsed with potable water and any remaining residue was removed with a wire brush in accordance with SSPC SP15.

A 5 inch length of neoprene tubing was placed over the pickled end of the reinforcing bar down to the electroplaters tape. The end of the neoprene tubing was sealed with one wrap of electroplaters tape. The cavity between the reinforcing bar and the rubber tubing was filled with a two-part epoxy meeting ASTM C881 Type IV, Grade 3, Class E, so that each end of the #4 reinforcing bars were fully encapsulated in the epoxy.

Figure 65 – Photograph of batch #4 reinforcing bar end treatment

Reinforcing Bar End Preparation for Batch 5 – Four inches of each end was wire brushed to remove all mill scale in accordance with SSPC SP15. The adjacent four inches (4 to 8 inches from each end) was covered with electroplaters tape. Four inches at each end of the reinforcement bar was then soaked in a 0.1 N NaOH solution at 120 degrees F for 8 hours.

A 5 inch length of neoprene tubing was placed over the pickled end of the reinforcing bar down to the electroplaters tape. The end of the neoprene tubing was sealed with one wrap of electroplaters tape. The cavity between the reinforcing bar and the rubber tubing was filled with a two-part epoxy meeting ASTM C881 Type IV, Grade 3, Class E, so that each end of the #4 reinforcing bars were fully encapsulated in the epoxy.

Figure 66 - Photograph of batch #5 reinforcing bar end treatment

<u>Concrete Repair Area Reinforcing Bars</u>

Two 21 inch long reinforcing bars, designated as half-length reinforcing bars, were installed in the "Hotspot" repair area of batches 1 and 2. The reinforcement was coated only on the end protruding from the test specimen. The clear cover to the reinforcement was 1.5-inches for 15 of the test specimens in each batch.

Non-conductive glass fiber reinforcement polymer (GFRP) reinforcing bars meeting the requirements of ACI 440.6 – 08 were used to provide support to the top mat reinforcement in repair slabs, allowing the #4 bars to be electrically discontinuous.

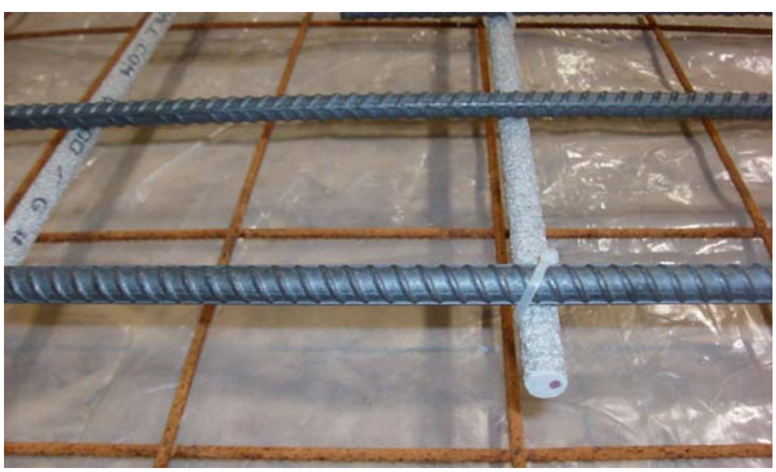


Figure 67 - GFRP Reinforcement Bar

Welded Wire Fabric

Weld wire fabric (WWF) sheets with designation W4 x W4 – 6 x 6 and conforming to ASTM A185 were used as the bottom layer of reinforcement in each test specimen. The welded wire sheets were cut 30 inches x 36 inches. The wire fabric was placed on non-metallic bar supports to provide 1-inch of concrete cover from the bottom surface. Wire connection locations were cleaned by wire brushing to SSPC SP15. Wire connections were brazed to the WWF and totally encapsulated in 2-part waterproof epoxy.

Figure 68 - Stack of Weld Wire Form Sheets with Installed Electrical Leads

Figure 69 - Weld Wire Fabric Located in Bottom of Form

Casting and Finishing

The concrete was cast into the prepared forms filling the form from bottom to top. The concrete was consolidated with a 1.375-inch diameter concrete vibrator. Each specimen was struck-off and finished with a bull-float and trowel according to standard concrete finishing practices. The perimeter of the slabs received a tooled edge. When finishing was complete the surface was textured with a light broom finish.

Figure 70 – Hotspot Repair Form and Reinforcement Configuration

Figure 71 – Forms ready for concrete placement

Figure 72 – Concrete placement in forms

Figure 73 – Concrete placement

Figure 74 - Finishing Test Specimen

Figure 75 - Installing Tooled Edge

Figure 76 - Broom Finish Application

Figure 77 - Broom Finish Application to Hotspot

Concrete Repair "Hotspot"

Fifteen (15) test specimens each in batches 1 and 2 are used to evaluate three different techniques to initiate early corrosion in the repair area, hotspot:

1. Plain concrete, depressed cover,
2. High water content concrete, and
3. Chloride-spiked concrete.

Each slab was fabricated with a 3 inch deep x 9 inch x 20 inch long removable wood block out in the area of the half-length reinforcing bars. The concrete was placed around the exterior of the block out first. The block out was then removed and filled with one of the hotspot concrete mixtures to accelerate corrosion activity on the reinforcing bars inside the modified area. The block out creates a rectangular separation between the two concrete types at the slab surface. The block out is removed prior to finishing. The hotspots are described as follows:

Plain concrete, depressed cover – Five slabs in batch 1 and 2 were fabricated with a 1 inch deep x 8 inch wide x 15 inch long depressed area over the half-length reinforcing bars. The depressed area was created by a flat piece of wood equal to the size of the desired depression. The depressed area was located 4 inches from the edge of the test specimen to allow the installation of a perimeter dam. The surface was then finished with a light broom finish as described previously.

High water content concrete – Five of the test specimens in batch 1 and 2 were produced with a high water-to-cement ratio concrete over the half-length reinforcing bars made by adding sufficient water to the base mixture to elevate the concrete to 0.70 w/c or greater.

Approximately 2 cubic feet of the ready-mixed concrete was obtained and mixed with additional water in a laboratory mixer. The modified concrete was then placed in the blocked-out areas. The block out was removed and the concrete vibrated to ensure good bond between the layers. The surface was then finished with a light broom finish as described previously.

Chloride-spiked concrete – Five of the test specimens in batches 1 and 2 were produced with chloride-spiked concrete over the half-length reinforcing bars. The chloride spiked concrete was made by adding calcium chloride flake to the base concrete mixture. Approximately 2 cubic feet of the ready-mixed concrete was obtained and mixed with 3 lbs. of flake calcium chloride in a laboratory concrete mixer. The modified concrete was then placed in the blocked-out areas. The block out was removed and the concrete vibrated to ensure good bond between the layers. The surface was then finished with a light broom finish as described previously.

Table 31 – Concrete Repair Hotspot Mixture Designs

Concrete Repair Hotspot Mixture Designs, lbs./yd^3										
Batch No.	w/c	Cement	Water	Coarse Aggregate	Fine Aggregate	Admixed Chloride	Target Air Content, %	AEA, oz./cwt	MRWR, oz./cwt	HRWR, oz./cwt
Chloride-Spiked Hotspot										
1A	.40	564	225	1750	1407	20	6%	0.5	-	6
2	.60	564	338	1440	1412	20	6%	1	-	-
High Water Content Hotspot										
1	.40	564	423	1450	1177	-	6%	0.5	-	-
2	.60	564	395	1450	1251	-	6%	1	-	-

Figure 78 – Construction of depressed cover hotspot

Figure 79 – Construction with block out for modified concrete hotspot

Figure 80 – Slab with depressed cover hotspot

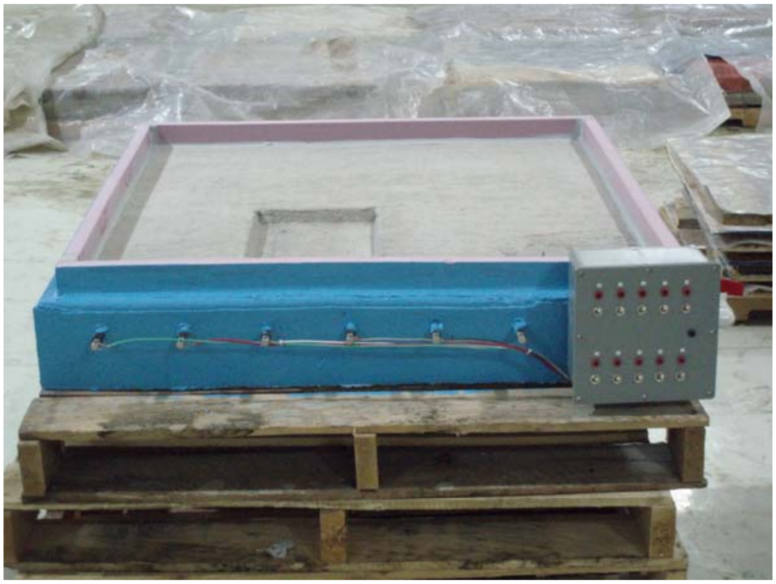


Figure 81 – Completed slab with depressed cover hotspot

Resistivity Measurement Pins

Four (4) grade 304 stainless steel pins were cast into the unreinforced coring area for electrical resistivity measurements. Each pin was spaced 2 inches apart beginning with the first pin 3 inches from the edge. The center 1½ inches of each pin was coated with shrink wrap. The pins are inserted in the concrete such that the top of the shrink wrap extends ½-inch above the concrete surface, and the bottom inch of the pin is bare and in intimate contact with the concrete at a depth of 1-2 inches from the surface.

Figure 82 - Resistivity Measurement Pins

Figure 83 – Resistivity measurement pins inserted during concrete finishing

Figure 84 – Completed slab with resistivity pins

Curing

All slabs were moist cured for 7 days by covering with wet burlap and plastic. The slabs were then allowed to dry for at least one week prior to dam installation and coating of the vertical surfaces with colored two part epoxy paint.

Figure 85 - Test specimens covered with burlap and plastic

Figure 86 – Test specimens after form removal

<u>Ponding Dams</u>

Strips of 1-inch thick by 2-inch tall closed cell insulation board were adhered within 2-inches of the test specimen perimeter with silicone caulk, after the concrete in the test specimens had cured for a minimum of 7 days.

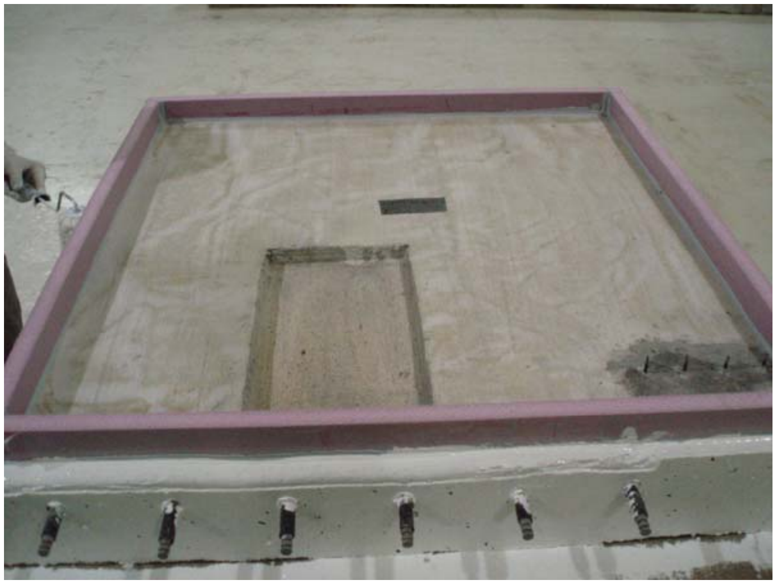


Figure 87 – Installation of Closed Cell Insulation to Form Ponding Dam

Coating

The sides of each test specimen were coated with a colored two part epoxy Sherwin Williams Macropoxy® 646 Part A & B Marine coating to seal the vertical surfaces of the concrete. The top and bottom surfaces remained uncoated and exposed to the environment allowing the test specimens to dry from two sides.

Figure 88 - Application of Epoxy to Test Specimen

Test Specimen Identification

Each of the test specimens was labeled with a designation V1 thru V100. The test specimens were color coated with an epoxy paint corresponding to the batch designation and date of casting as follows:

1. Batch #1 – WHITE
2. Batch #2 – BLUE
3. Batch #3 – GREEN
4. Batch #4 – YELLOW
5. Batch #5 – RED

Wiring

There are two wiring system configurations:

1. Ten-circuit system for the Hotspot repair test specimens and
2. Seven-circuit system for the topical test specimens for batches 3, 4, and 5.

Individual reinforcing bars were connected to the welded wire fabric across a 1.0 ohm, 1 watt shunt resistor. Connection of the reinforcement and welded wire fabric to monitoring equipment was made in a NEMA 4X weather-proof junction box that was mounted to the test specimen. AWG 16 stranded copper wire was used to make the connection between each reinforcing bar to terminal blocks inside the junction box.

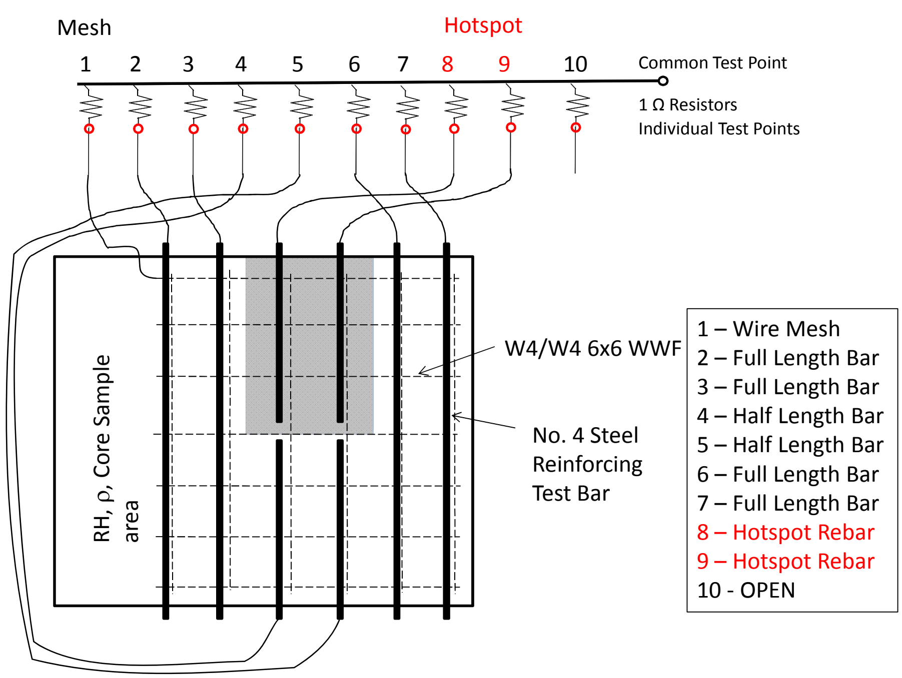


Figure 89 - Wiring Diagram for Hotspot Repair Test Specimen

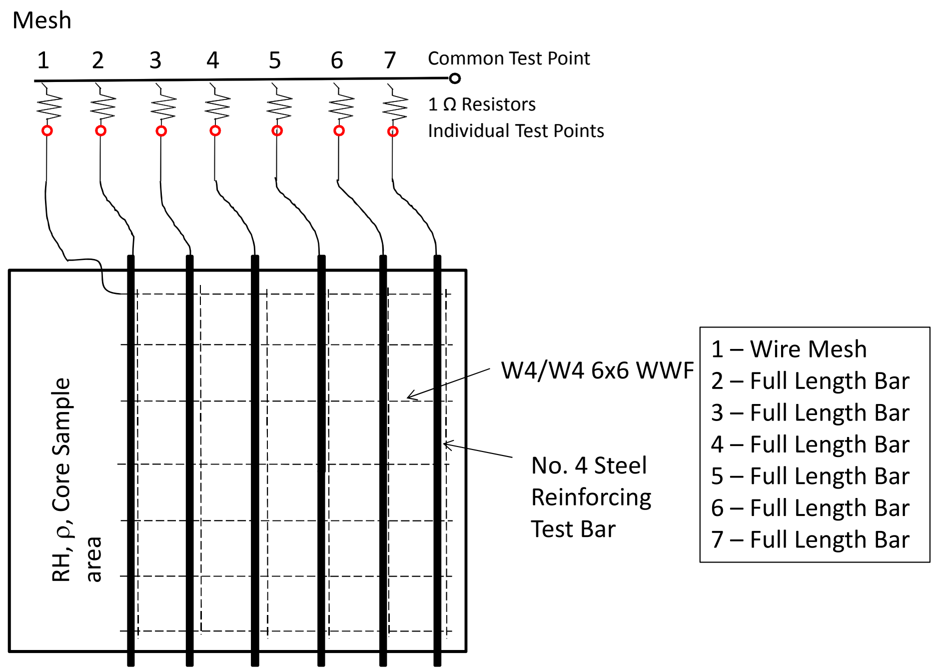


Figure 90 - Wiring Diagram for Topical Test Specimen

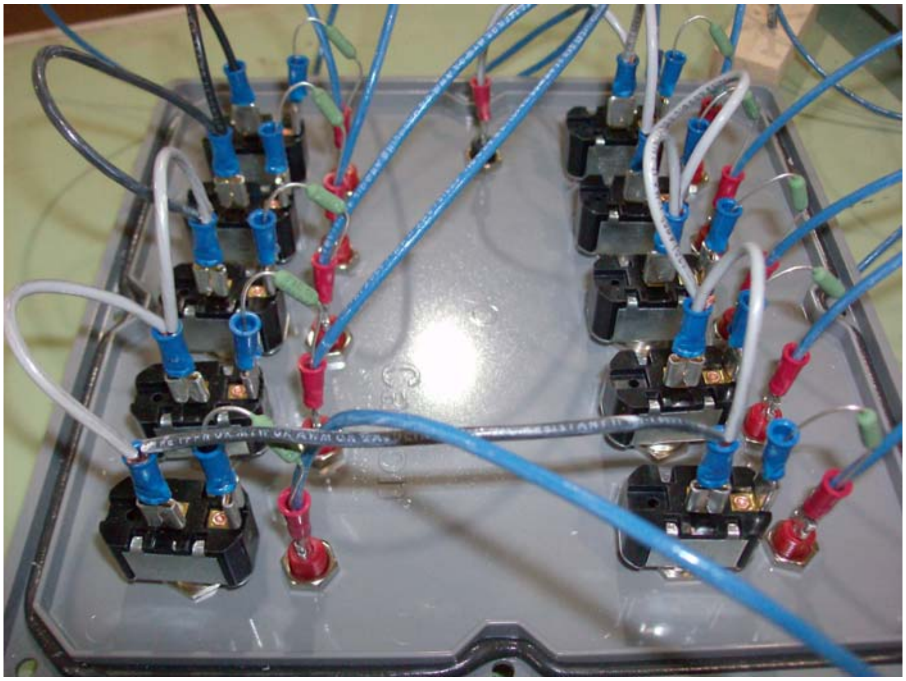


Figure 91 - Wiring in NEMA 4X Box for Ten Circuit System for Repair Test Slab

Figure 92 - Test Specimen with Completed Wiring and Junction Box

<u>Storage of Test Specimens</u>

Upon slab completion, the test specimens were stored in a controlled warehouse environment on steel racks in the TCG facility with temperature between 65 and 85 °F and relative humidity less than 70%.

Figure 93 – Storage of test specimens

Ponding Cycle

Twenty-eight (28) days after casting, the slabs were commissioned by connecting the reinforcement and WWF through the junction box toggle switches and started the initial ponding cycle as described below:

Ponding Solution: The ponding solution was 5.0 ± 0.1% NaCl solution by mass. The NaCl was food grade and mixed with tap water. The ponding solution was batched in 250 and 300 gallon capacity tanks.

Ponding Cycle: The ponding cycle consisted of two weeks ponded with 5% NaCl solution followed by two weeks drying at relative humidity less than 70%. The cycle was repeated every 4 weeks (2 weeks wetting, 2 weeks drying). During the wetting period a plastic cover was placed over the top of the test specimen to prevent excessive evaporation over the two week period. After the wetting period, the plastic cover was removed and the solution was emptied from each test specimen using a PVC drainage system that was cast into the test specimens.

Figure 94 - PVC Piping Installed to Provide Drainage for Ponding Solution

Appendix B – Characterization Tests

TCG cast and cured forty-one (41) four-by-eight-inch and four (4) three-by-six-inch concrete cylinders from the same batches of concrete used to manufacture the test slabs.

Fresh Concrete Properties

TCG tested each concrete batch for fresh concrete properties according to the following procedures:

- ASTM C 138 "Density (Unit weight), Yield, and Air Content (Gravimetric) of Concrete"
- ASTM C 143 "Slump of Hydraulic Cement Concrete"
- ASTM C 231 "Air Content of Freshly Mixed Concrete by the Pressure Method"
- ASTM C 1064 "Temperature of Freshly Mixed Concrete"

Hardened Concrete Properties

TCG tested each concrete batch for hardened concrete properties according to the following procedures:

- ASTM C 39 "Compressive Strength of Cylindrical Concrete Specimens". The compressive strength was tested at 3, 7, 28, 56, 90, 180, and 365 days on 4-inch diameter x 8-inch tall cylinders in replicates of three specimens.
- ASTM C 1202 "Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. The resistivity was tested at 28, 90, 180, and 365 days on 4-inch diameter x 8-inch tall cylinders in replicates of three specimens.
- ASTM C 1152 "Acid-Soluble Chloride Content Determination in Concrete". The background chloride content was tested at 28 days on bottom portions of three cylinders removed for testing the ASTM C 1202 procedure.

Chloride Transport Properties

The chloride ingress data from the chloride ponding portion of this test program is collected for later analysis using numerical modeling (not part of this project). TCG characterized the chloride transport properties according to the following procedures:

- ASTM C 1556 "Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion". Testing occurred at 28 and 365 days on 3 specimens for each age.
- ASTM C 642 "Density, Absorption, and Voids in Hardened Concrete". One 4-inch diameter by 8-inch cylinders was tested each at 28 and 365 days.
- BS 1881: Part 122 "Method for determination of water absorption". Water absorption was tested on two 3-inch diameter by 6-inch cylinders each at 28 and 365 days.

Figure 95 – Casting cylinders for concrete characterization

Appendix C – Corrosion Monitoring and Chloride Penetration Measurements

TCG conducted periodic corrosion monitoring and chloride penetration measurements consisting of the following:

Corrosion Potential: (ASTM C 876)
The half-cell corrosion potential was measured in each reinforcement bar, for each test slab per ASTM C876 "Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete." The corrosion potential was measured at the end of each two week ponding period, before the surface of the concrete had dried, but after removal of the ponding solution. One potential measurement was obtained per bar per ponding cycle. Corrosion potentials were collected at the same locations on the slabs throughout the duration of the test as marked by a small drill bit depression in the concrete surface above each bar. The recorded half-cell potential was measured using a copper/copper-sulfate reference electrode and normalized to a standard temperature of 77 degrees F. The voltmeter used had internal circuit impedance greater than 10 MΩ (megohms) to ensure measurement errors were minimized.

Time-to-Corrosion Initiation:
At the onset of corrosion, the corrosion potential at five equally spaced points on the concrete surface over the bar was recorded. The corrosion potential measurements along the bar were intended to identify the location where corrosion activity has initiated.

Potential Mapping
Periodic half-cell potential mapping was conducted using grid pattern above each rebar and 6" spacing along each rebar for a total of 30 measurements. Potential mapping was conducted with all the top bars and WWF electrically connected. These measurements were conducted primarily just before repairs were made and at the end of testing.

Macrocell Corrosion Current Monitoring:
The macrocell corrosion current was measured as the voltage drop across the shunt resistor using a voltmeter with microvolt resolution. The macrocell current was measured for each reinforcing bar and the bottom WWF mat. All measurements were conducted at the end of each wet period of the ponding cycle just before removal of the ponding solution.

Mat-to-Mat Resistance Monitoring:
The concrete resistance between layers was measured prior to ponding, after the first cycle, and after the 6th, 12th, 18th, and 24th ponding cycles. The mat-to-mat resistance measurements were made between all test bars and the WWF using the 2-pin measurement technique and an AC soil resistance meter. This measurement takes place with the top bars electrically connected and WWF electrically discontinuous from the top mat reinforcing bars.

Electrical Resistivity:

The electrical resistivity of the concrete was determined at the reinforcing level using the embedded stainless steel pins and an AC soil resistivity meter in accordance with the ASTM G57 Wenner 4-pin method. Electrical resistivity measurements were recorded at the start and end of the initial ponding cycle, and at the end of the 6^{th}, 12^{th}, 18^{th}, and 24^{th} ponding cycle.

Chloride Profiles:

Cores for chloride profiles were obtained in each slab specimen when corrosion initiated in at least 3 reinforcing bars for slabs without a hotspot (70 slabs). Three additional cores were taken from each batch of concrete after 6, 12, 18, and 24 cycles. Cores were taken from the designated slab area to extract 1.75-inch diameter, 2.25-inch minimum length concrete samples to determine chloride profiles. The cores were cut into slices 3/8-inch thick, and crushed to meet the No. 20 sieve. The acid soluble chloride was then determined according to ASTM C1152.

Internal Relative Humidity:

Just prior to topical treatments in 0.75-inch cover slabs, ports were installed at the level of the top reinforcing steel to house automatic data-loggers for measuring relative humidity and temperature (Omega, OM-EL-USB-2). The ports consisted of drilling holes approximately 5-inch deep in the sides of selected slabs and inserting PVC tubing keeping the inside exposed to the concrete. The sensors were placed inside the ports and sealed with a fitted rubber cork and electrical tape. The data-loggers were removed periodically to download the recorded measurements.

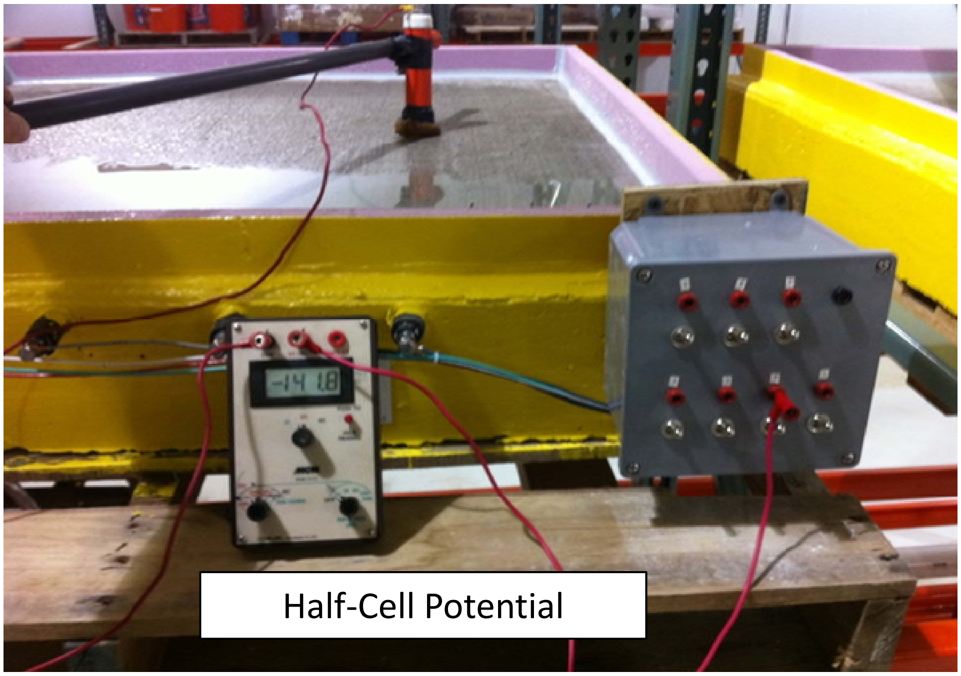


Figure 96 – Half-cell potential measurement

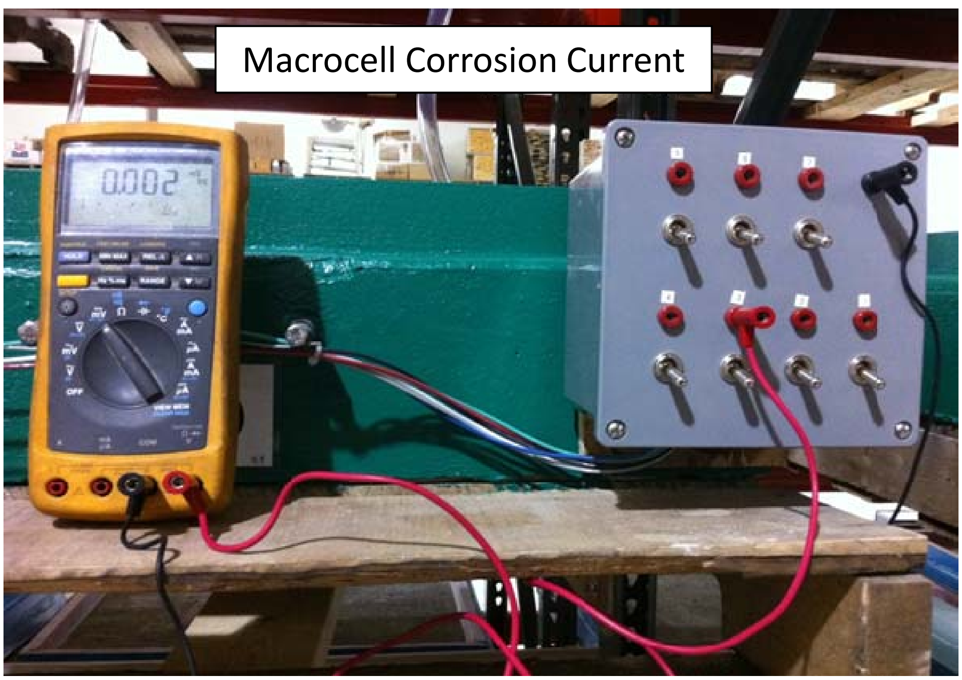


Figure 97 – Macrocell current measurements

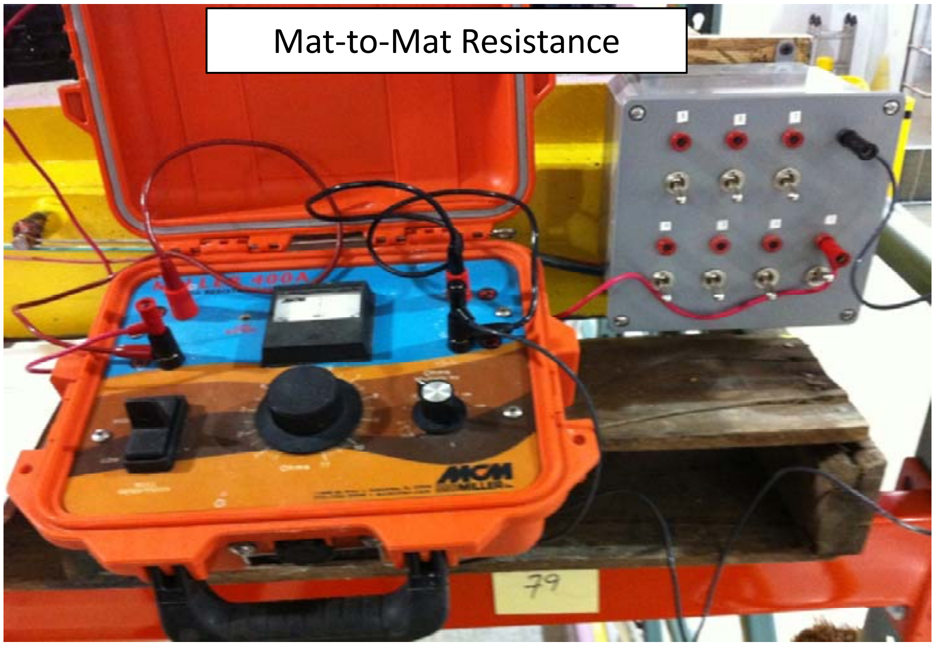


Figure 98 – Mat-to-mat resistance measurement

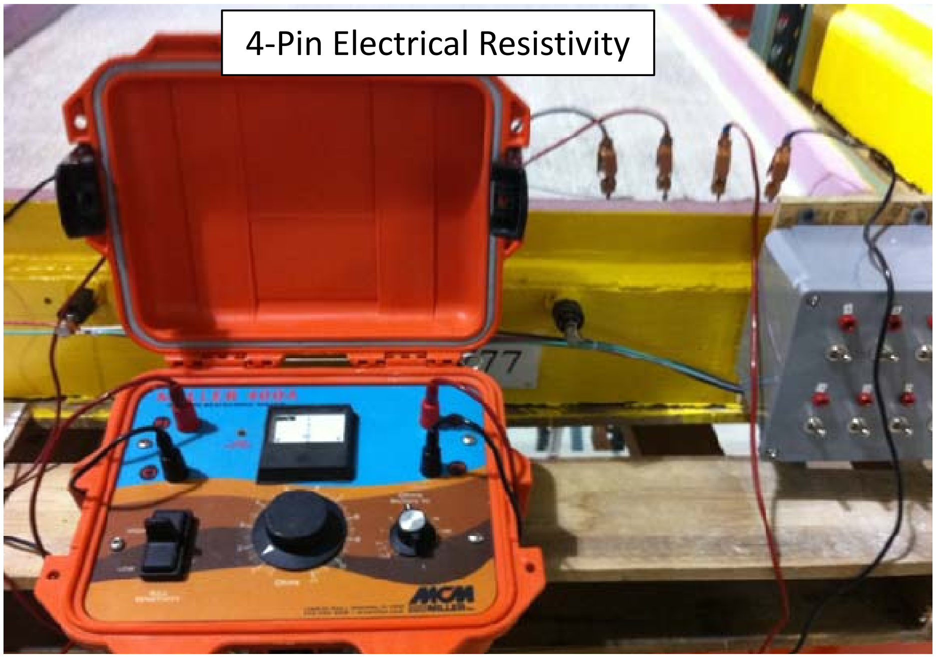


Figure 99 - Wenner 4-pin electrical resistivity measurement

Figure 100 – Installation of internal relative humidity and temperature ports

Figure 101 – Installed port for housing data-loggers

Appendix D – Application of Corrosion Mitigation Treatments

This section describes the procedures for applying each topical and repair corrosion mitigation treatments. The treatments are as follows:

- Topical Treatments
  - A. Calcium Nitrite Inhibitor (CNI)
  - B. 40% silane Sealer (Sealer)
  - C. Epoxy Coated Membrane (Epoxy)
- Repair Treatments
  - D. Repair mixture, 0.40 w/c, 6.5 SK, Type I/II portland cement (Repair)
  - E. Repair mixture with rebar coating (Rebar Coating)
  - F. Repair mixture with galvanic anode (Anode)
  - G. Repair mixture with 40% silane sealer (Sealer)

Topical Treatments

Calcium Nitrite Inhibitor - Treatment "A"

1. Prepare surface by washing to remove surface chlorides and loose debris, and then dry with pressurized air.
2. Use a back-pressure liquid applicator to spray apply three (3) surface applications at 125 ft^2/gal as recommended by the manufacturer.
3. Allow each application to dry prior to subsequent applications.

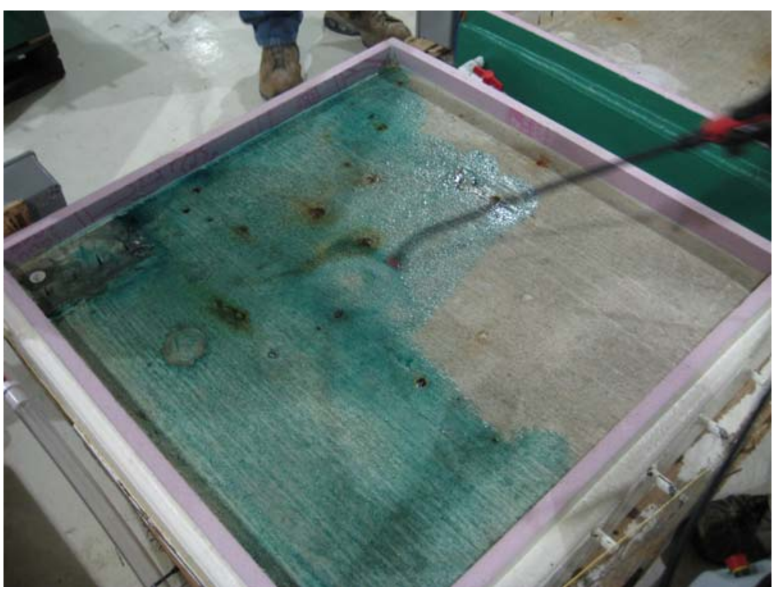


Figure 102 – Applying calcium nitrite inhibitor to slab surface

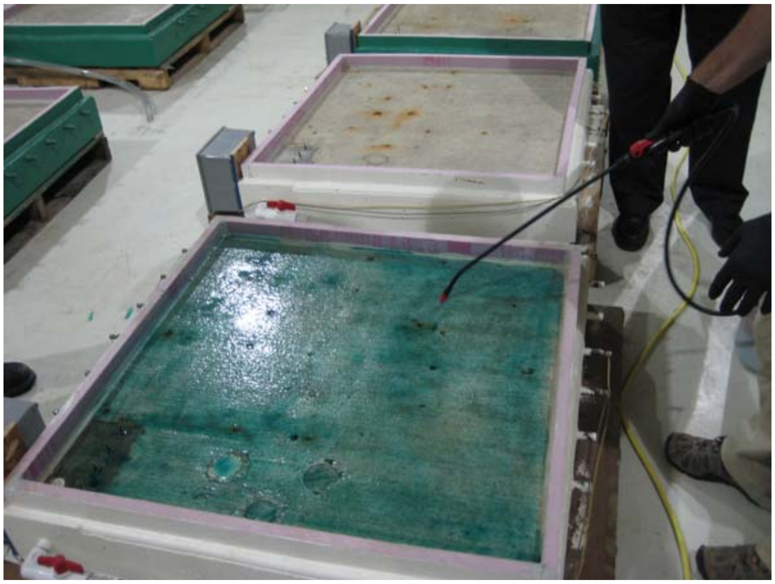


Figure 103 – Slab with completed application of calcium nitrite inhibitor

Treatment "B" - 40% Silane Sealer

1. Prepare surface by washing to remove surface chlorides and loose debris, and then dry with pressurized air.
2. Evenly apply 40% silane sealer across slab surface using brushes and rollers at 125-250 ft^2/gal as recommended by the manufacture
3. Allow treatment to dry and reapply for a total of three applications

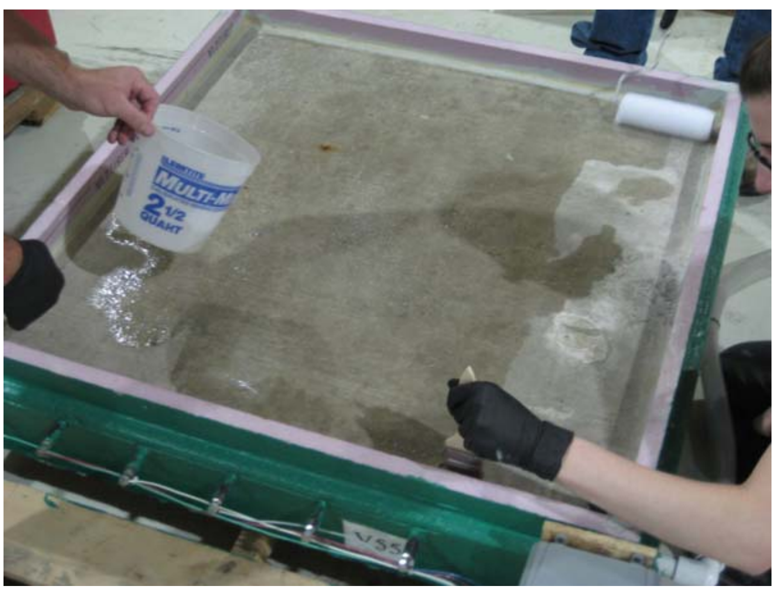


Figure 104 – Applying 40% silane sealer to slab surface

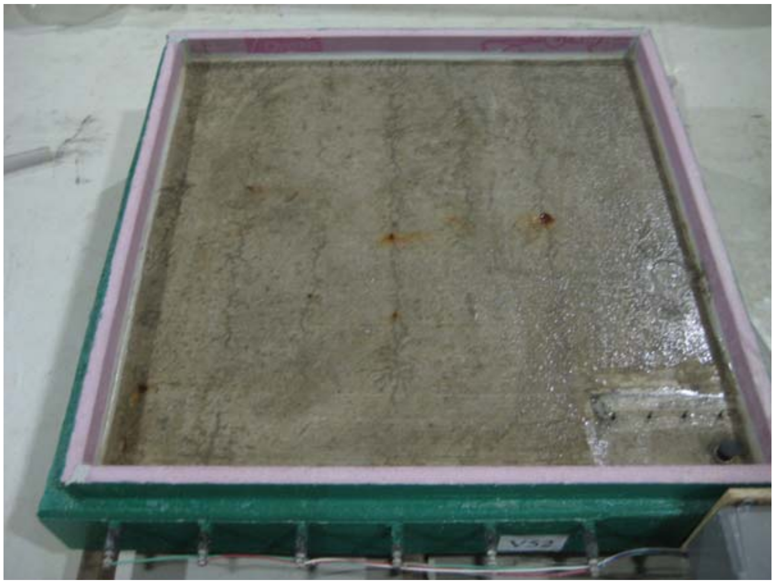


Figure 105 – Slab with completed application of 40% silane sealer

Treatment "C" - Epoxy Coated Membrane

1. Prepare surface by washing to remove surface chlorides and loose debris.
2. Drill 2-inch diameter core holes approximately 1-inch deep.
3. Chip out concrete to rebar depth.
4. Create potential measurement well by filling the hole with grout and inserting the PVC pipe, then adding grout so the pipe is three-quarter full.
5. To provide profile for proper adhesion shot-blast slab surface to remove laitance and miscellaneous surface contamination.
6. Vacuum or remove sand with pressurized air.
7. Apply primer to slab surface at a rate of 200-250 ft^2/gal as recommended by the manufacture and allow to dry to a tack-free consistency.
8. Apply base coat at 60 ft^2/gal (25 wet mils) as recommended by the manufacture and allow to cure overnight and have slight tack.
9. Apply top-coat at 60 ft^2/gal, then broadcast aggregate at 10-15 lbs./100 ft^2 while top coat is still wet and use roller to spread evenly according to manufacturer's instructions.

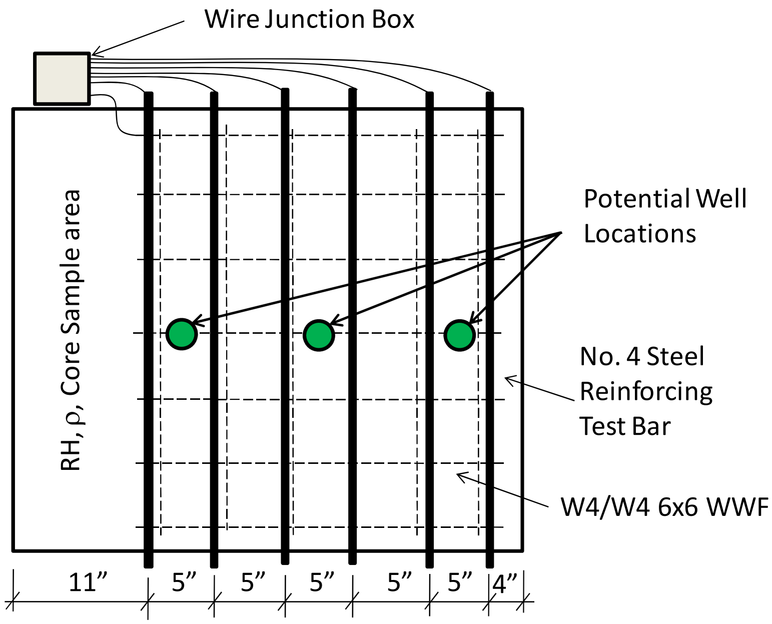


Figure 106 – Plan view schematic of potential measurement well locations (3 per slab)

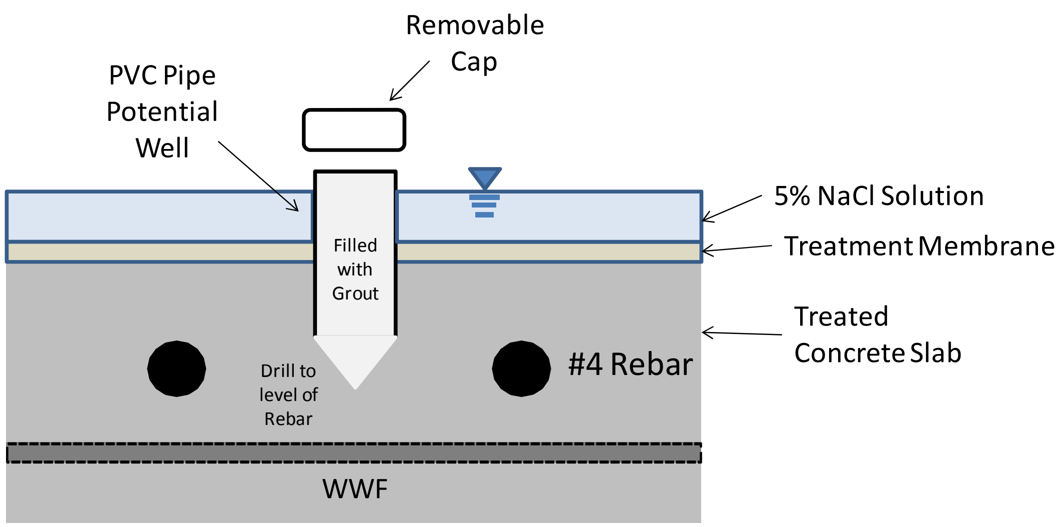


Figure 107 – Profile view schematic of potential measurement well

Figure 108 – Installation of potential measurement wells

Figure 109 – Shot blasting slab surface

Figure 110 – Application of primer

Figure 111 – Completed application of primer

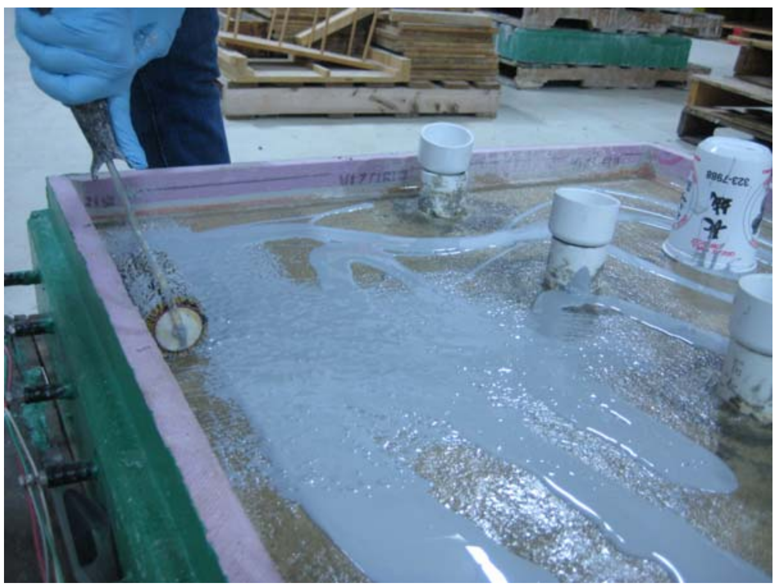


Figure 112 – Application of base coat

Figure 113 – Completed application of base coat

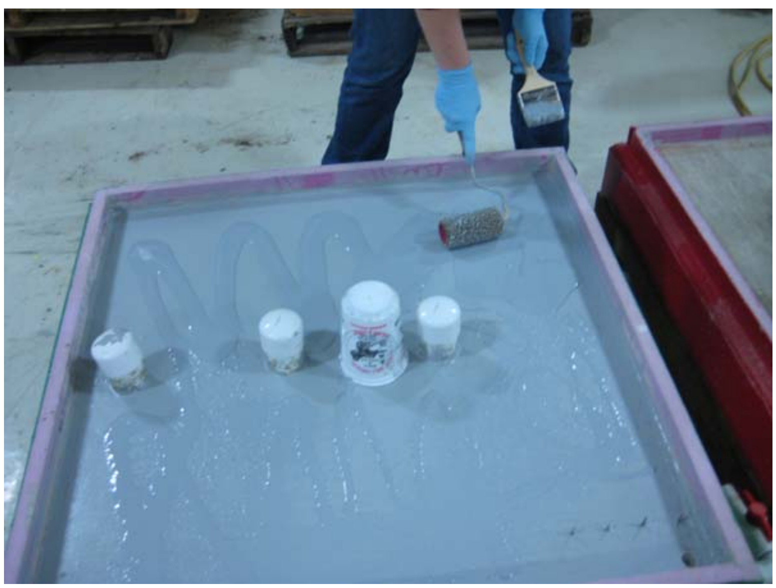


Figure 114 – Application of top coat

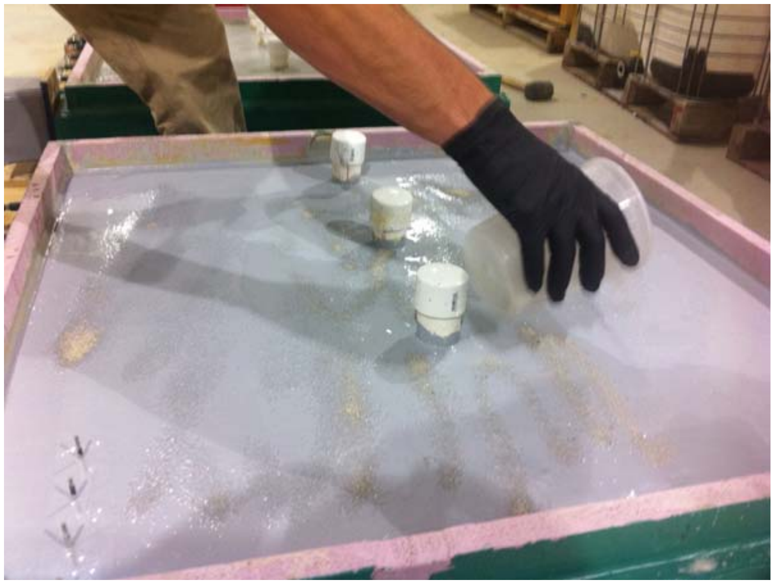


Figure 115 – Aggregate broadcast to wet top coat surface

Figure 116 – Spreading aggregate evenly with roller

Figure 117 – Completed epoxy coating surface

Repair Treatments

Treatment "D" – Repair Mixture

1. To prevent damage disconnect rebar wiring and remove ponding dam on the front face of the slab.
2. Saw cut and chip out concrete in the original hotspot area approximately 9-inch wide x 20-inch long x 3-inch deep.
3. Remove and measure corroded area of steel on hotspot bars.
4. Roughen the saw cut edges and existing concrete substrate surface.
5. Wash and vacuum or blow with pressurized air to remove any extra debris.
6. Prepare rebar by wire brushing to remove all corrosion products.
   - If more than 20% area of rebar is corroded replace with new bars and prepare as original bars.
7. Reinstall forms and rebar in their original position.
8. Cast repair material with the following characteristics:
   - 0.40 w/c, 6.5 SK, Type I/II cement (No SCMs)
   - Slump between 3-7"
   - Nominal max size aggregate 3/8"

Table 32 – Repair Concrete Mixture Design

Batch ID	w/c	Cement, lbs./yd^3	Water, lbs./yd^3	Coarse Aggregate, lbs./yd^3	Fine Aggregate, lbs./yd^3	Air Entrainment, %
Repair	0.40	611	244	1700	1354	6

9. Install repair material with a scrub coat, no bonding agents are used to prevent electrical isolation of the patch.
10. Consolidate by rodding and finish with a magnesium trowel, apply broom finish.
11. Moist cure repair for a minimum of 7 days, then allow to air dry.
12. Replace dams and wiring removed during repair installation.

Notes: Slabs typically skipped one ponding cycle to allow repair mortar to cure and allow dams to be replaced. Slabs were repaired in an alternating sequence when the repair criteria were met for each slab.

Figure 118 – Saw cut and chip out concrete in hotspot area

Figure 119 – Remove rebars and measure corroded area of steel

Figure 120 – Roughen saw cut edges

Figure 121 – Clean and blow out repair area

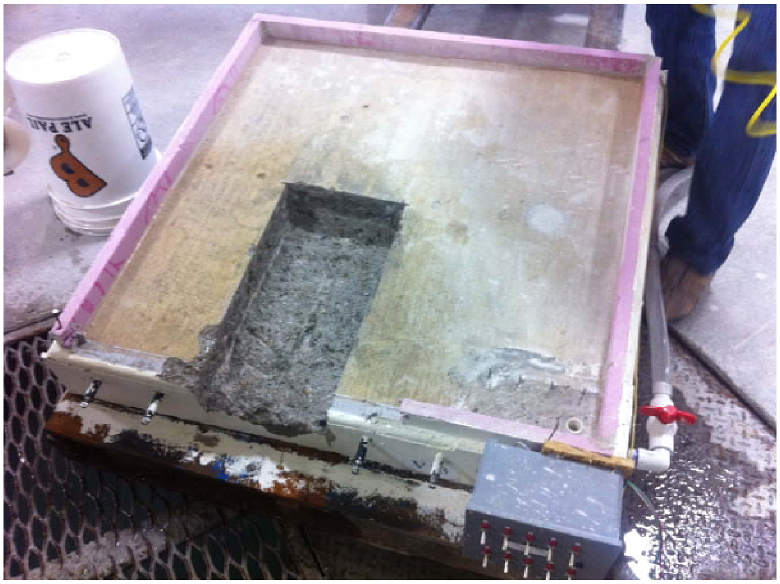


Figure 122 – Cleaned repair area

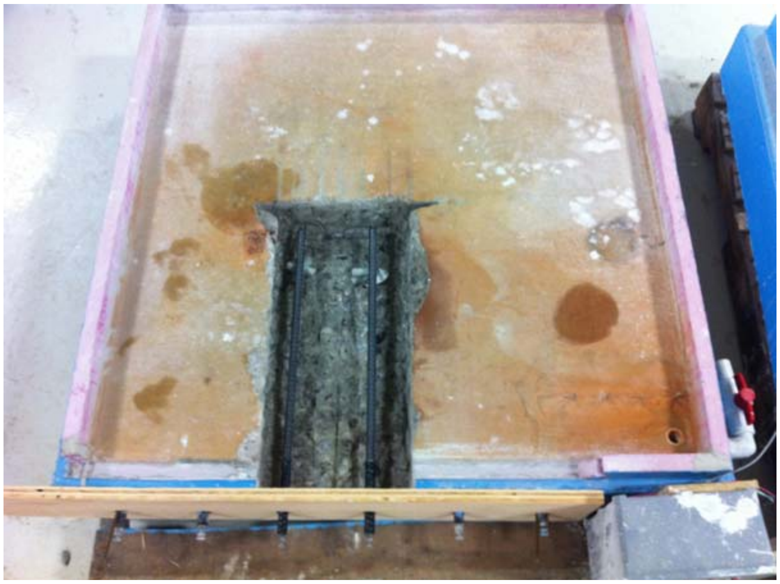


Figure 123 – Reinstall form and rebars

Figure 124 – Slab with completed repair mixture treatment

Treatment "E" – Repair Mixture with Rebar Coating

1. Perform steps 1-5 listed previously in "Repair mixture".
2. Prepare rebar by wire brushing to remove all corrosion products.
    - If more than 20% area of rebar is corroded replace with new bars and prepare as original bars
3. Mix and apply two-part cementitious rebar coating according to manufacturer's instructions.
4. Perform steps 7-12 listed previously in "Repair Mixture".

Figure 125 – Components of cementitious rebar coating

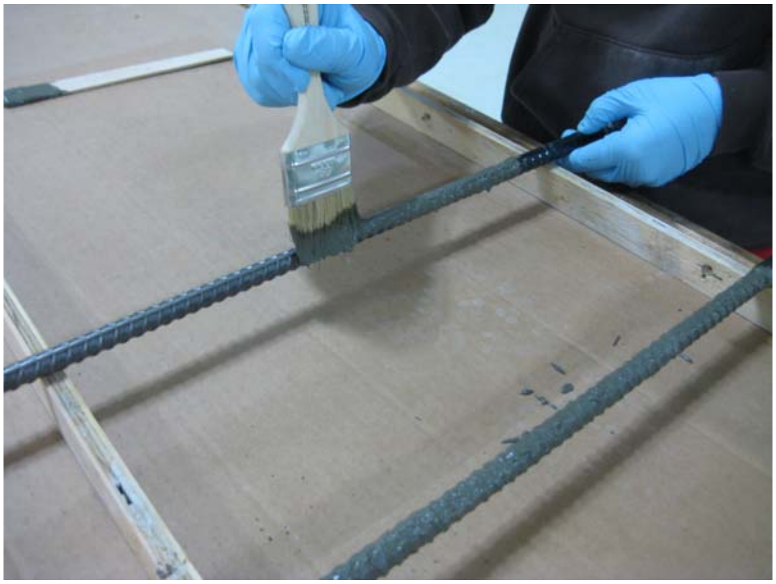


Figure 126 – Application of cementitious rebar coating

Treatment "F" – Repair Mixture with Galvanic Anode

1. Perform steps 1-7 listed previously in "Repair mixture".
2. Install galvanic anode according to manufacturer's instructions and place between the two half-length rebar located in the hotspot.
3. The galvanic anode is externally connected to the hotspot rebar through the existing junction box.
4. Perform steps 7-12 listed previously in "Repair Mixture".

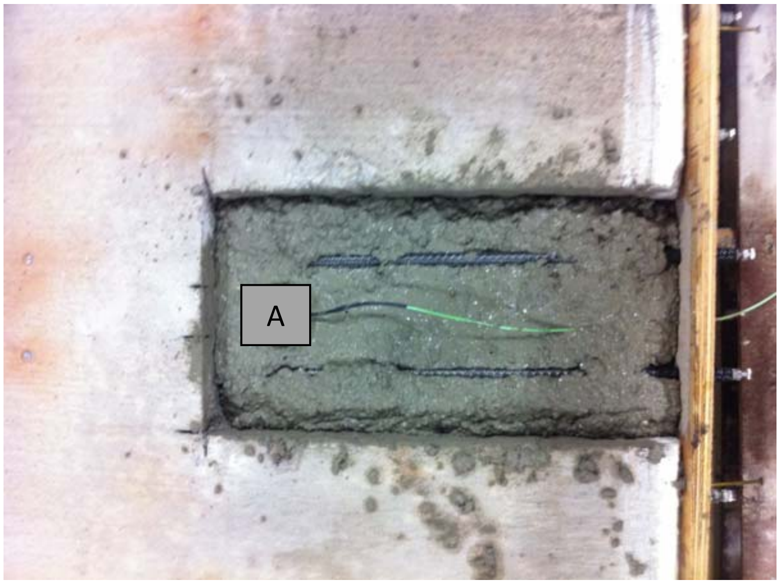


Figure 127 – Installation of Galvanic Anode

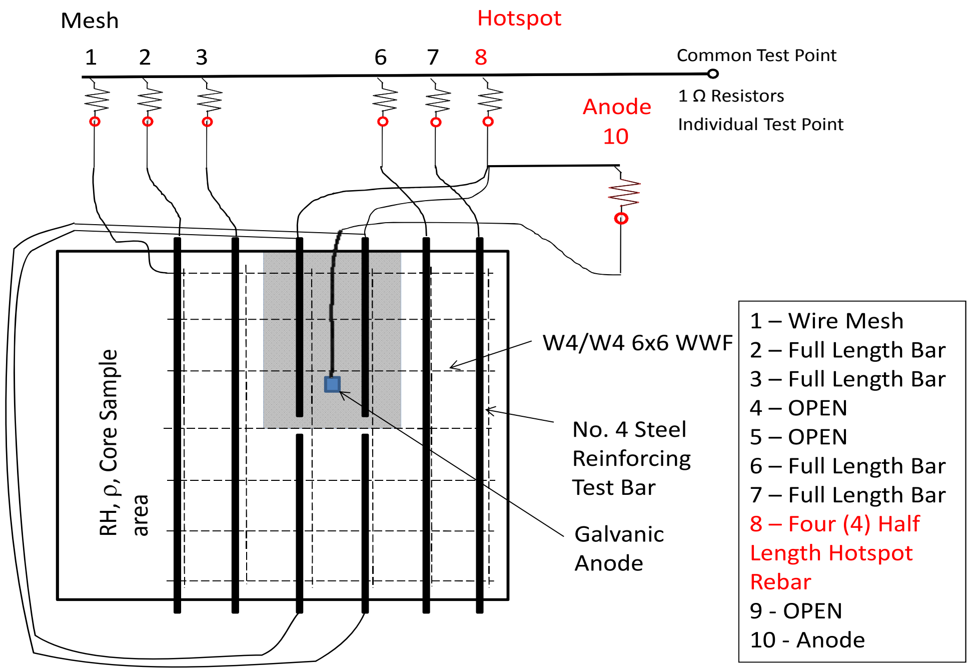


Figure 128 - Wiring Diagram for Test Specimen Repaired with Galvanic Anode

Treatment "G" – Repair Mixture with 40% Silane Sealer

1. Perform steps 1-13 listed previously in "Repair mixture".
2. After 7 days of wet curing allow slab to dry and apply 40% silane sealer as described in Treatment "B".

Appendix E – Forensic Examinations

Rebar Removal

This section describes the steps taken when conducting forensic examinations. The steps are as follows:

1. Remove ponding dams, wiring, and junction boxes.
2. Cut parallel slots, approximately 1-inch adjacent to both sides, the length of the rebar and rinse to clean.
3. Mark the top of each rebar prior to removal to identify during visual examinations.
4. Use an industrial hammer drill to chip away the surrounding concrete and remove bars.
5. Use a small hammer to remove any remaining concrete attached to the bars.
6. Clean slab of loose concrete and debris and replace rebar in original positions.
7. Photograph bird's eye view of slab with rebar placed in position to identify areas of corrosion. Photograph for both top and bottom sides of rebar.
8. Remove bars for visual inspection.
9. Cut samples for measuring chloride content at the rebar level, either between rebar or from the designated core area.

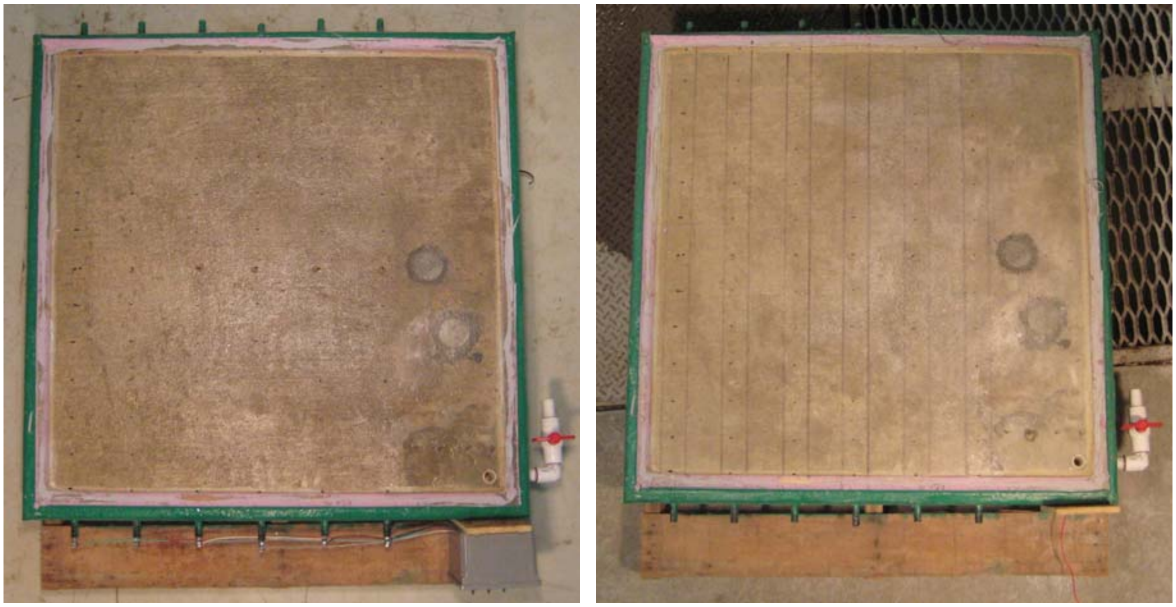


Figure 129 – Remove ponding dams, wiring, and junction boxes

Figure 130 – Cut parallel to rebar

Figure 131 – Chip away and remove concrete adjacent to rebar

Figure 132 – Embedded rebar exposed without visible corrosion

Figure 133 – Embedded rebar exposed with visible corrosion

Figure 134 – Bird's eye view of exposed rebar positioned in slab

Visual Examination

After the reinforcing bars are physically extracted from the concrete slab each rebar undergoes a visual examination to determine the amount and severity of corrosion. The rebars are divided into the following sections:

- Two coated sections ~4 inches long on each end (end treatments).
- Two exposed sections adjacent to the end coatings 1.5-inches long.
- Eleven (11) exposed sections underneath the ponding area 3-inches long.

Each exposed section was evaluated on both top and bottom sides according to the following rating scales.

Table 33 – Rating system for estimating corroded area of steel

Rating	Description
0	No visual corrosion
1	< 1% Area corroded
2	< 5%
3	< 15%
4	< 40%
5	> 40%

Table 34 – Rating system for estimating the severity of corrosion observed

Rating	Identification
L	Light
M	Moderate
H	Heavy
P	Pitting

The visual ratings for each section are then compiled to calculate the total corrosion based on level of severity for each individual rebar and individual slabs for comparison. The following photographs are visual examples of the ratings.

Figure 135 – Light corrosion

Figure 136 – Moderate corrosion

Figure 137 – Heavy corrosion

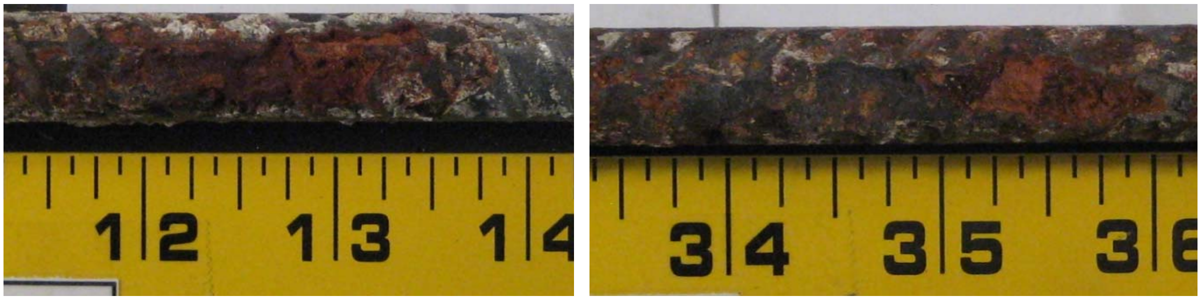


Figure 138 – Pitting corrosion

The end treatments are then cut and removed to expose the steel and record any signs of visual corrosion. Analysis of the end treatments are separated from the exposed steel with the purpose of evaluating effectiveness of end treatment type.

Figure 139 – Corrosion observed underneath CN paste/shrink tube end coating

Figure 140 – H_2SO_4 Pickle/Epoxy end treatment with no visual signs of corrosion

Appendix F – Corrosion Rate Results

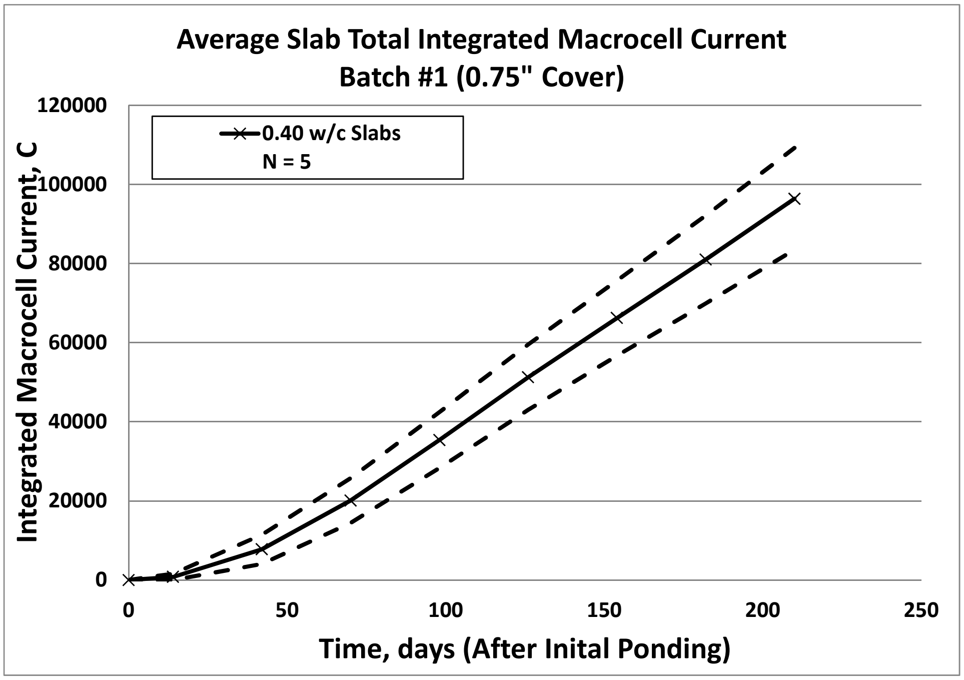


Figure 141 – Total integrated current as a function of time, average per slab, 0.75-inch topical slabs, Batch #1

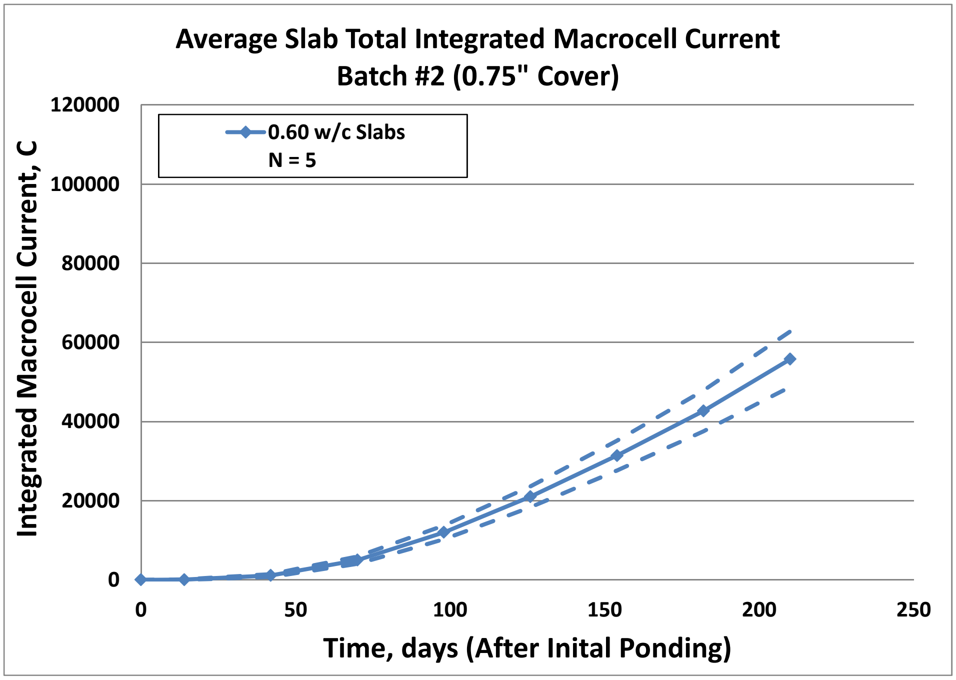


Figure 142 - Total integrated current as a function of time, average per slab, 0.75-inch topical slabs, Batch #2

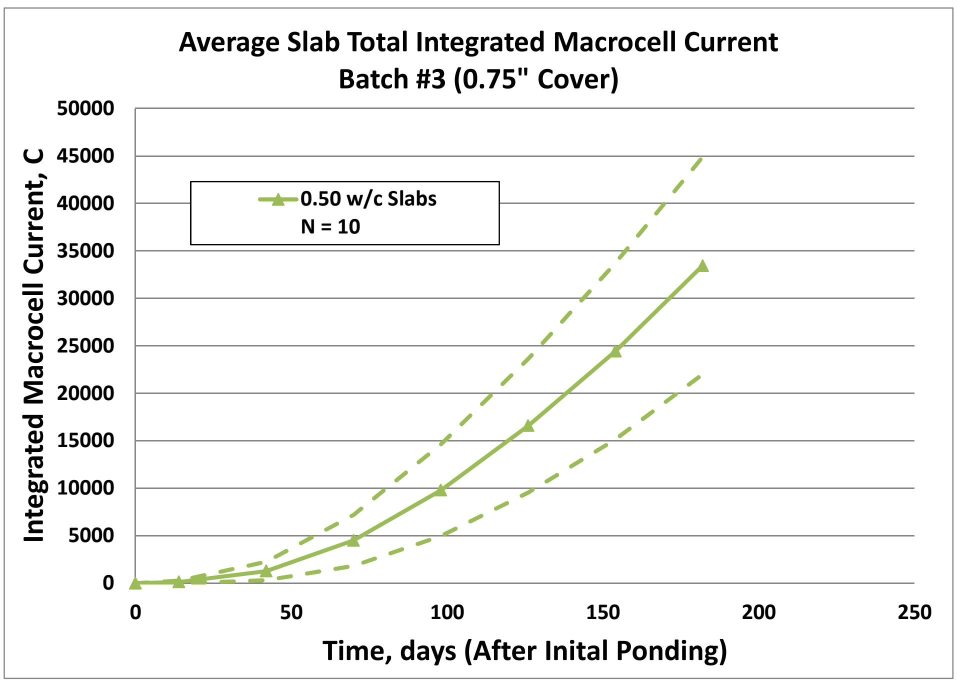


Figure 143 - Total integrated current as a function of time, average per slab, 0.75-inch topical slabs, Batch #3

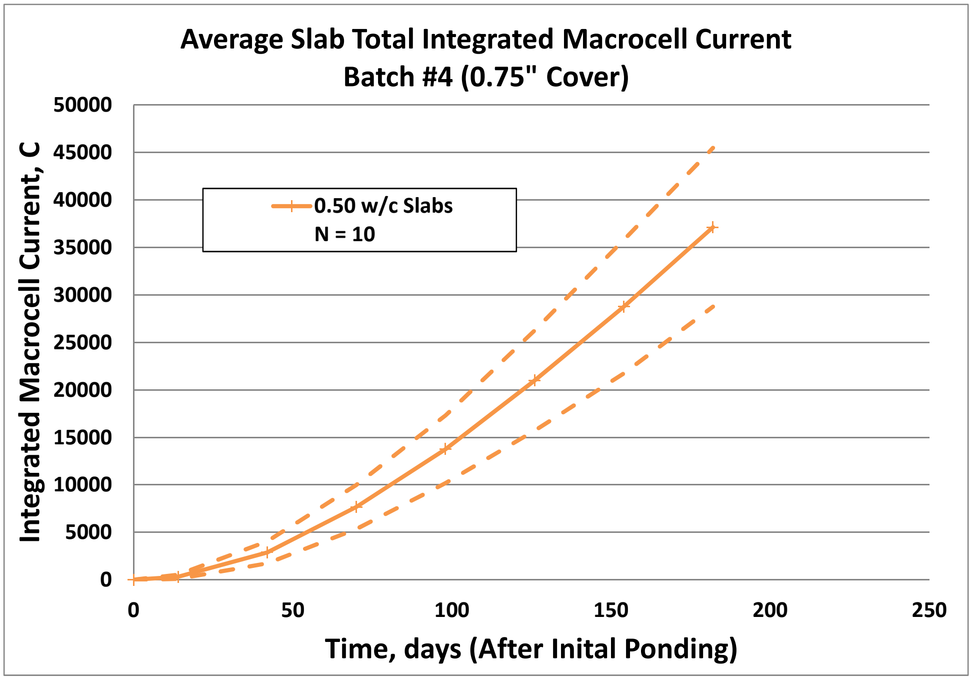


Figure 144 - Total integrated current as a function of time, average per slab, 0.75-inch topical slabs, Batch #4

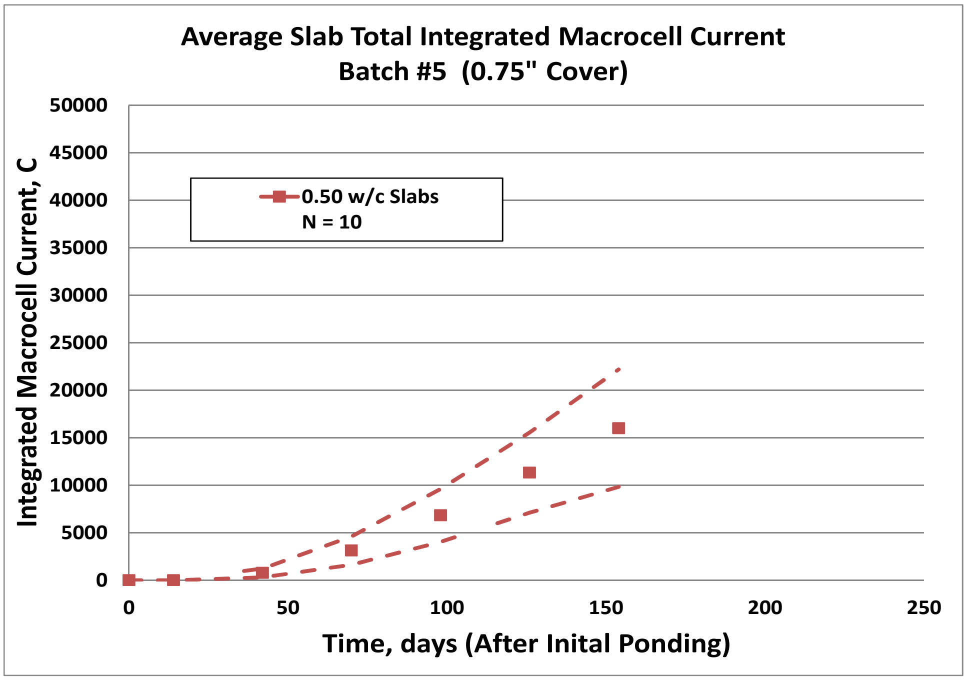


Figure 145 - Total integrated current as a function of time, average per slab, 0.75-inch topical slabs, Batch #5

Appendix G – Corrosion Damage at Time of Treatment Results

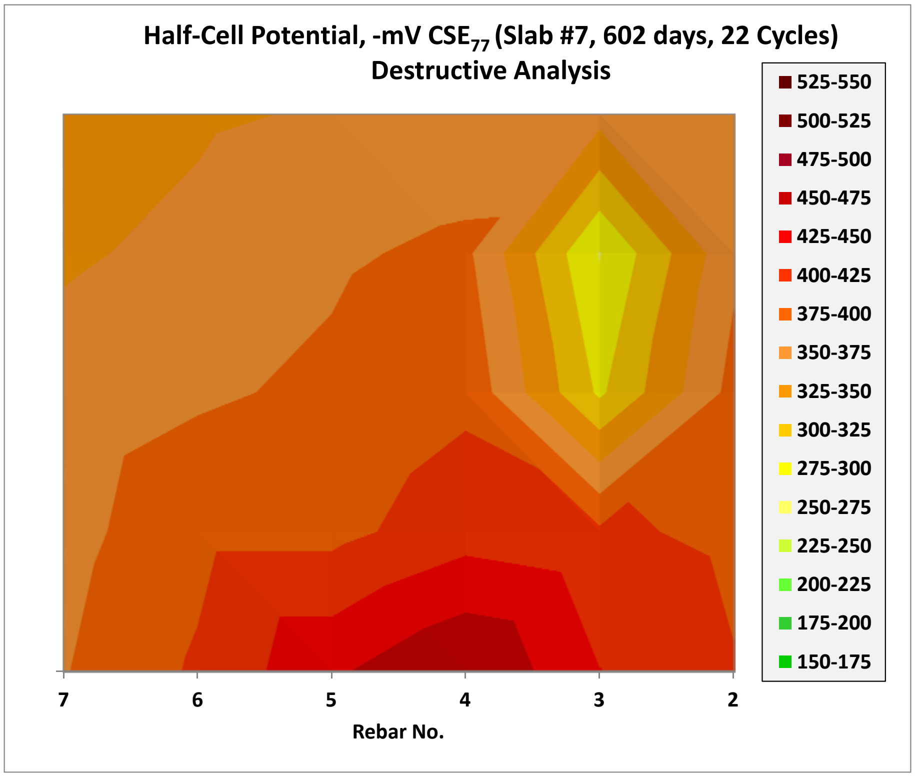


Figure 146 – Half-cell potential mapping prior to destructive analysis, repair slab #7

Table 35 – Summary of destructive analysis findings, repair slab #7

Slab 7	Final Measurements		Visually Examined Corrosion			
Rebar No.	Integrated Current, Coulombs	Half-Cell Potential, mV CSE_{77} (Disconnected)	Light	Moderate	Heavy	Total
Main Rebar						
2	548	-359	0.1%	2.7%	1.5%	4.2%
3	392	-349	1.7%	1.1%	1.1%	4.0%
4	148	-356	0.2%	0.2%	2.3%	2.7%
5	368	-350	0.0%	0.2%	1.4%	1.6%
6	715	-342	0.0%	5.6%	0.0%	5.7%
7	715	-352	0.6%	2.0%	1.5%	4.1%
Total	2886	-	-	-	-	-
Hotspot Rebar						
8	N/A	-490	0.1%	3.2%	11.4%	14.7%
9	N/A	-384	8.6%	1.6%	0.0%	10.2%
Total	-	-	-	-	-	-

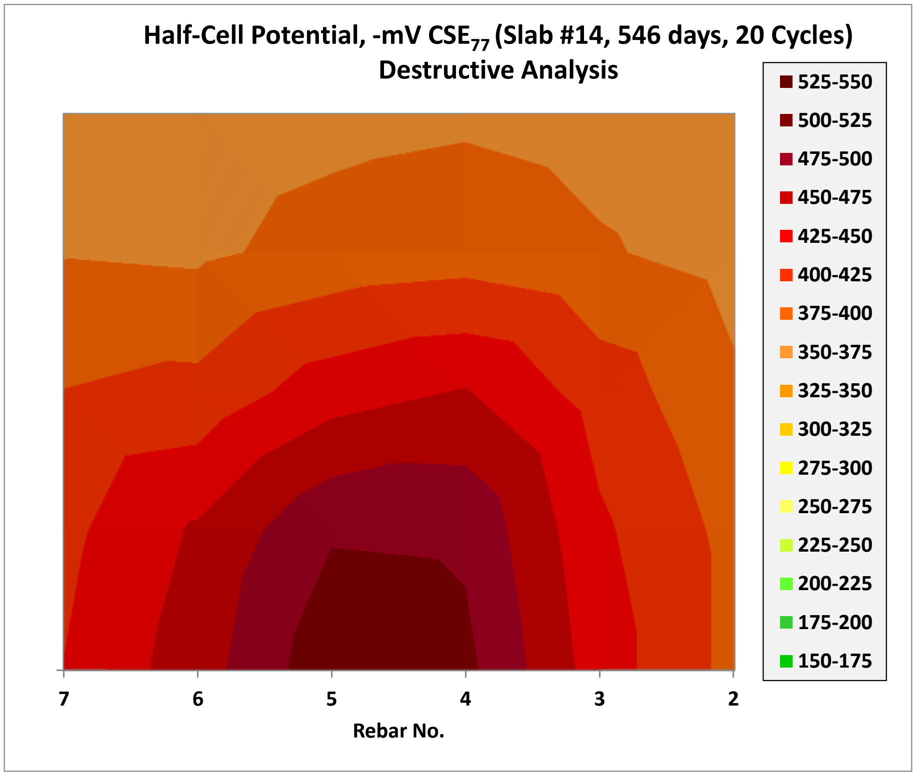


Figure 147 – Half-cell potential mapping prior to destructive analysis, repair slab #14

Table 36 - Summary of destructive analysis findings, repair slab #14

Slab 14	Final Measurements		Visually Examined Corrosion			
Rebar No.	Integrated Current, Coulombs	Half-Cell Potential, mV CSE_{77} (Disconnected)	Light	Moderate	Heavy	Total
Main Rebar						
2	15	-197	0.5%	0.0%	0.0%	0.4%
3	747	-406	0.1%	2.1%	2.0%	4.2%
4	1425	-467	0.0%	3.8%	0.0%	3.8%
5	377	-447	0.0%	3.0%	1.5%	4.5%
6	1044	-407	0.0%	0.5%	2.9%	3.5%
7	0	-181	0.0%	0.0%	0.0%	0.0%
Total	3608	-	-	-	-	-
Hotspot Rebar						
8	N/A	-493	0.0%	0.2%	28.5%	28.8%
9	N/A	-571	0.0%	0.0%	33.2%	33.2%
Total	-	-	-	-	-	-

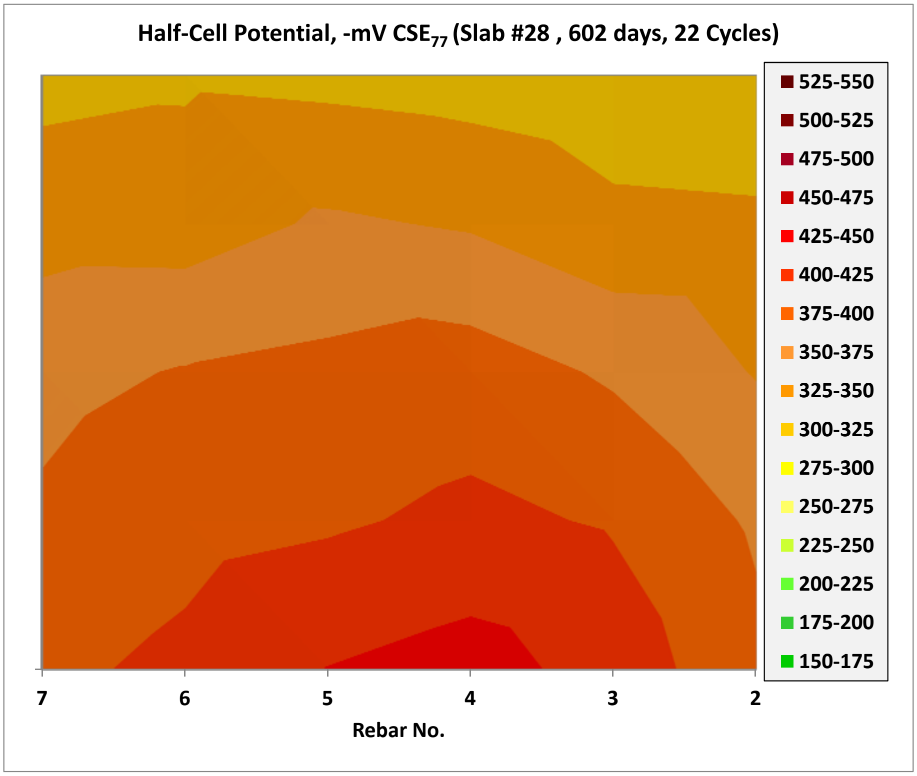


Figure 148 – Half-cell potential mapping prior to destructive analysis, repair slab #28

Table 37 - Summary of destructive analysis findings, repair slab #28

Slab 28	Measurements Prior to Analysis		Visually Examined Corrosion			
Rebar No.	Integrated Current, Coulombs	Half-Cell Potential, mV CSE_{77} (Disconnected)	Light	Moderate	Heavy	Total
Main Rebar						
2	15	-182	0.1%	0.0%	0.0%	0.1%
3	2698	-425	4.5%	2.1%	1.7%	8.3%
4	339	-395	0.0%	3.3%	0.0%	3.3%
5	5	-182	0.0%	0.0%	0.0%	0.0%
6	0	-177	0.0%	0.0%	0.0%	0.0%
7	0	-173	0.0%	0.0%	0.0%	0.0%
Total	3057	-	-	-	-	-
Hotspot Rebar						
8	N/A	-558	3.9%	0.0%	8.8%	12.6%
9	N/A	-503	0.0%	2.9%	14.1%	17.0%
Total	-	-	-	-	-	-

Appendix H - Corrosion Mitigation Results

Topical Treatments - 0.75-inch Cover

Batch #1

Table 38 – Batch #1, 0.40 w/c, 0.75" cover treatments

Slab No.	Treatment	Days (After Initial Ponding)	Completed Ponding Cycles Prior to Treatment	Number of Rebar Initiated Corrosion	Total Slab Integrated Current, Coulombs	Average Half-Cell Potential, mV CSE_{77}
16	CNI	217	8	8	93179	-578
17	Control	(217)	(8)	8	88019	-572
18	Control	(217)	(8)	8	101046	-582
19	Control	(217)	(8)	8	83400	-585
20	CNI	217	8	8	116119	-571

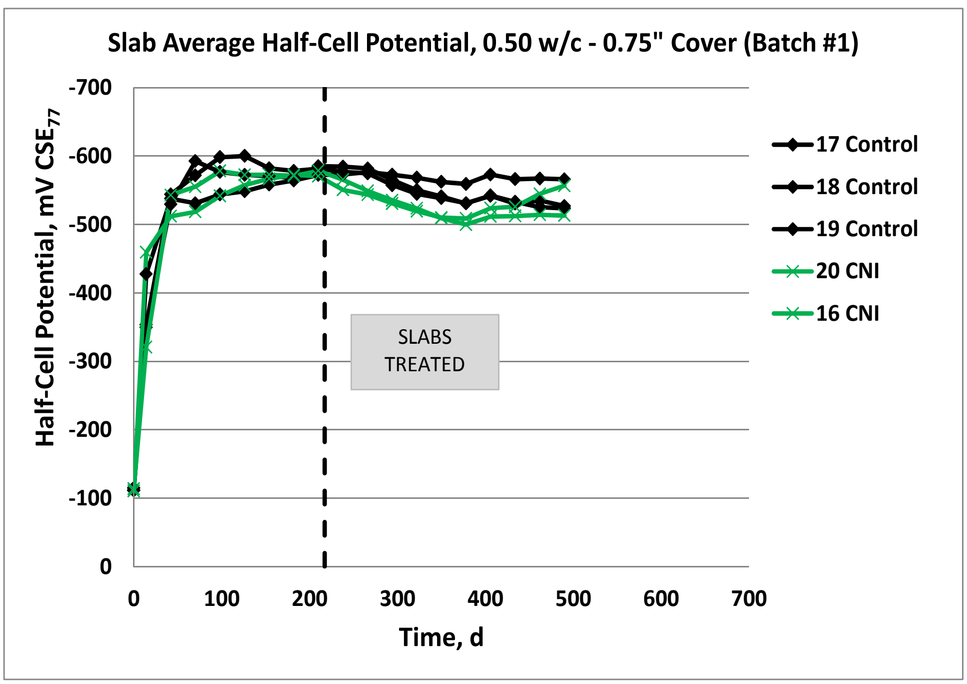


Figure 149 - Slab average half-cell potential as a function of time
(Individual slabs, Batch #1, 0.40 w/c, 0.75" cover)

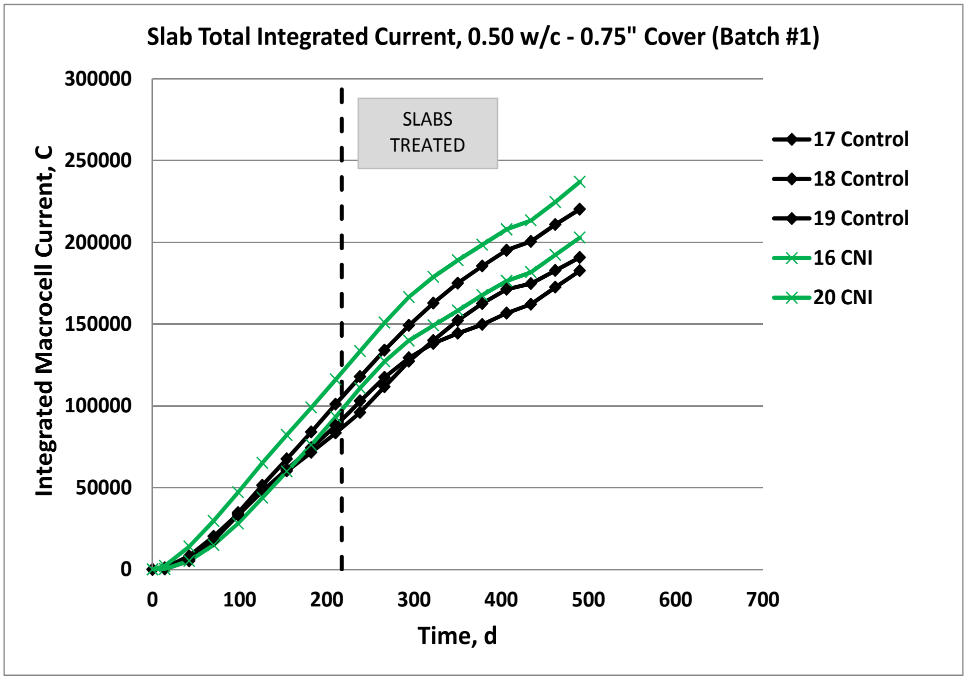


Figure 150 - Slab total integrated current as a function of time (Individual slabs, Batch #1, 0.40 w/c, 0.75" cover)

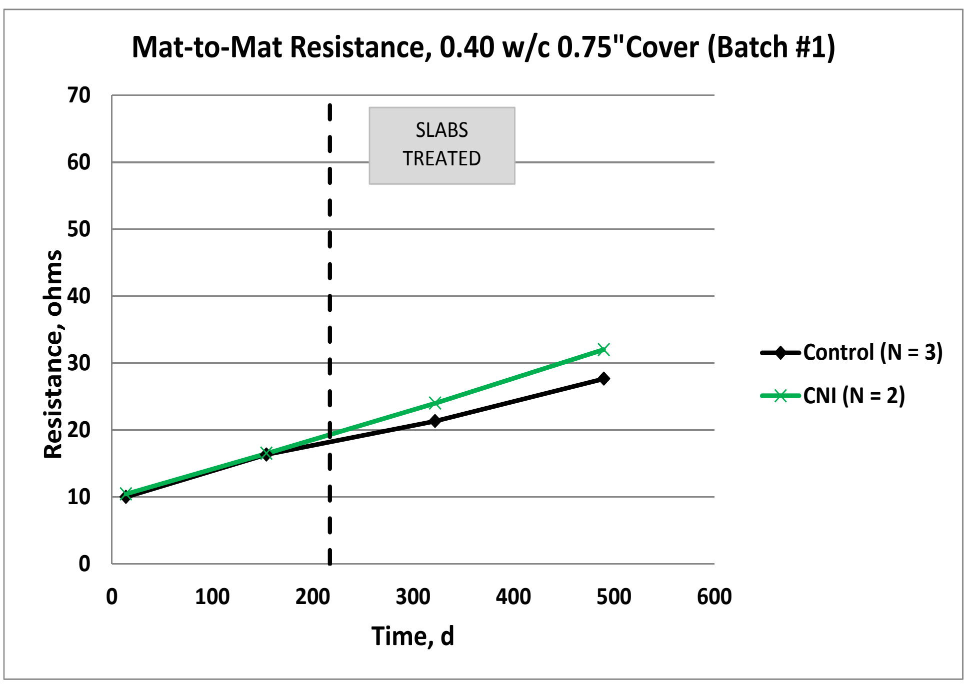


Figure 151 - Average mat-to-mat resistance as a function of time (Batch #1, 0.40 w/c, 0.75" cover)

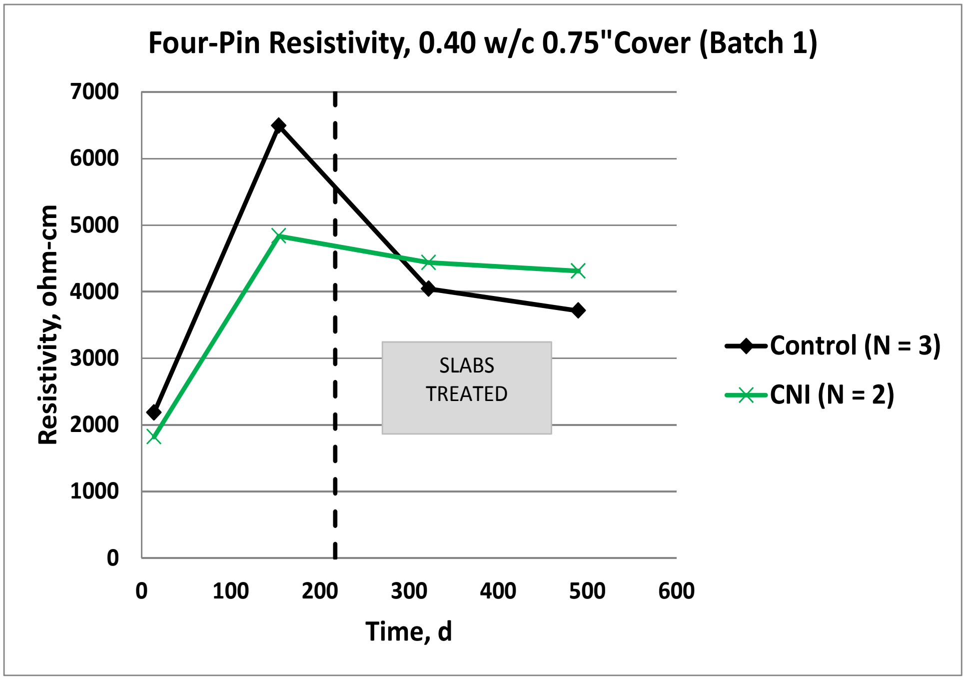


Figure 152 - Average 4-pin resistivity as a function of time
(Batch #1, 0.40 w/c, 0.75" cover)

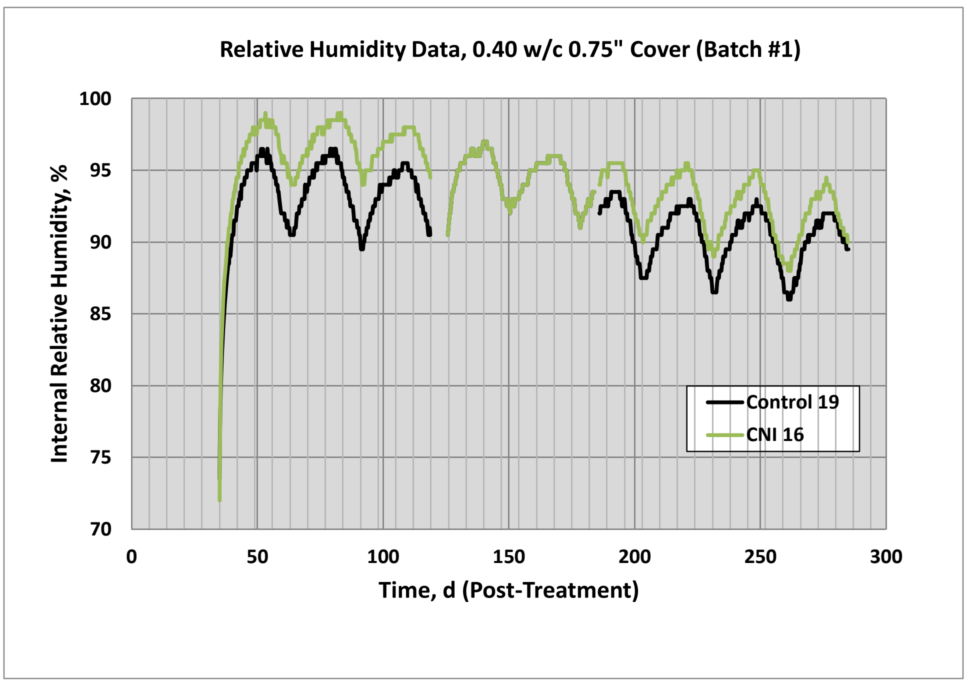


Figure 153 – Relative humidity as a function of time
(Batch #1, 0.40 w/c, 0.75" cover)

Batch #2

Table 39 - Batch #2, 0.60 w/c, 0.75" cover treatments

Slab No.	Treatment	Days (After Initial Ponding)	Completed Ponding Cycles Prior to Treatment	Number of Rebar Initiated Corrosion	Total Slab Integrated Current, Coulombs	Average Half-Cell Potential, mV CSE_{77}
36	Control	(217)	(8)	7	60293	-554
37	CNI	217	8	7	60434	-542
38	Control	(217)	(8)	7	46998	-538
39	Control	(217)	(8)	8	61783	-580
40	CNI	217	8	8	49266	-554

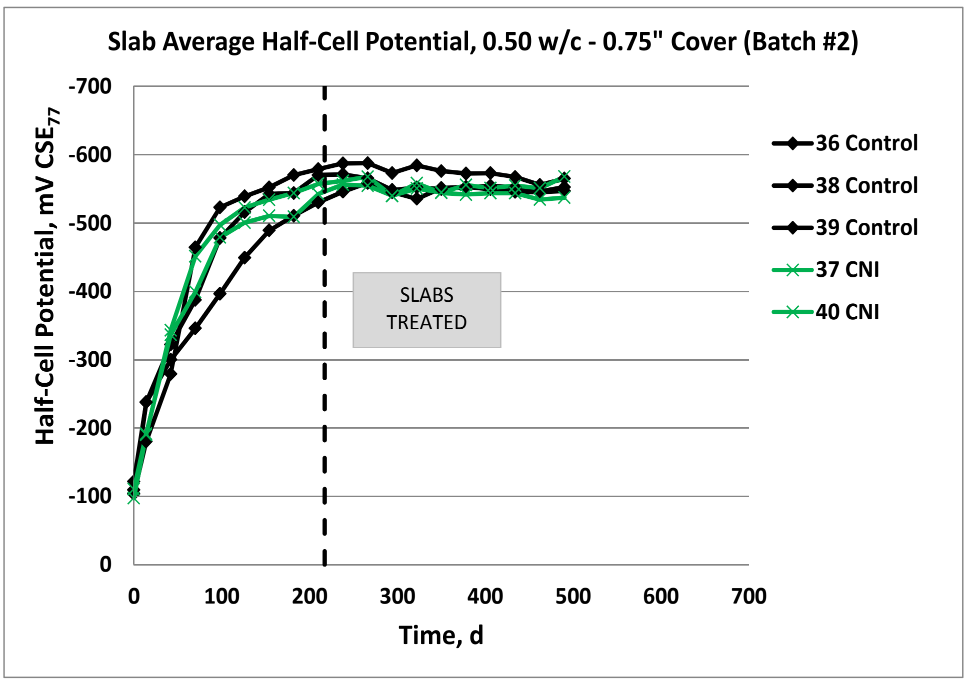


Figure 154 - Slab average half-cell potential as a function of time (Individual slabs, Batch #2, 0.60 w/c, 0.75" cover)

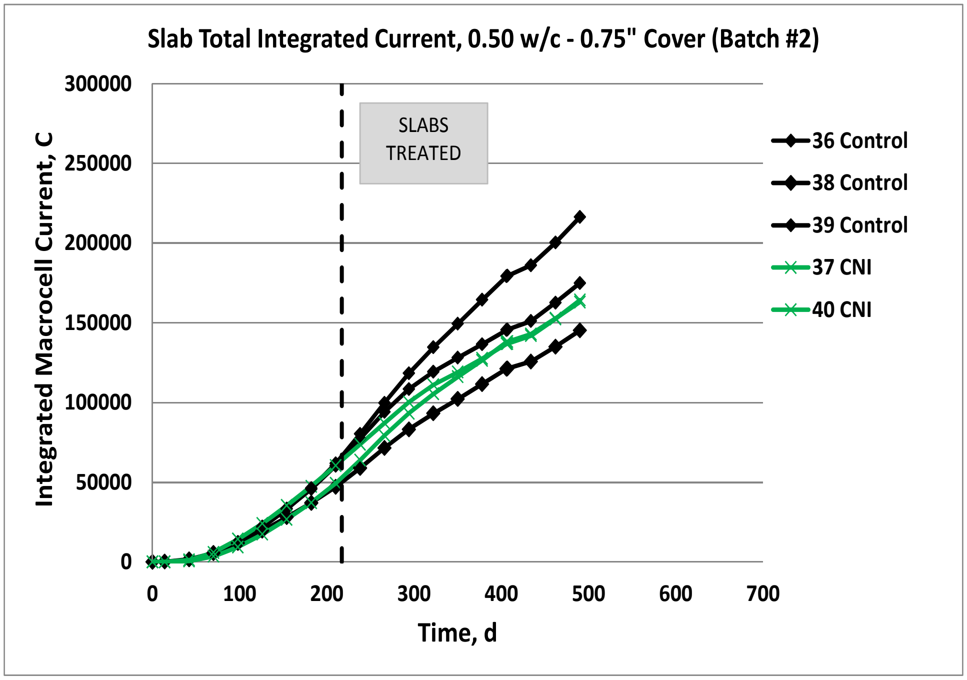


Figure 155 - Slab total integrated current as a function of time (Individual slabs, Batch #2, 0.60 w/c, 0.75" cover)

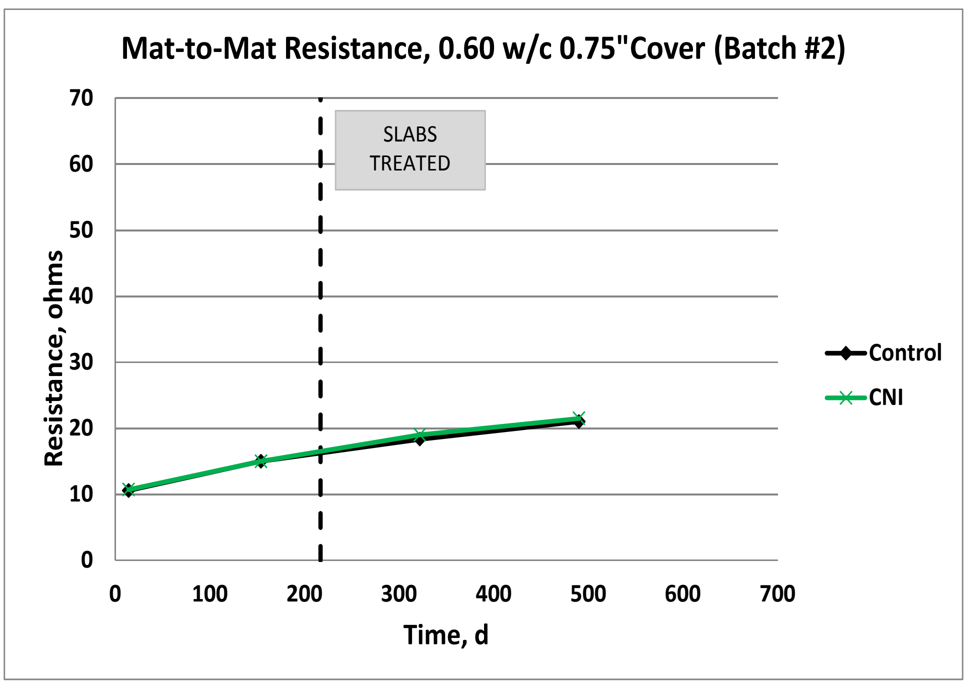


Figure 156 - Average mat-to-mat resistance as a function of time (Batch #2, 0.60 w/c, 0.75" cover)

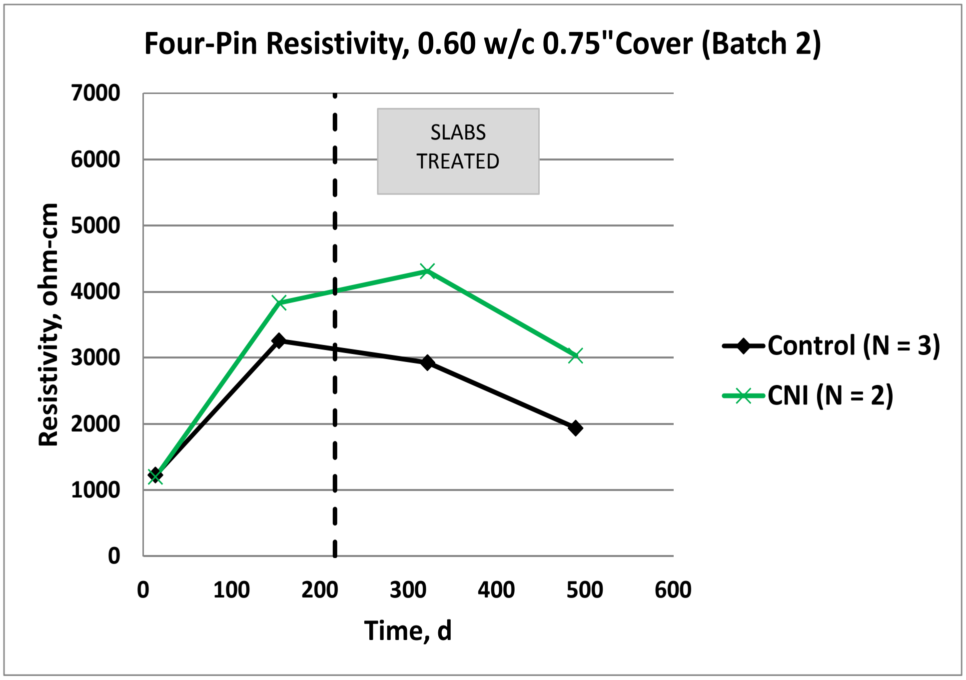


Figure 157 - Average 4-pin resistivity as a function of time (Batch #2, 0.60 w/c, 0.75” cover)

Batch #3

Table 40 - Batch #3, 0.50 w/c, 0.75" cover treatments

Slab No.	Treatment	Days (After Initial Ponding)	Completed Ponding Cycles Prior to Treatment	Number of Rebar Initiated Corrosion	Total Slab Integrated Current, Coulombs	Average Half-Cell Potential, mV CSE_{77}
51	CNI	189	7	4	55164	-566
52	Sealer	189	7	5	50282	-577
53	CNI	189	7	5	33607	-542
54	Control	(189)	(7)	6	22257	-508
55	Sealer	189	7	6	34327	-531
56	Control	(189)	(7)	5	22726	-455
57	Control	(189)	(7)	5	25556	-495
58	Epoxy	189	7	6	36950	-522
59	Control	(189)	(7)	5	23740	-509
60	Epoxy	189	7	6	29843	-531

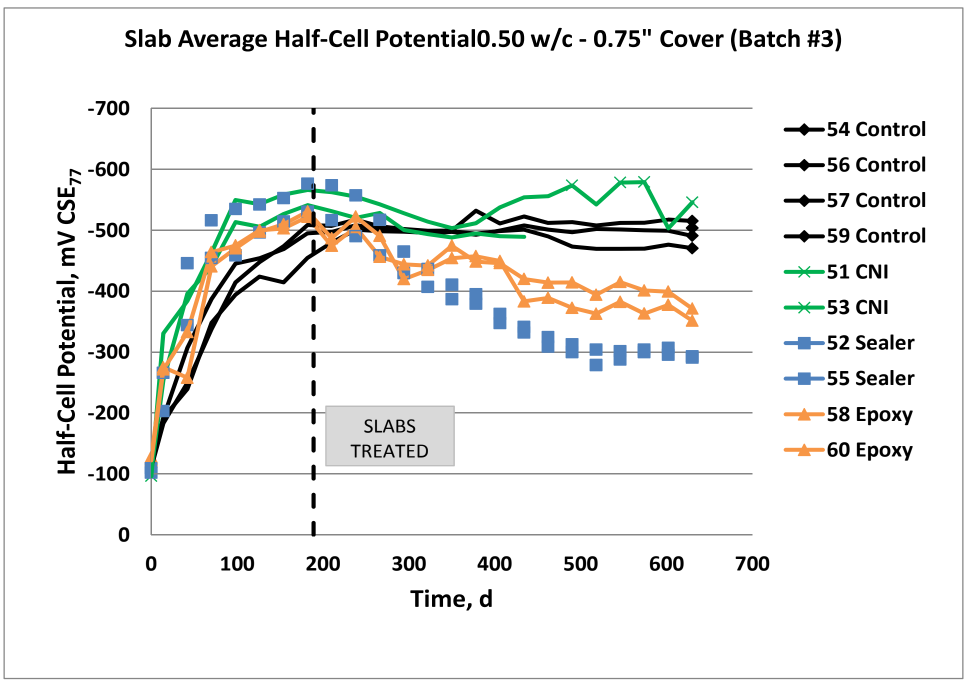


Figure 158 - Slab average half-cell potential as a function of time (Individual slabs, Batch #3, 0.50 w/c, 0.75" cover)

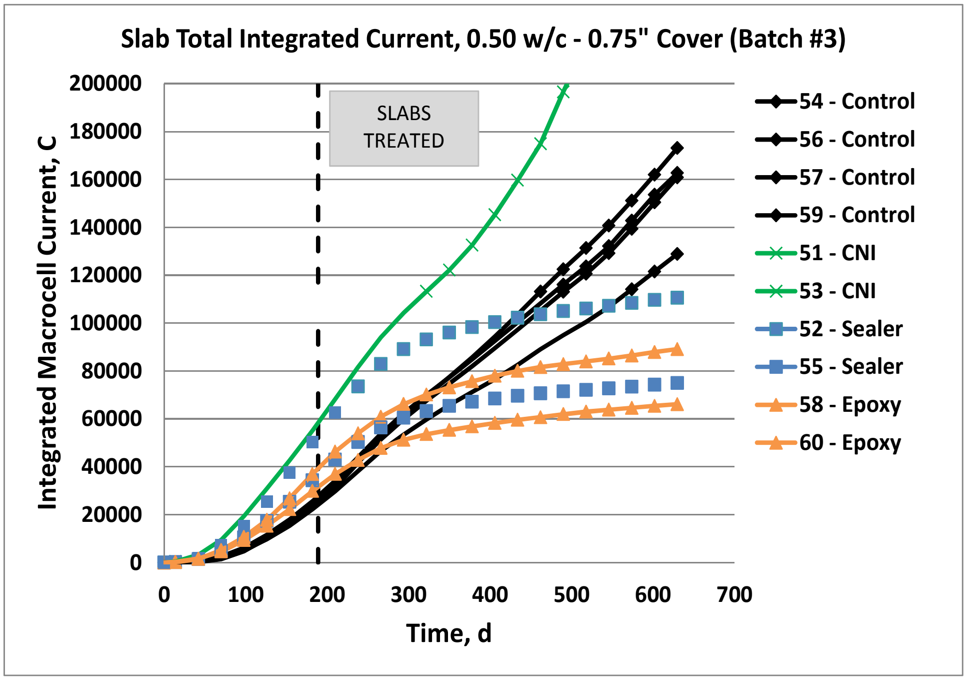


Figure 159 – Slab total integrated current as a function of time (Individual slabs, Batch #3, 0.50 w/c, 0.75" cover)

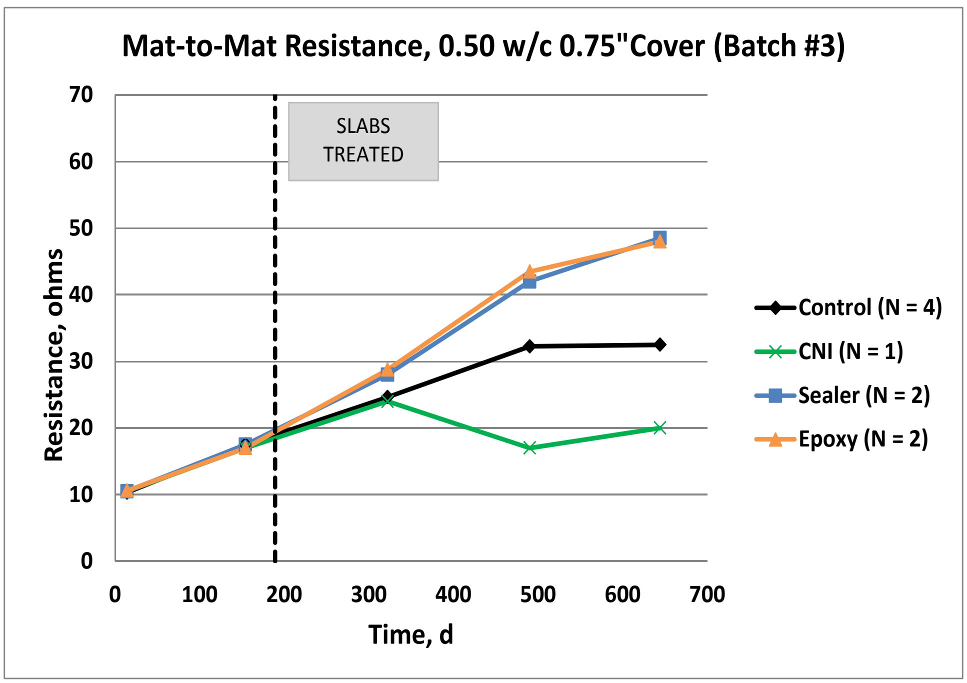


Figure 160 - Average mat-to-mat resistance as a function of time (Batch #3, 0.50 w/c, 0.75" cover)

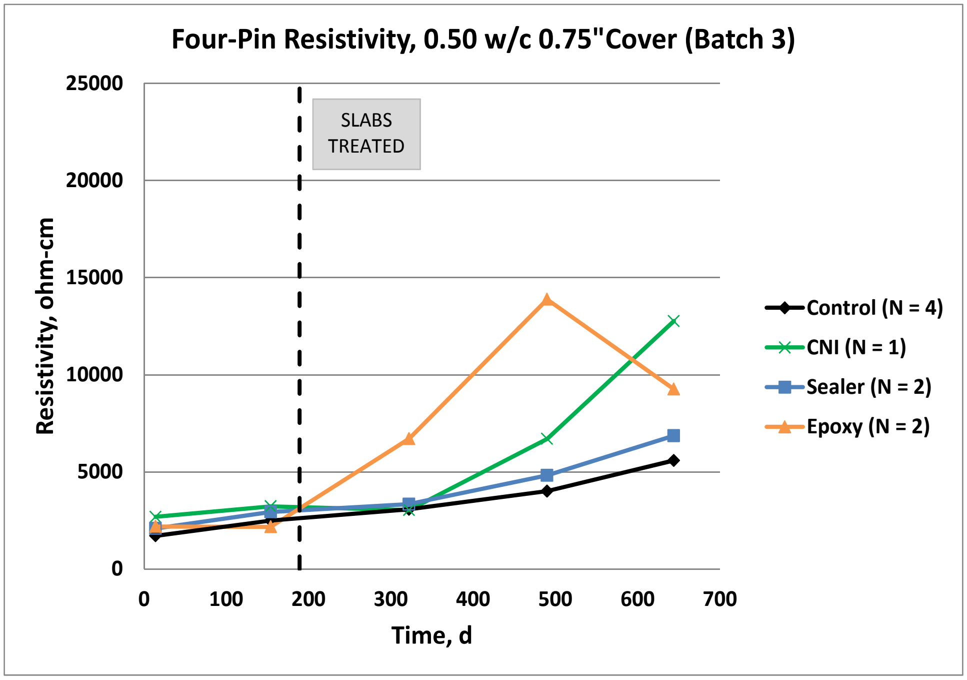


Figure 161 - Average 4-pin resistivity as a function of time (Batch #3, 0.50 w/c, 0.75" cover)

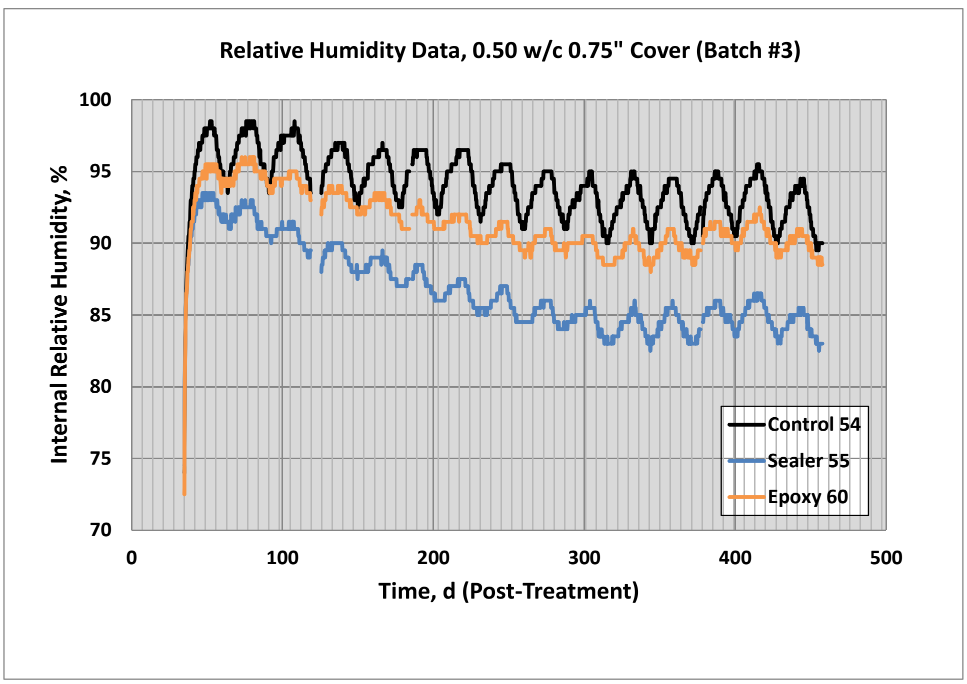


Figure 162 - Relative humidity as a function of time (Batch #3, 0.50 w/c, 0.75" cover)

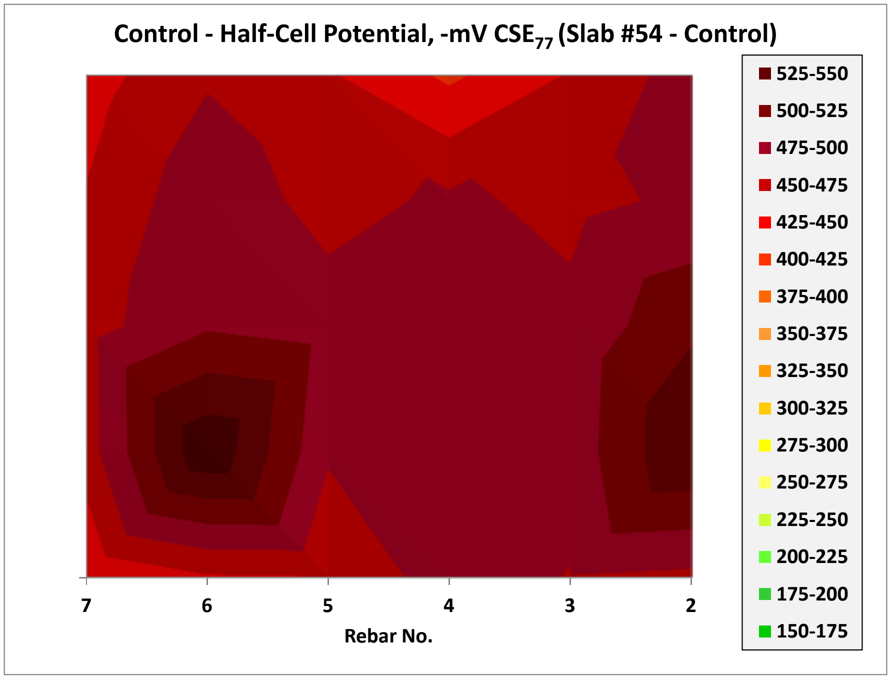


Figure 163 – Half-cell potential mapping prior to destructive analysis, slab #54 - Control

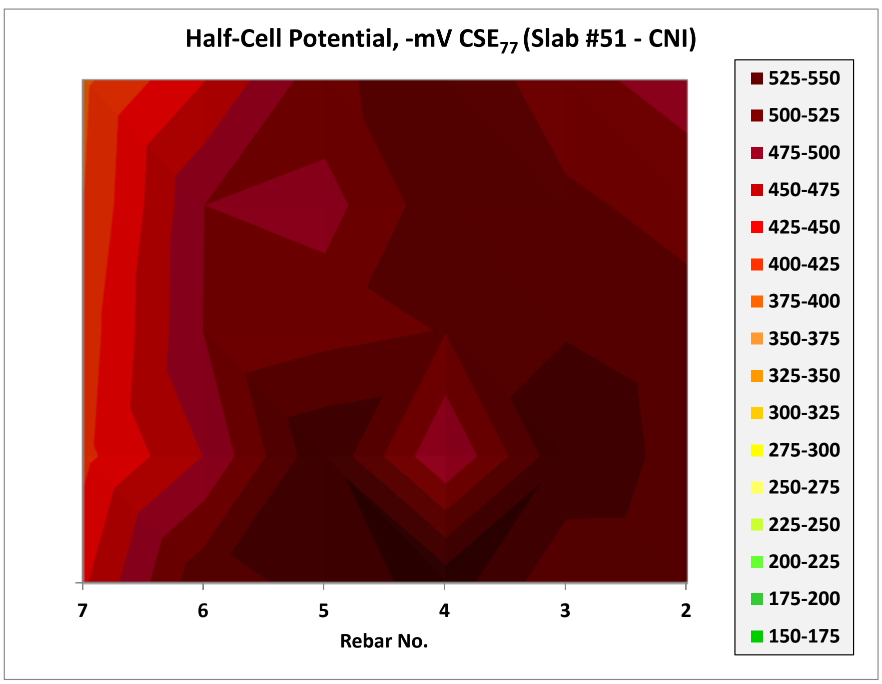


Figure 164 – Half-cell potential mapping prior to destructive analysis, slab #51 - CNI

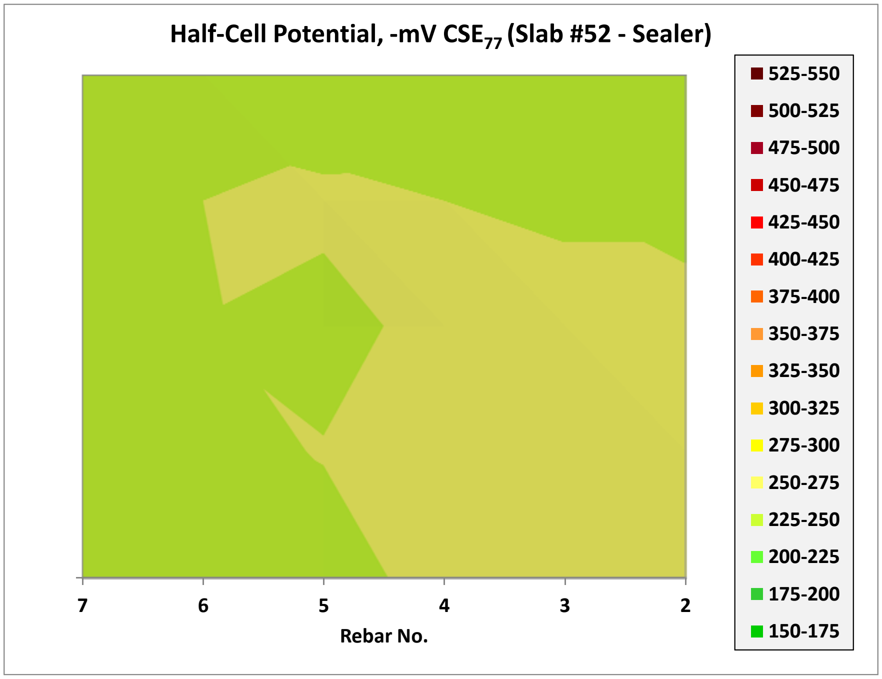


Figure 165 Half-cell potential mapping prior to destructive analysis, slab #52 - Sealer

Table 41 – Destructive Analysis Results and Treatment Evaluation for Slab #54 - Control

Slab #54 - Control										
	Pre-Treatment		Final Measurements		Difference		Visually Examined Corrosion			
Rebar #	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Light	Moderate	Heavy	Total
2	4026	-507	25554	-570	21528	-63	0.0%	7.1%	39.2%	46.4%
3	1332	-479	2879	-462	1547	17	0.0%	5.4%	19.7%	25.1%
4	651	-476	8907	-506	8256	-30	0.0%	1.0%	18.0%	19.0%
5	3058	-545	26002	-490	22944	55	0.0%	2.5%	30.9%	33.3%
6	6003	-531	45228	-527	39225	4	0.1%	5.0%	33.8%	38.9%
7	7187	-509	20312	-467	13125	42	0.1%	3.6%	26.8%	30.4%
Average	3709	-508	21480	-504	17771	4	0.0%	4.1%	28.1%	32.2%
Total	22257	-	128882	-	106625	-	-	-	-	-

Table 42 – Destructive Analysis Results and Treatment Evaluation for Slab #51 - CNI

Slab #51 - CNI										
	Pre-Treatment		Final Measurements		Difference		Visually Examined Corrosion			
Rebar #	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Light	Moderate	Heavy	Total
2	6425	-555	11863	-598	5438	-43	0.1%	0.4%	36.0%	36.6%
3	22611	-616	143803	-625	121192	-9	0.0%	0.0%	70.0%	70.0%
4	16360	-615	75712	-614	59352	1	0.0%	0.0%	67.1%	67.1%
5	9742	-618	57916	-587	48174	31	0.0%	0.0%	65.9%	65.9%
6	25	-529	3551	-503	3526	26	0.8%	5.9%	15.7%	22.4%
7	0	-465	704	-349	704	116	0.6%	4.1%	10.6%	15.2%
Average	9194	-566	48925	-546	39731	20	0.3%	1.7%	44.2%	46.2%
Total	55164	-	293549	-	238385	-	-	-	-	-

Table 43 – Destructive Analysis Results and Treatment Evaluation for Slab #52 - Sealer

Slab #52 - Sealer										
	Pre-Treatment		Final Measurements		Difference		Visually Examined Corrosion			
Rebar #	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Light	Moderate	Heavy	Total
2	12642	-605	25412	-294	12770	311	0.0%	5.1%	59.6%	64.7%
3	60	-516	1597	-290	1537	226	0.1%	5.3%	16.6%	22.3%
4	15454	-617	29628	-299	14174	318	0.1%	6.2%	49.0%	55.2%
5	5652	-581	18458	-294	12806	287	0.0%	3.8%	36.2%	40.0%
6	10885	-601	26049	-281	15164	320	0.0%	4.3%	47.9%	52.2%
7	5590	-539	9478	-287	3888	252	0.0%	0.2%	33.2%	33.4%
Average	8380	-577	18437	-291	10057	286	0.0%	4.2%	40.4%	44.6%
Total	50282	-	110622	-	60340	-	-	-	-	-

Table 44 – Destructive Analysis Results and Treatment Evaluation for Slab #58 - Epoxy

Slab #58 - Epoxy										
	Pre-Treatment		Final Measurements		Difference		Visually Examined Corrosion			
Rebar #	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Light	Moderate	Heavy	Total
2	5894	-529	14075	-391	8181	138	0.0%	8.8%	29.7%	38.5%
3	11968	-542	20770	-399	8802	143	0.3%	6.7%	29.9%	36.8%
4	5460	-511	16430	-387	10970	124	0.0%	11.0%	34.4%	46.4%
5	9175	-536	17992	-391	8817	145	0.4%	4.2%	25.0%	29.7%
6	3554	-528	14128	-334	10574	194	0.0%	9.3%	34.8%	44.2%
7	899	-487	5726	-326	4827	161	0.1%	6.3%	40.4%	46.8%
Average	6158	-522	14854	-371	8695	151	0.1%	7.7%	32.4%	40.4%
Total	36950	-	89121	-	52171	-	-	-	-	-

Batch #4

Table 45 - Batch #4, 0.50 w/c, 0.75" cover treatments

Slab No.	Treatment	Days (After Initial Ponding)	Completed Ponding Cycles Prior to Treatment	Number of Rebar Initiated Corrosion	Total Slab Integrated Current, Coulombs	Average Half-Cell Potential, mV CSE_{77}
71	Control	(189)	(7)	4	28967	-467
72	Control	(189)	(7)	6	55457	-536
73	CNI	189	7	6	41313	-525
74	Control	(189)	(7)	3	29428	-462
75	Sealer	189	7	6	40461	-517
76	Sealer	189	7	6	38492	-497
77	Control	(189)	(7)	6	30027	-500
78	Epoxy	189	7	6	33121	-490
79	CNI	189	7	6	31025	-490
80	Epoxy	189	7	6	42894	-515

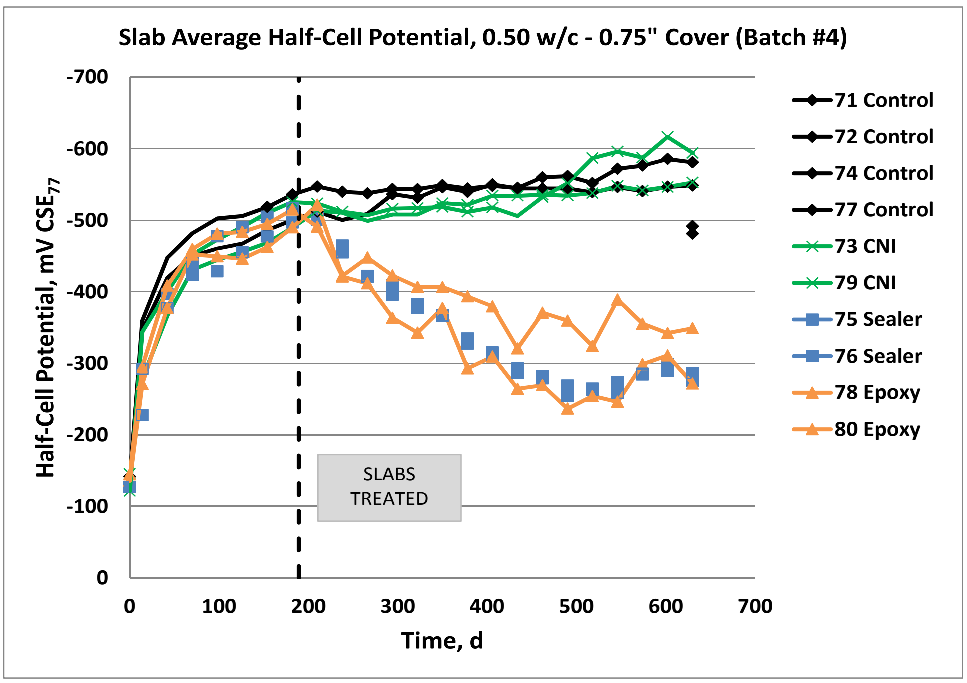


Figure 166 - Slab average half-cell potential as a function of time (Individual slabs, Batch #4, 0.50 w/c, 0.75" cover)

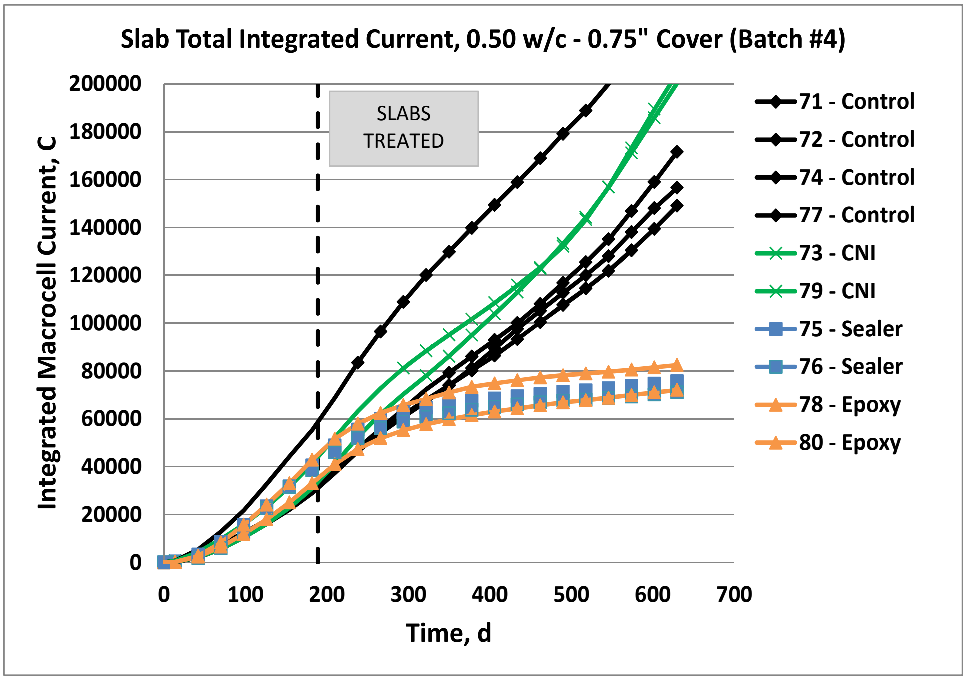


Figure 167 - Slab total integrated current as a function of time (Individual slabs, Batch #4, 0.50 w/c, 0.75" cover)

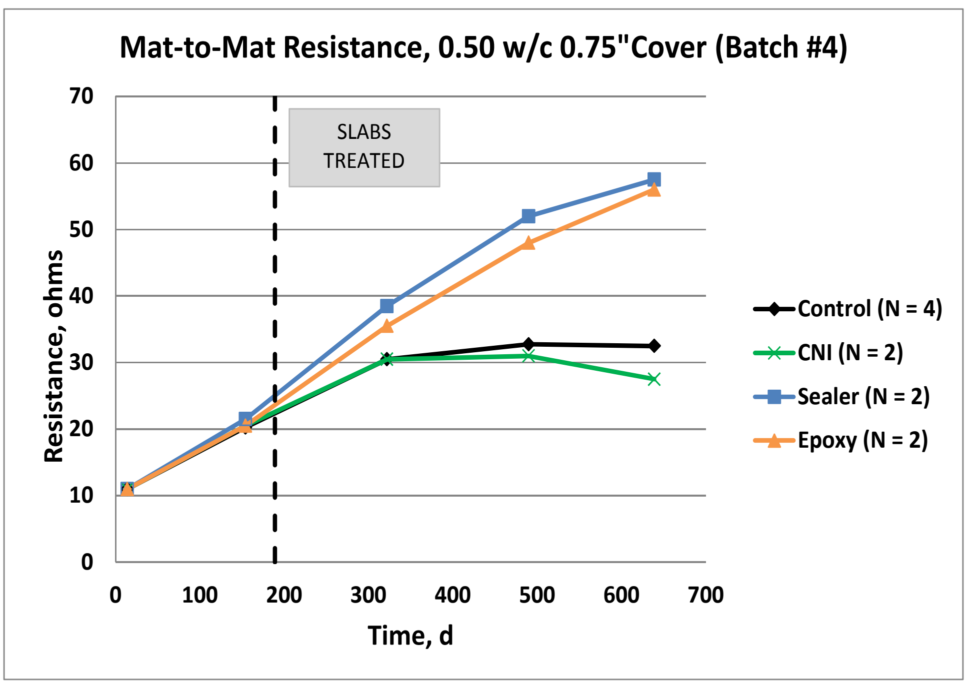


Figure 168 - Average mat-to-mat resistance as a function of time (Batch #4, 0.50 w/c, 0.75" cover)

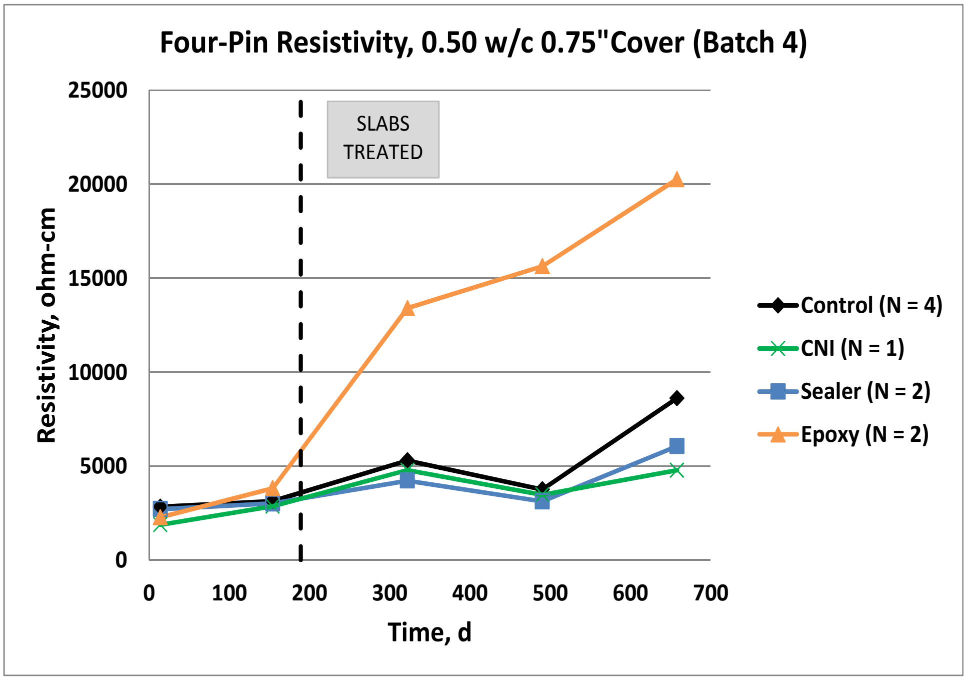


Figure 169 - Average 4-pin resistivity as a function of time (Batch #4, 0.50 w/c, 0.75" cover)

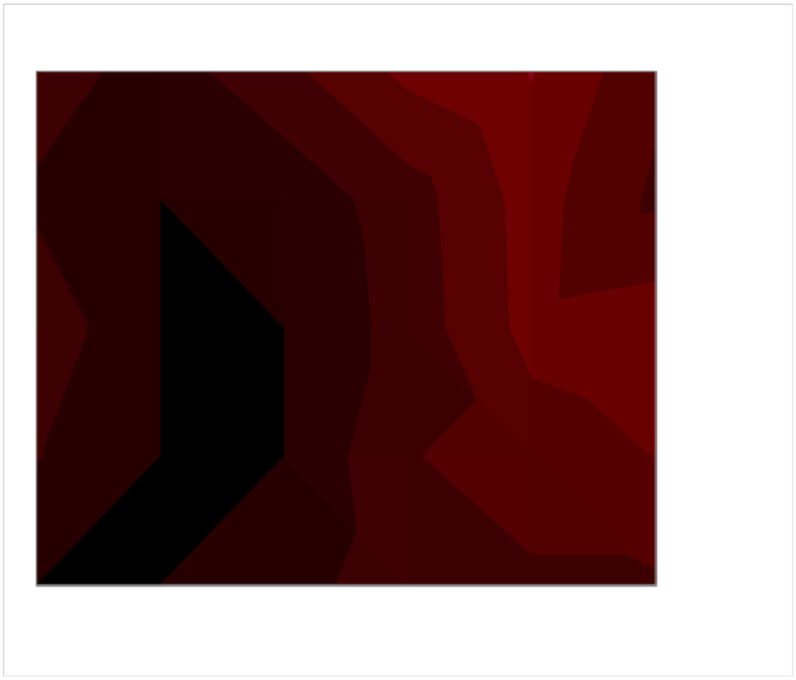


Figure 170 - Half-cell potential mapping prior to destructive analysis, slab #72 - Control

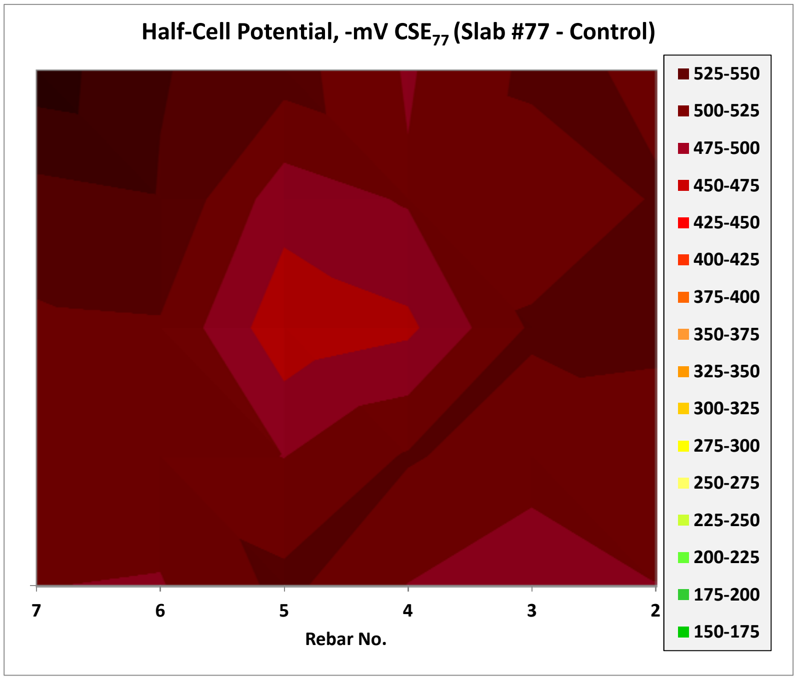


Figure 171 - Half-cell potential mapping prior to destructive analysis, slab #77 - Control

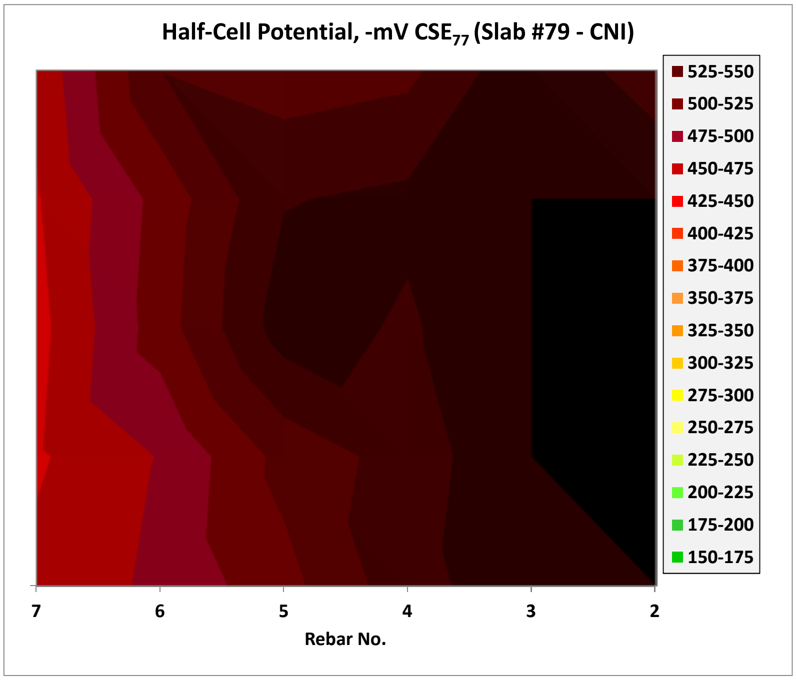


Figure 172 - Half-cell potential mapping prior to destructive analysis, slab #79 - CNI

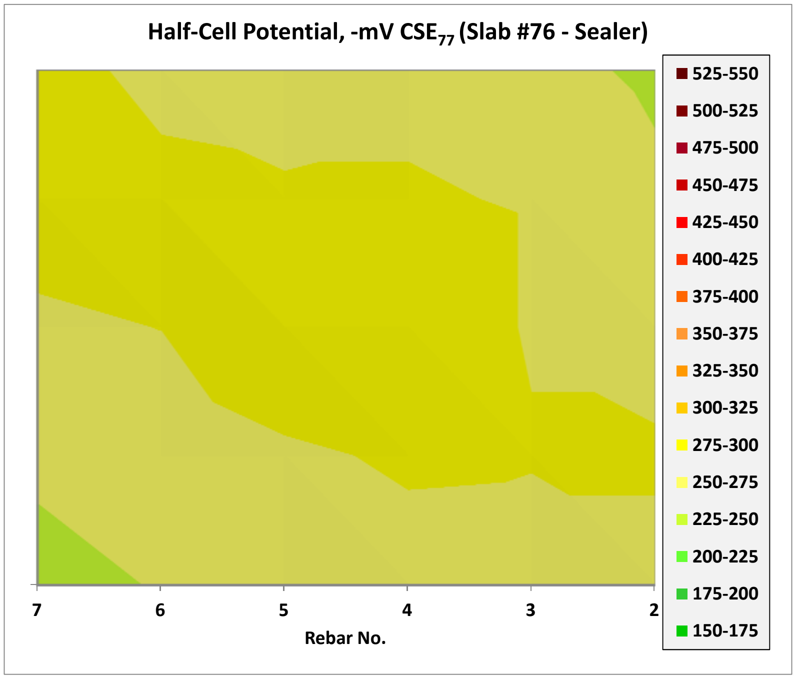


Figure 173 - Half-cell potential mapping prior to destructive analysis, slab #76 - Sealer

Table 46 – Destructive Analysis Results and Treatment Evaluation for Slab #72 - Control

Slab #72 - Control										
	Pre-Treatment		Final Measurements		Difference		Visually Examined Corrosion			
Rebar #	Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Light	Moderate	Heavy	Total
2	11543	-592	61294	-560	49751	32	0.0%	5.3%	46.9%	52.3%
3	5175	-492	9325	-528	4150	-37	1.1%	5.9%	13.3%	20.3%
4	3374	-509	22151	-580	18777	-72	0.2%	7.6%	21.3%	29.1%
5	8104	-534	40935	-621	32831	-88	0.5%	2.3%	34.2%	37.0%
6	22493	-589	93959	-634	71466	-46	0.0%	1.3%	65.2%	66.5%
7	4768	-502	17900	-560	13132	-59	0.2%	9.1%	22.8%	32.1%
Average	9243	-536	40927	-581	31685	-45	0.3%	5.3%	34.0%	39.6%
Total	55457	-	245564	-	190107	-	-	-	-	-

Table 47 – Destructive Analysis Results and Treatment Evaluation for Slab #77 - Control

Slab #77 - Control										
	Pre-Treatment		Final Measurements		Difference		Visually Examined Corrosion			
Rebar #	Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Light	Moderate	Heavy	Total
2	11027	-529	35001	-561	23974	-33	0.6%	5.1%	33.6%	39.3%
3	4388	-496	22933	-559	18545	-64	3.6%	5.9%	28.0%	37.5%
4	2679	-479	7729	-537	5050	-59	0.8%	5.1%	25.1%	31.0%
5	1958	-478	26372	-536	24414	-59	0.0%	6.8%	27.1%	33.9%
6	7252	-514	35003	-548	27751	-35	0.4%	5.5%	28.8%	34.7%
7	2723	-509	22024	-548	19301	-40	0.2%	14.2%	24.2%	38.8%
Average	5004	-500	24844	-548	19839	-48	0.9%	7.1%	27.8%	35.9%
Total	30027	-	149062	-	119035	-	-	-	-	-

Table 48 – Destructive Analysis Results and Treatment Evaluation for Slab #79 - CNI

Slab #79 - CNI										
	Pre-Treatment		Final Measurements		Difference		Visually Examined Corrosion			
Rebar #	Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Light	Moderate	Heavy	Total
2	7483	-556	57224	-626	49741	-71	0.2%	7.8%	36.5%	44.5%
3	11421	-543	88182	-627	76761	-85	0.0%	6.3%	53.0%	59.3%
4	2455	-463	8162	-563	5707	-101	0.0%	5.6%	21.6%	27.2%
5	8435	-534	37339	-589	28904	-56	3.8%	2.3%	34.8%	40.9%
6	324	-369	324	-378	0	-10	1.9%	20.1%	22.9%	44.9%
7	908	-476	9200	-531	8292	-56	0.1%	5.0%	2.8%	8.0%
Average	5171	-490	33405	-552	28234	-63	1.0%	7.9%	28.6%	37.5%
Total	31025	-	200431	-	169406	-	-	-	-	-

Table 49 – Destructive Analysis Results and Treatment Evaluation for Slab #76 - Sealer

Slab #76 - Sealer										
	Pre-Treatment		Final Measurements		Difference		Visually Examined Corrosion			
Rebar #	Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Light	Moderate	Heavy	Total
2	5174	-525	11073	-290	5899	235	5.6%	13.6%	9.0%	28.3%
3	3285	-503	7443	-296	4158	207	0.6%	19.0%	4.0%	23.6%
4	238	-460	4056	-293	3818	167	7.7%	8.2%	3.9%	19.7%
5	23305	-552	35723	-304	12418	248	4.4%	11.5%	18.9%	34.9%
6	5051	-516	10700	-257	5649	259	1.5%	17.8%	16.9%	36.2%
7	1438	-427	2070	-274	632	153	0.4%	7.7%	2.9%	11.1%
Average	6415	-497	11844	-286	5429	211	3.4%	13.0%	9.3%	25.6%
Total	38492	-	71065	-	32573	-	-	-	-	-

Table 50 – Destructive Analysis Results and Treatment Evaluation for Slab #78 - Epoxy

Slab #78 - Epoxy										
	Pre-Treatment		Final Measurements		Difference		Visually Examined Corrosion			
Rebar #	Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Light	Moderate	Heavy	Total
2	16441	-529	27116	-365	10675	164	4.0%	24.0%	20.3%	48.5%
3	2432	-465	6962	-380	4530	85	11.9%	11.3%	7.3%	30.5%
4	7269	-522	13744	-365	6475	157	2.5%	1.7%	1.1%	5.4%
5	4012	-495	12733	-371	8721	124	2.5%	17.0%	12.1%	31.6%
6	1946	-468	9064	-327	7118	141	0.2%	6.4%	19.8%	26.4%
7	1021	-463	2431	-283	1410	180	1.7%	13.3%	18.7%	33.8%
Average	5520	-490	12008	-349	6488	141	3.8%	12.3%	13.2%	29.4%
Total	33121	-	72050	-	38929	-	-	-	-	-

Batch #5

Table 51 - Batch #5, 0.50 w/c, 0.75" cover treatments

Slab No.	Treatment	Days (After Initial Ponding)	Completed Ponding Cycles Prior to Treatment	Number of Rebar Initiated Corrosion	Total Slab Integrated Current, Coulombs	Average Half-Cell Potential, mV CSE_{77}
91	Control	(161)	(6)	6	14744	-477
92	CNI	161	6	6	25400	-513
93	Control	(161)	(6)	4	7455	-393
94	Epoxy	161	6	6	20193	-506
95	Control	(161)	(6)	4	8773	-413
96	CNI	161	6	6	17950	-508
97	Epoxy	161	6	6	10227	-503
98	Sealer	161	6	6	24344	-553
99	Sealer	161	6	5	16914	-478
100	Control	(161)	(6)	6	14105	-526

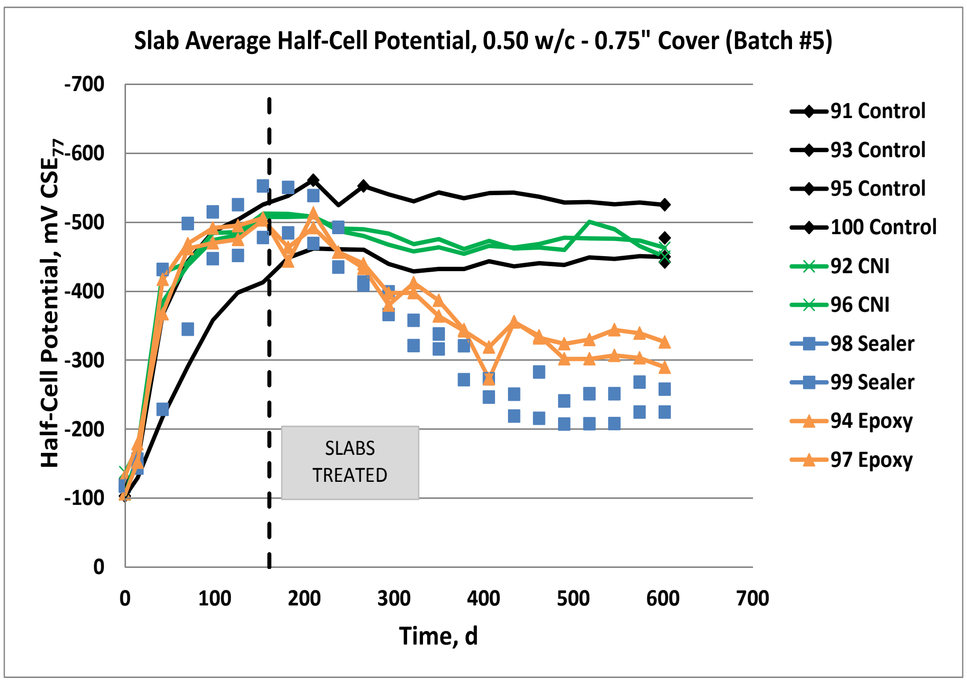


Figure 174 - Slab average half-cell potential as a function of time (Individual slabs, Batch #5, 0.50 w/c, 0.75" cover)

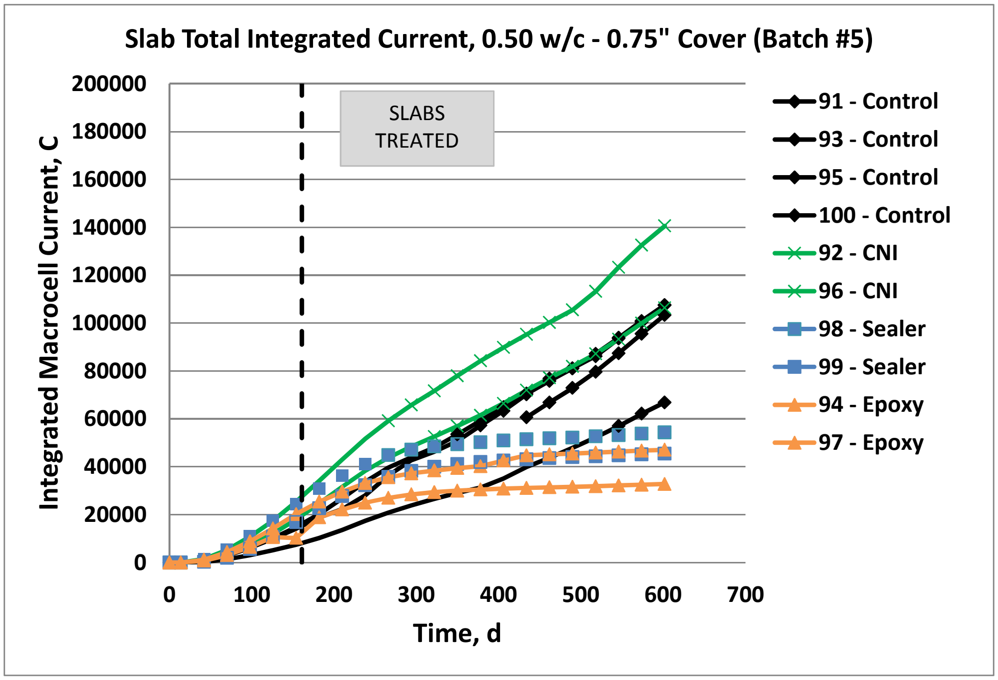


Figure 175 - Slab total integrated current as a function of time (Individual slabs, Batch #5, 0.50 w/c, 0.75" cover)

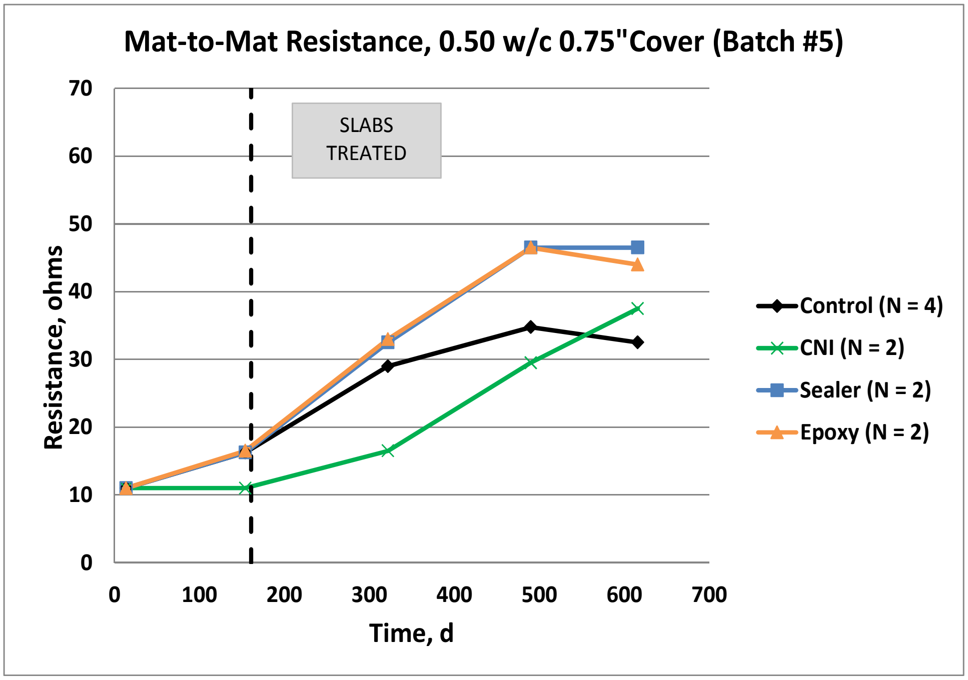


Figure 176 - Average mat-to-mat resistance as a function of time (Batch #5, 0.50 w/c, 0.75" cover)

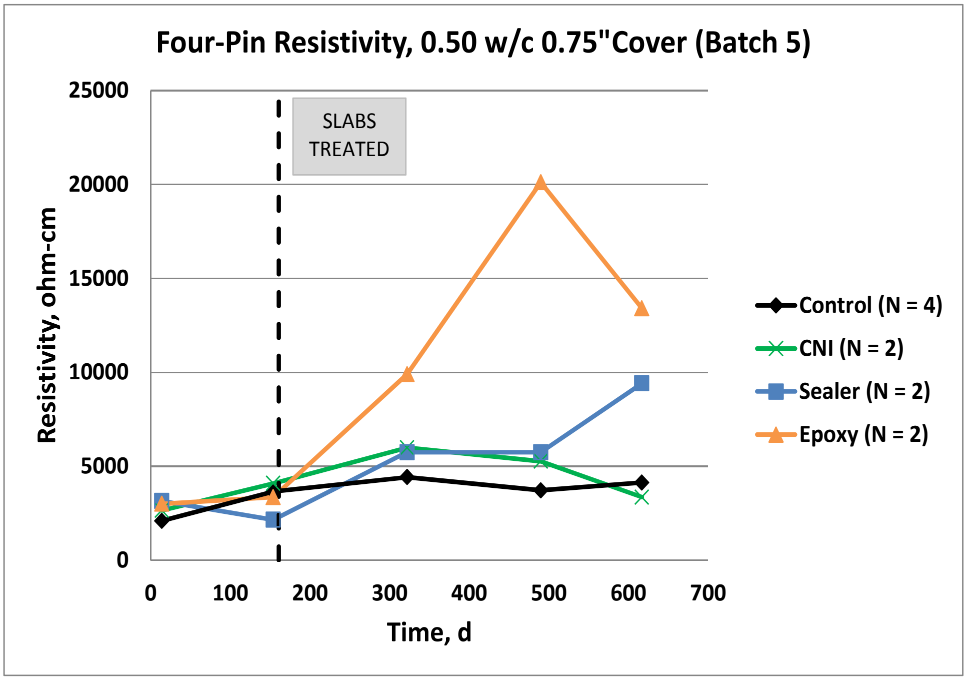


Figure 177 - Average 4-pin resistivity as a function of time (Batch #5, 0.50 w/c, 0.75" cover)

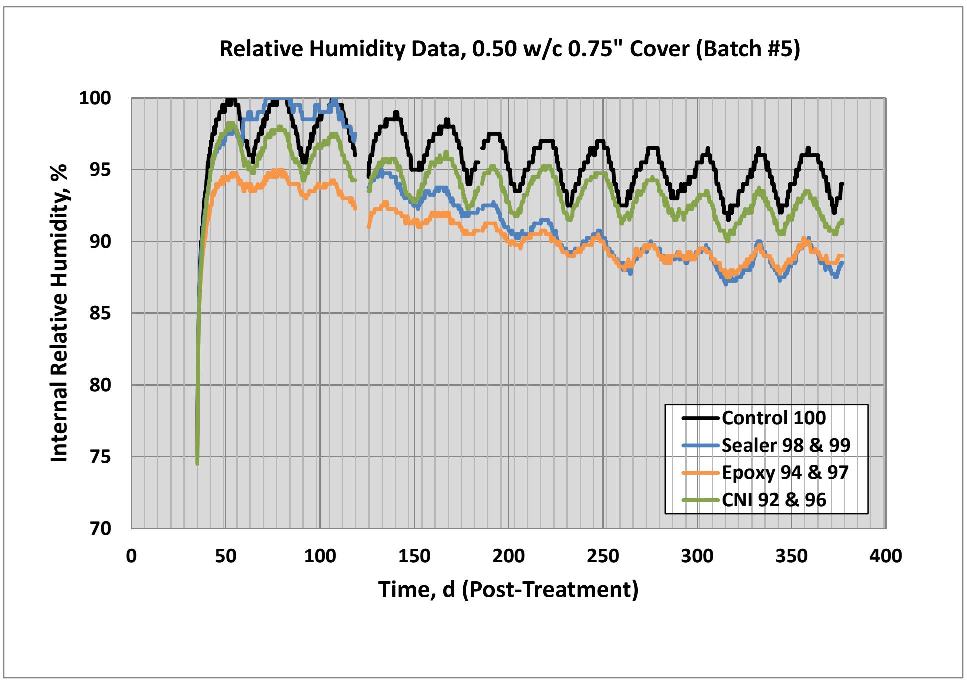


Figure 178 - Relative humidity as a function of time (Batch #5, 0.50 w/c, 0.75" cover)

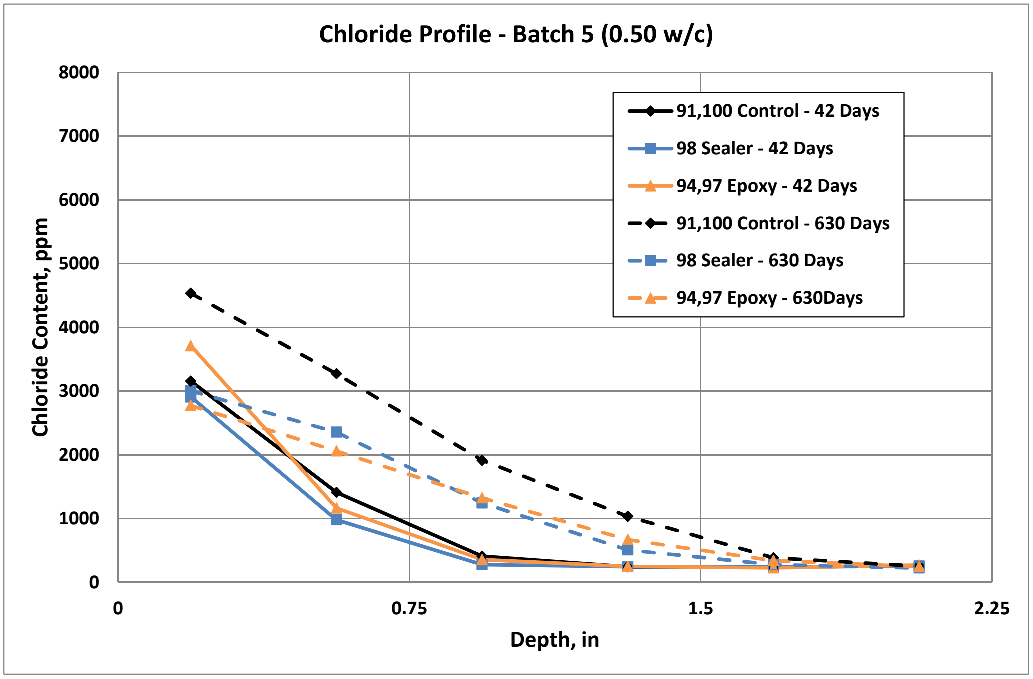


Figure 179 – Average chloride content as a function of depth at prior to treatment (42 days) and post-treatment (630 days) for control, sealer, and epoxy treated slabs – Batch #5

Figure 180 - Half-cell potential mapping prior to destructive analysis, slab #91 - Control

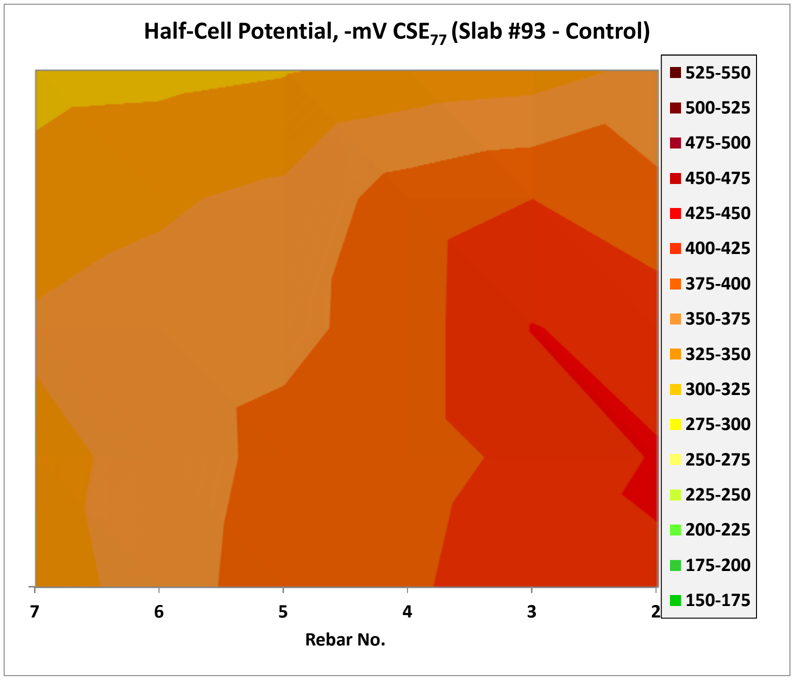


Figure 181 - Half-cell potential mapping prior to destructive analysis, slab #93 - Control

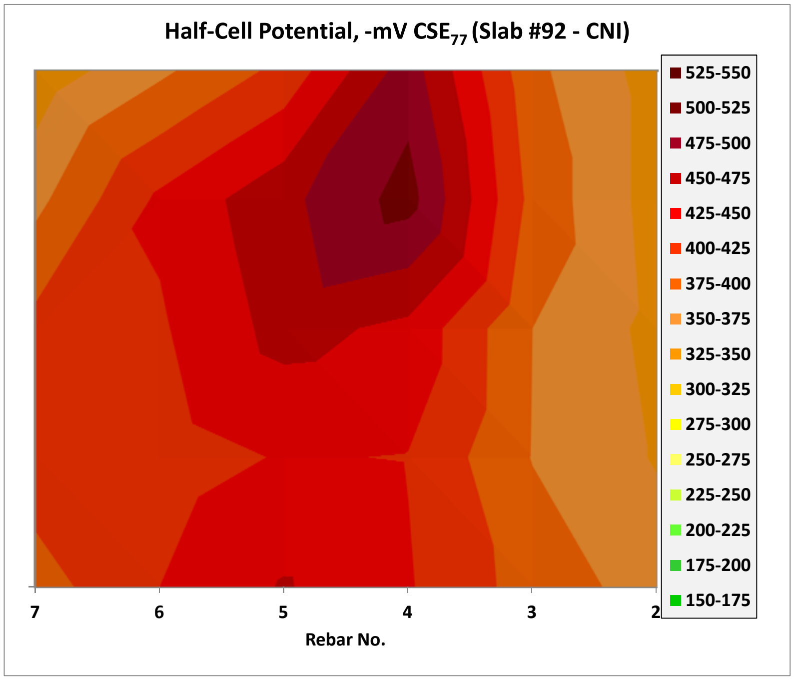


Figure 182 - Half-cell potential mapping prior to destructive analysis, slab #92 - CNI

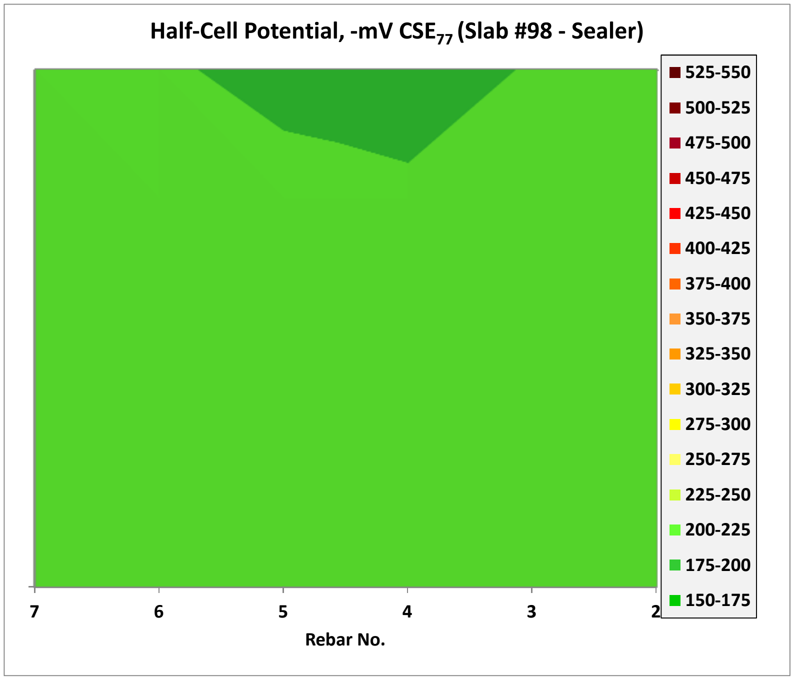


Figure 183 - Half-cell potential mapping prior to destructive analysis, slab #98 - Sealer

Table 52 – Destructive Analysis Results and Treatment Evaluation for Slab #91 - Control

Slab #91 - Control										
	Pre-Treatment		Final Measurements		Difference		Visually Examined Corrosion			
Rebar #	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Light	Moderate	Heavy	Total
2	7749	-556	49764	-523	42015	33	0.2%	4.5%	27.1%	31.8%
3	423	-478	2407	-386	1984	92	0.0%	1.4%	5.5%	6.9%
4	1037	-480	25519	-548	24482	-68	1.3%	2.1%	17.8%	21.2%
5	1175	-467	2395	-454	1220	13	0.6%	1.6%	8.1%	10.3%
6	3729	-496	26791	-537	23062	-41	0.0%	1.5%	27.6%	29.1%
7	632	-387	632	-415	0	-28	2.0%	0.1%	0.9%	3.0%
Average	2457	-477	17918	-477	15461	0	0.7%	1.9%	14.5%	17.1%
Total	14744	-	107508	-	92764	-	-	-	-	-

Table 53 - Destructive Analysis Results and Treatment Evaluation for Slab #98 – Control

Slab #93 - Control										
	Pre-Treatment		Final Measurements		Difference		Visually Examined Corrosion			
Rebar #	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Light	Moderate	Heavy	Total
2	0	-354	7924	-506	7924	-152	1.5%	7.8%	3.6%	12.9%
3	1246	-442	13526	-504	12280	-62	0.0%	2.4%	16.1%	18.5%
4	530	-387	5922	-425	5392	-38	0.4%	2.8%	4.2%	7.4%
5	2725	-367	28729	-446	26004	-79	1.6%	3.5%	15.5%	20.6%
6	2947	-466	10123	-394	7176	72	0.0%	2.3%	8.1%	10.4%
7	7	-340	644	-378	637	-38	0.1%	0.3%	3.3%	3.6%
Average	1242	-393	11145	-442	9902	-50	0.6%	3.2%	8.5%	12.2%
Total	7455	-	66868	-	59413	-	-	-	-	-

Table 54 – Destructive Analysis Results and Treatment Evaluation for Slab #92 - CNI

Slab #92 - CNI										
	Pre-Treatment		Final Measurements		Difference		Visually Examined Corrosion			
Rebar #	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Light	Moderate	Heavy	Total
2	3752	-494	11612	-373	7860	121	0.1%	8.8%	7.3%	16.2%
3	1328	-477	6904	-395	5576	82	0.5%	4.1%	2.9%	7.5%
4	14340	-606	69611	-547	55271	59	0.0%	4.9%	41.3%	46.2%
5	2463	-518	20185	-482	17722	36	0.4%	2.6%	14.4%	17.4%
6	1807	-493	23620	-475	21813	18	0.4%	1.1%	19.9%	21.4%
7	1710	-487	8644	-428	6934	59	3.7%	5.3%	6.6%	15.6%
Average	4233	-513	23429	-450	19196	63	0.9%	4.5%	15.4%	20.7%
Total	25400	-	140576	-	115176	-	-	-	-	-

Table 55 – Destructive Analysis Results and Treatment Evaluation for Slab #98 - Sealer

Slab #98 - Sealer										
	Pre-Treatment		Final Measurements		Difference		Visually Examined Corrosion			
Rebar #	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Light	Moderate	Heavy	Total
2	2175	-565	10313	-480	8138	85	0.0%	7.1%	15.3%	22.4%
3	404	-498	1475	-287	1071	211	0.1%	1.4%	2.2%	3.6%
4	6183	-596	12785	-245	6602	351	0.0%	4.2%	27.3%	31.5%
5	10568	-591	18149	-259	7581	332	0.7%	3.7%	16.1%	20.5%
6	4805	-584	10759	-249	5954	335	0.0%	8.0%	13.8%	21.8%
7	209	-481	830	-229	621	252	0.2%	1.3%	0.0%	1.4%
Average	4057	-553	9052	-292	4995	261	0.2%	4.3%	12.5%	16.9%
Total	24344	-	54311	-	29967	-	-	-	-	-

Table 56 – Destructive Analysis Results and Treatment Evaluation for Slab #94 - Epoxy

Slab #94 - Epoxy										
	Pre-Treatment		Final Measurements		Difference		Visually Examined Corrosion			
Rebar #	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Total Integrated Current (Coulombs)	Half-Cell Potential (mV CSE_{77})	Light	Moderate	Heavy	Total
2	4898	-547	14078	-339	9180	208	0.6%	1.2%	17.5%	19.3%
3	2705	-513	6164	-377	3459	136	0.0%	0.2%	7.2%	7.4%
4	3040	-521	6447	-295	3407	226	0.3%	1.3%	12.8%	14.3%
5	3998	-505	10459	-337	6461	168	0.1%	4.5%	9.6%	14.1%
6	5323	-514	9569	-321	4246	193	0.5%	2.1%	9.4%	12.0%
7	229	-437	392	-290	163	147	2.0%	1.9%	0.0%	3.9%
Average	3366	-506	7852	-327	4486	180	0.6%	1.9%	9.4%	11.8%
Total	20193	-	47109	-	26916	-	-	-	-	-

Topical Treatments – 1.5-inch Cover

Batch #3

Table 57 - Batch #3, 0.50 w/c, 1.5" cover treatments

Slab No.	Treatment	Days (After Initial Ponding)	Completed Ponding Cycles Prior to Treatment	Number of Rebar Initiated Corrosion	Total Slab Integrated Current, Coulombs	Average Half-Cell Potential, mV CSE_{77}
41	Sealer	602	22	4	11852	-341
42	Epoxy	574	22	2	5155	-261
43	Epoxy	742	27	2	5411	-281
44	Sealer	658	24	1	5499	-270
45	Epoxy	658	24	3	10778	-300
46	Destructive Analysis	-	-	-	-	-
47	Control	518	19	4	5152	-348
48	Sealer	518	19	3	3099	-281
49	Control	575	21	3	5427	-274
50	Control	658	24	1	5568	-286

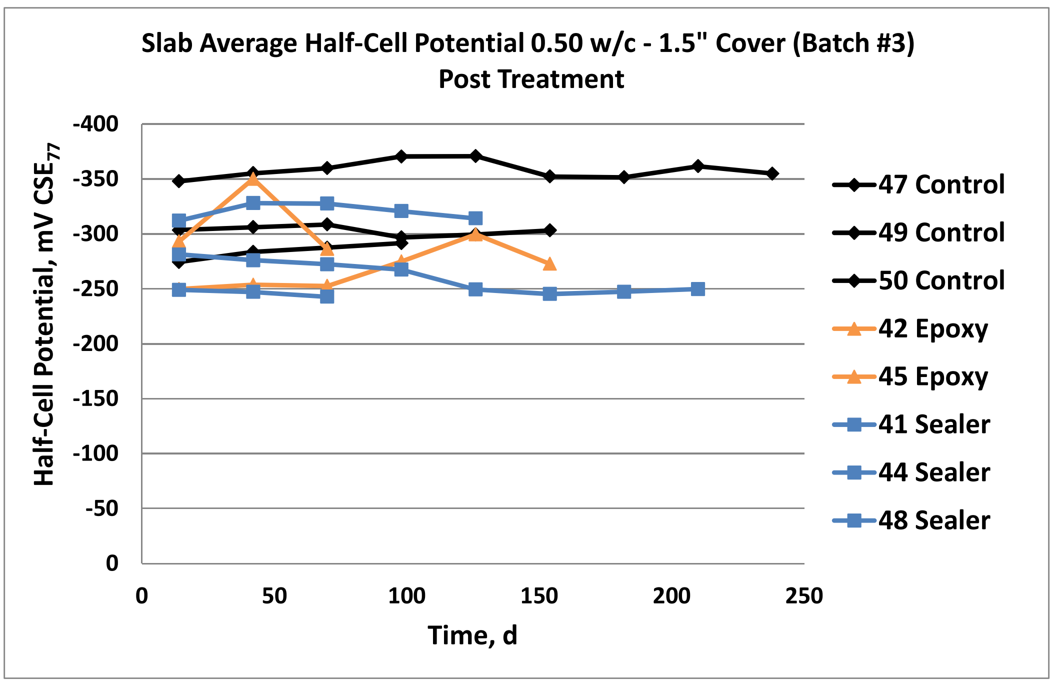


Figure 184 - Slab average half-cell potential as a function of time (Individual slabs, Batch #3, 0.50 w/c, 1.5" cover)

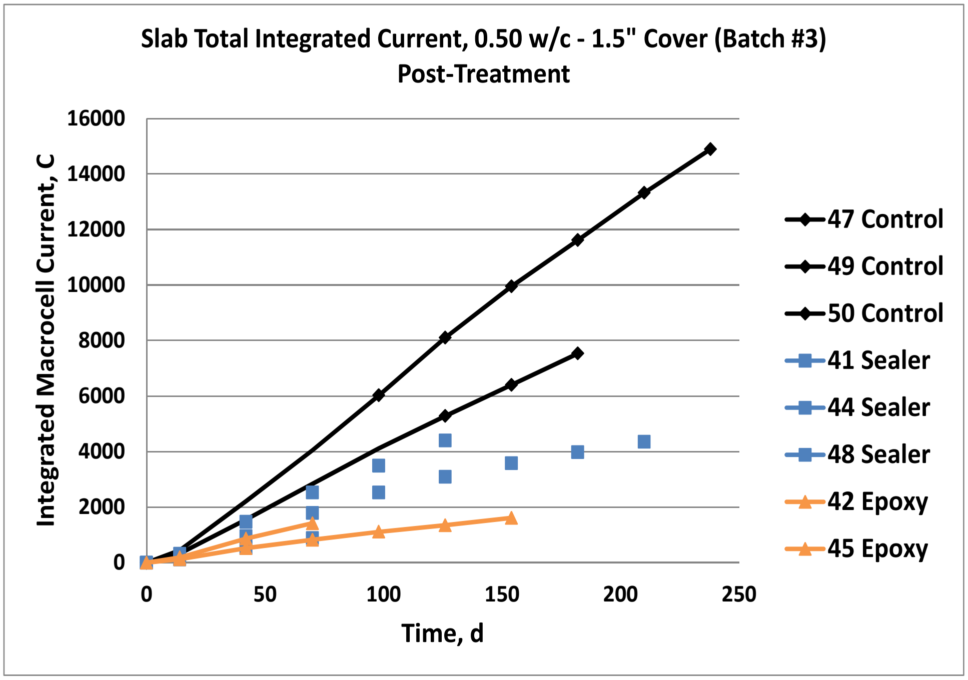


Figure 185 - Slab total integrated current as a function of time (Individual slabs, Batch #3, 0.50 w/c, 1.5" cover)

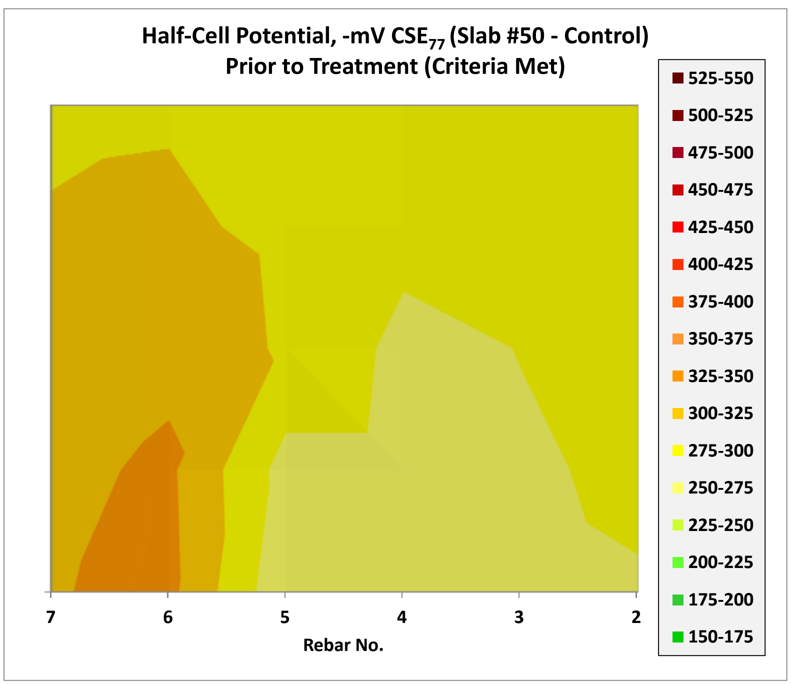


Figure 186 - Half-cell potential mapping prior to treatment, slab #77 - Control

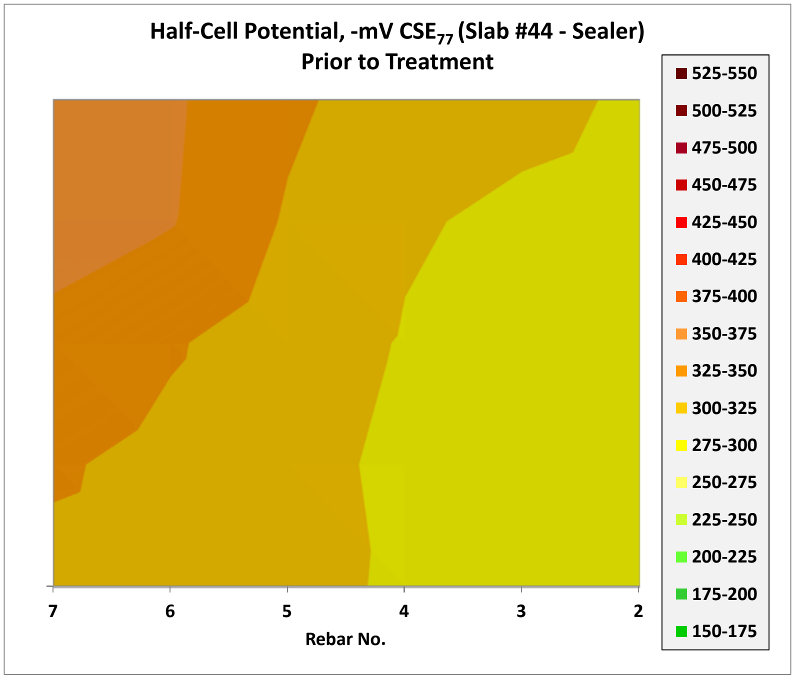


Figure 187 - Half-cell potential mapping prior to treatment, slab #44 - Sealer

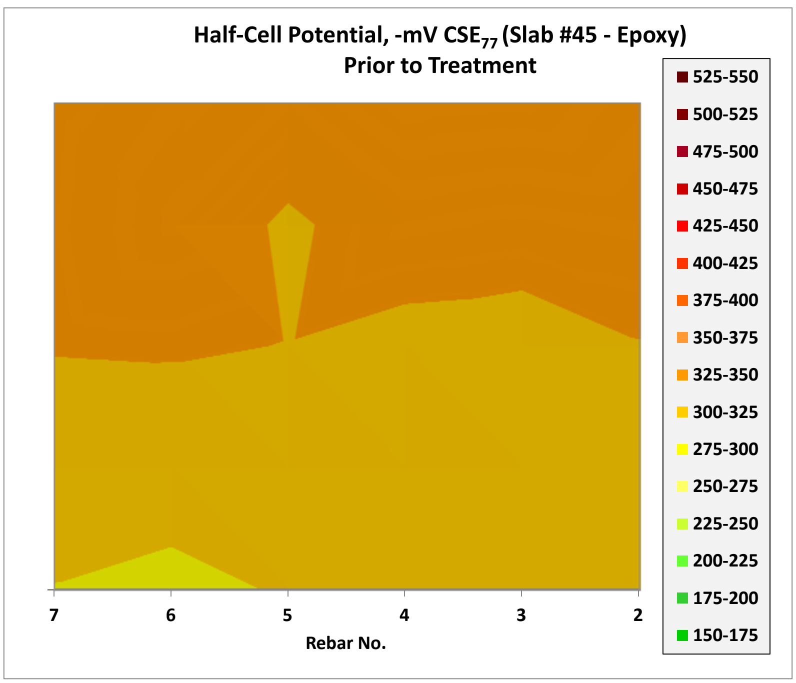


Figure 188 - Half-cell potential mapping prior to treatment, slab #45 - Epoxy

Batch #5

Table 58 - Batch #5, 0.50 w/c, 1.5" cover treatments

Slab No.	Treatment	Days (After Initial Ponding)	Completed Ponding Cycles Prior to Treatment	Number of Rebar Initiated Corrosion	Total Slab Integrated Current, Coulombs	Average Half-Cell Potential, mV CSE_{77}
81	-	-	-	-	-	-
82	-	-	-	-	-	-
83	-	-	-	-	-	-
84	-	-	-	-	-	-
85	-	-	-	-	-	-
86	-	-	-	-	-	-
87	-	-	-	-	-	-
88	Control	658	24	2	5262	-329
89	Control	630	23	2	7362	-291
90	Sealer	630	23	3	4507	-306

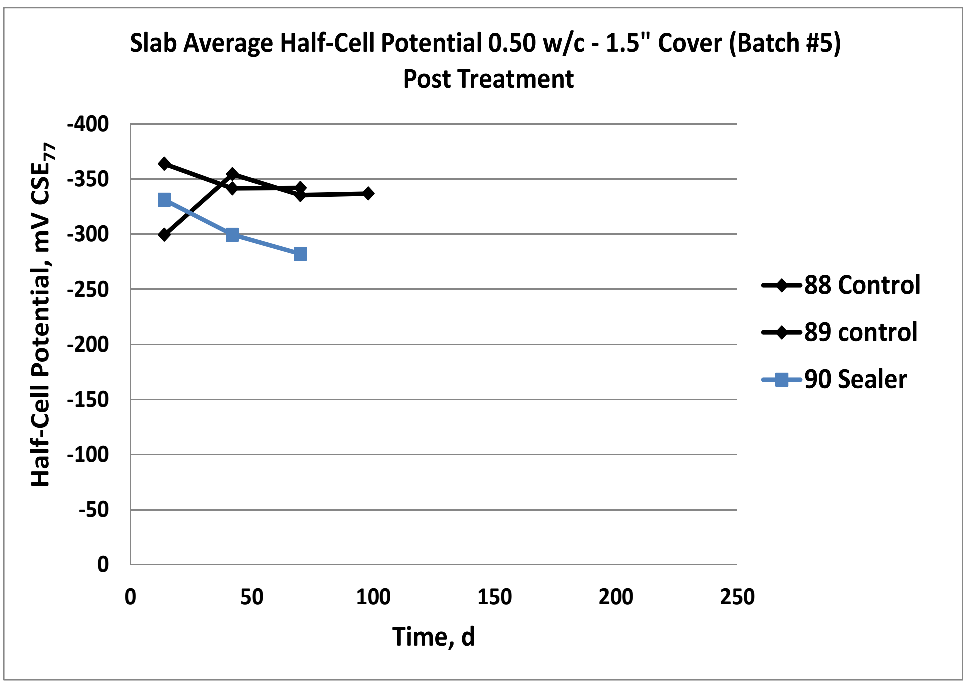


Figure 189 - Slab average half-cell potential as a function of time (Individual slabs, Batch #5, 0.50 w/c, 1.5" cover)

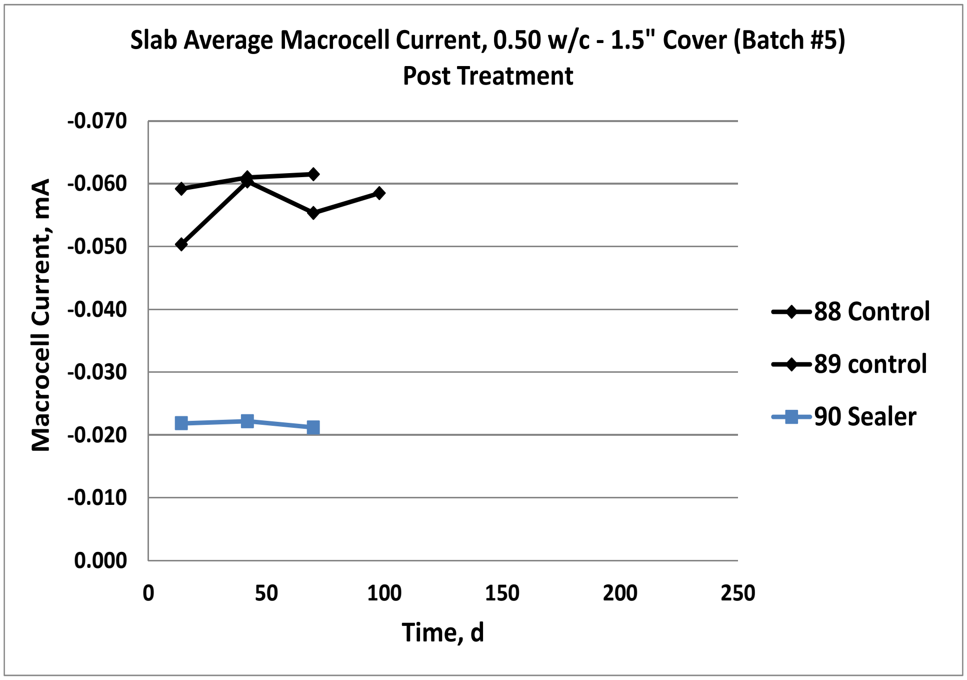


Figure 190 - Slab average macrocell current as a function of time (Individual slabs, Batch #5, 0.50 w/c, 1.5" cover)

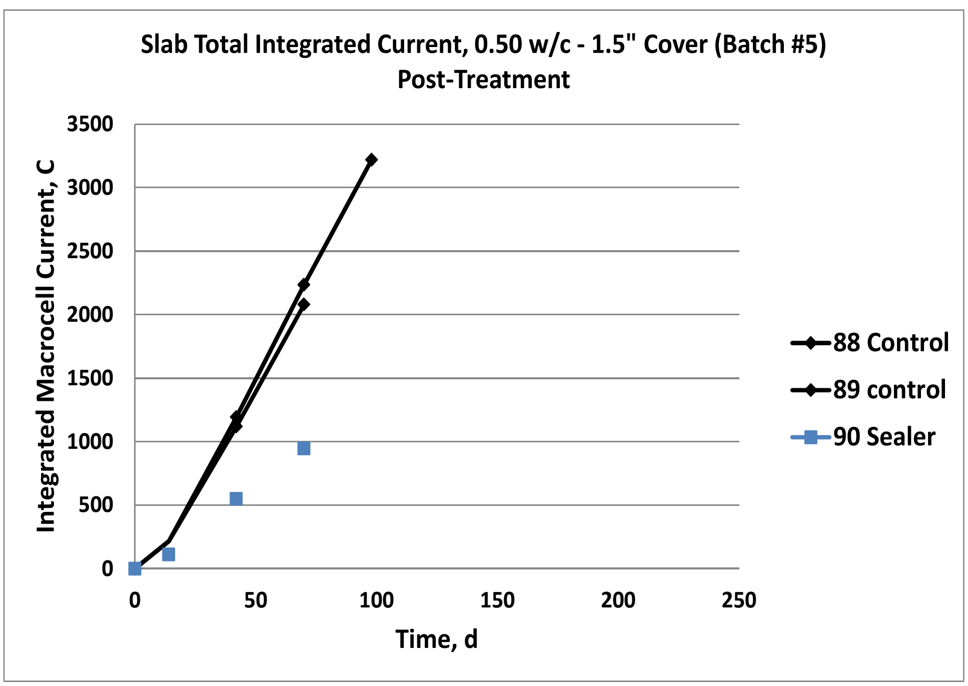


Figure 191 - Slab total integrated current as a function of time (Individual slabs, Batch #5, 0.50 w/c, 1.5" cover)

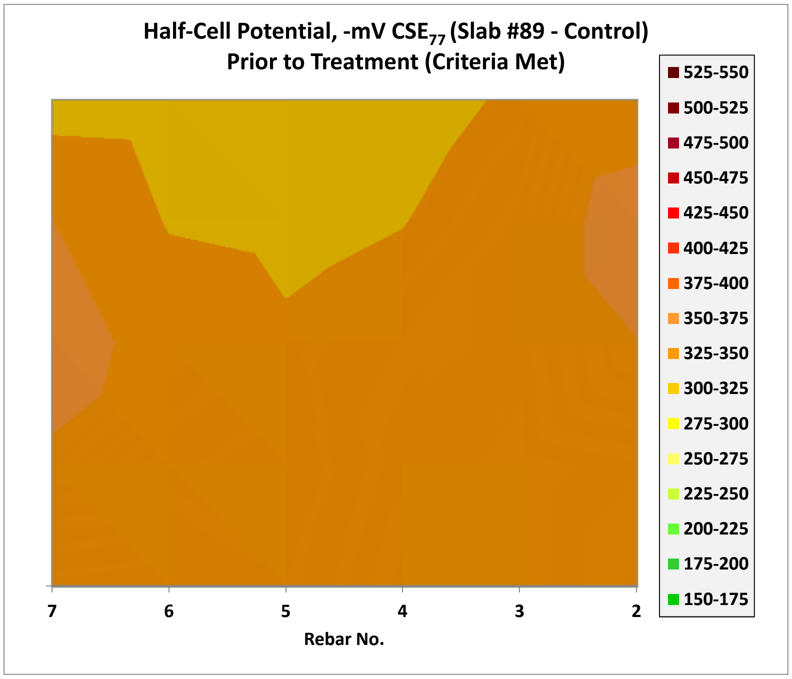


Figure 192 - Half-cell potential mapping prior to treatment, slab #89 - Control

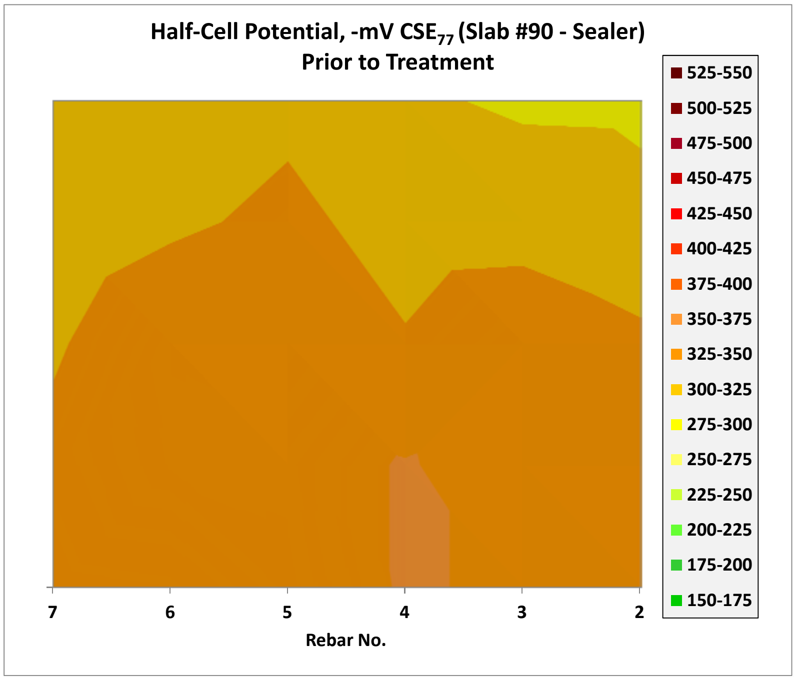


Figure 193 - Half-cell potential mapping prior to destructive analysis, slab #90 - Sealer

Repair Treatments

Batch #1

Table 59 - Batch #1, 0.40 w/c, 1.5" cover repairs

Slab No.	Treatment	Days (After Initial Ponding)	Completed Ponding Cycles Prior to Treatment	Number of Rebar Initiated Corrosion	Total Slab Integrated Current, Coulombs	Average Half-Cell Potential, mV CSE_{77}
1	-	-	-	-	-	-
2	-	-	-	-	-	-
3	Rebar Coating	658	24	4	2748	-311
4	Repair	658	24	1	2764	-262
5	-	-	-			
6	Rebar Coating	518	19	3	3108	-299
7	Destructive Analysis	-	-	-	-	-
8	Repair	518	19	4	2938	-346
9	Anode	518	19	2	2823	-273
10	Repair	490	18	3	4780	-302
11	Anode	490	18	2	3593	-309
12	Sealer	546	20	3	3722	-362
13	Sealer	490	18	3	2949	-293
14	Destructive Analysis	-	-	-	-	-
15	Rebar Coating	546	20	2	3063	-271

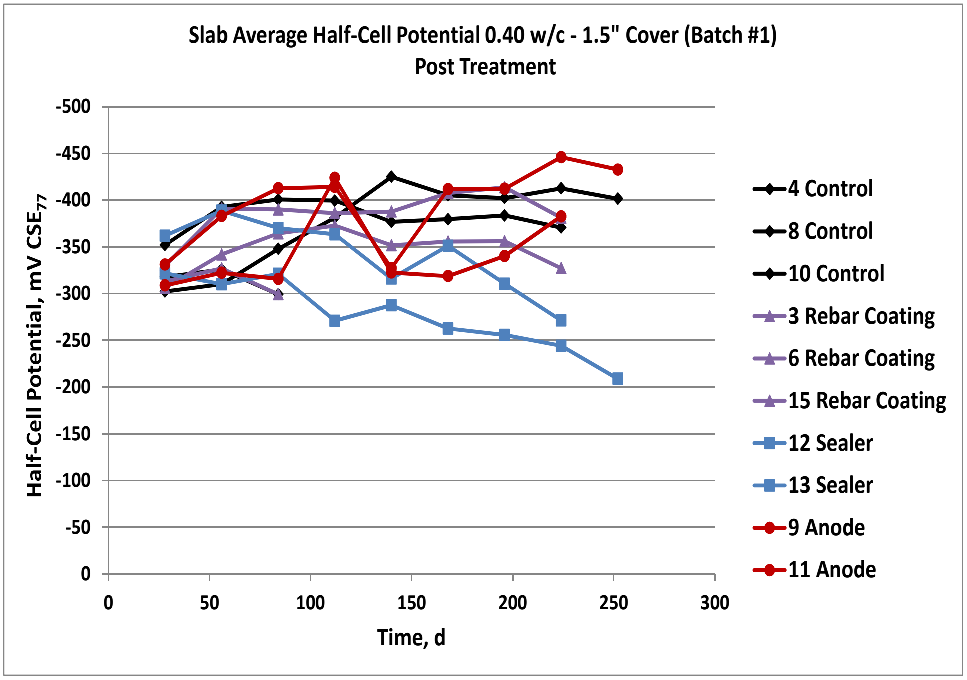


Figure 194 - Slab average half-cell potential as a function of time (Individual slabs, Batch #1, 0.40 w/c, 1.5” cover)

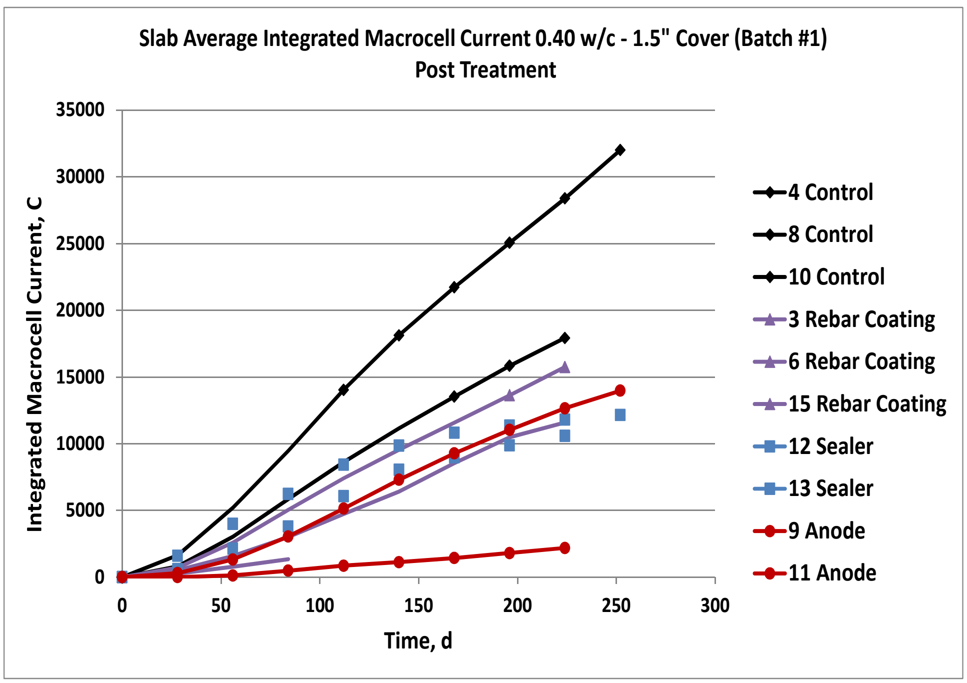


Figure 195 - Slab total integrated current as a function of time (Individual slabs, Batch #1, 0.40 w/c, 1.5” cover)

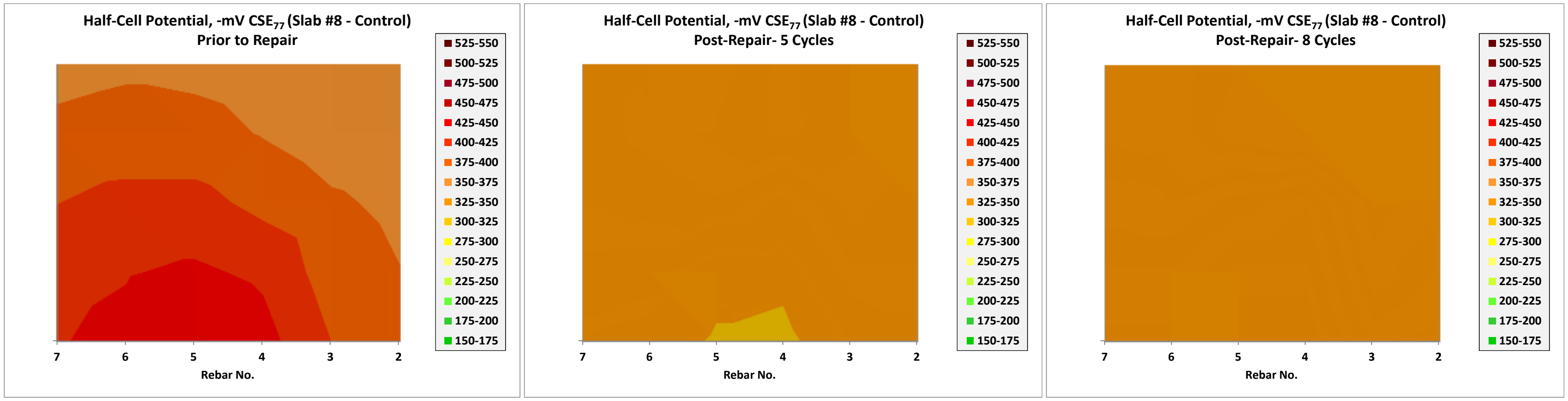


Figure 196 – Half-cell potential mapping prior to repair, 5 cycles after repair, and 8 cycles after repair – Slab #8 - Control

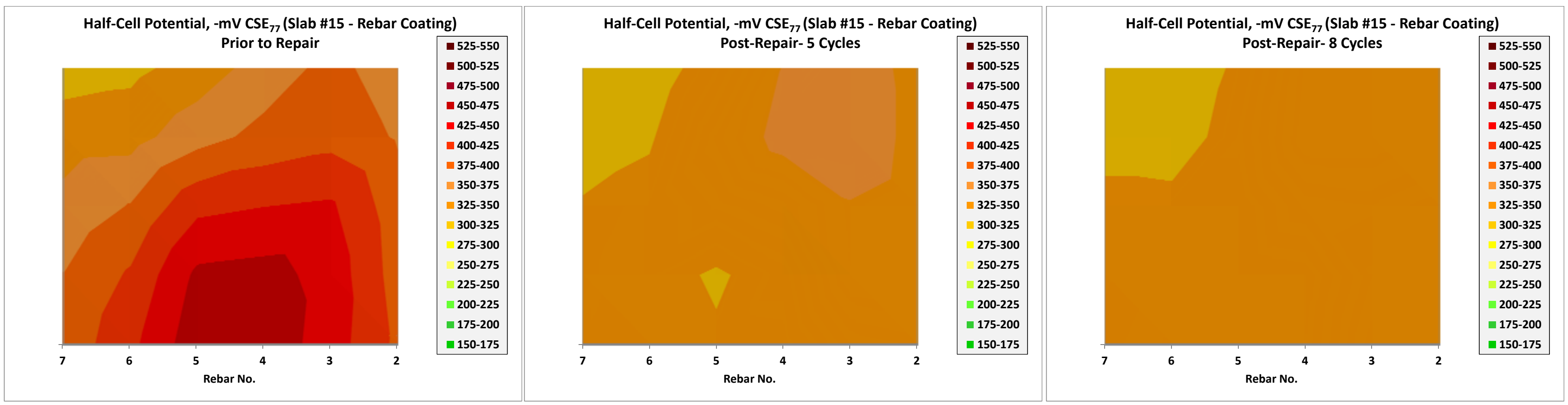


Figure 197 – Half-cell potential mapping prior to repair, 5 cycles after repair, and 8 cycles after repair – Slab #15 – Rebar Coating

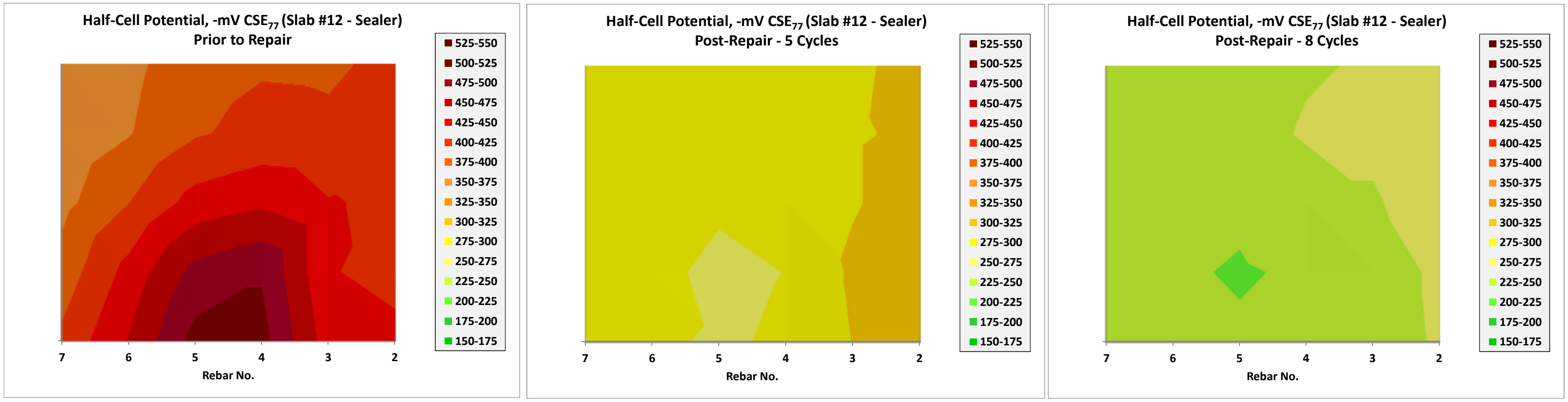


Figure 198 – Half-cell potential mapping prior to repair, 5 cycles after repair, and 8 cycles after repair – Slab #12 - Sealer

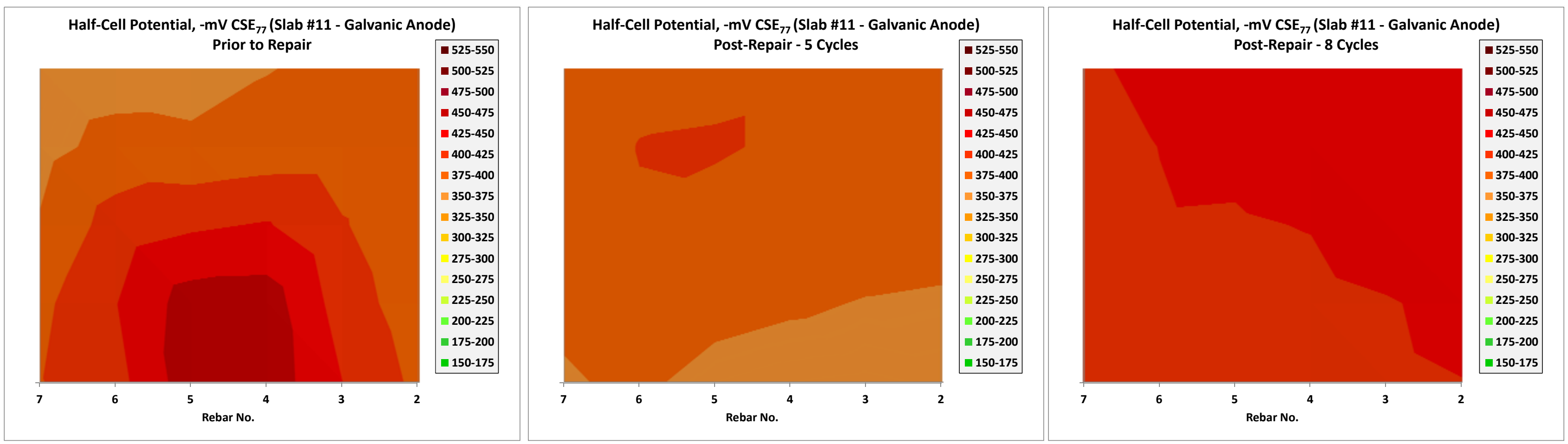


Figure 199 – Half-cell potential mapping prior to repair, 5 cycles after repair, and 8 cycles after repair – Slab #11 – Galvanic Anode

Batch #2

Table 60 – Batch #2, 0.60 w/c, 0.75" cover repairs

Slab No.	Treatment	Days (After Initial Ponding)	Completed Ponding Cycles Prior to Treatment	Number of Rebar Initiated Corrosion	Total Slab Integrated Current, Coulombs	Average Half-Cell Potential, mV CSE_{77}
21	Repair	686	25	1	2893	-246
22	-	-	-	-	-	-
23	Repair	602	22	0	4256	-241
24	Rebar Coating	602	22	1	2852	-256
25	-	-	-	-	-	-
26	Anode	602	22	2	2860	-283
27	Sealer	602	22	1	3871	-210
28	Destructive Analysis	-	-	-	-	-
29	-	-	-	-	-	-
30	-	-	-	-	-	-
31	-	-	-	-	-	-
32	-	-	-	-	-	-
33	-	-	-	-	-	-
34	-	-	-	-	-	-
35	Rebar Coating	686	25	1	2858	-247

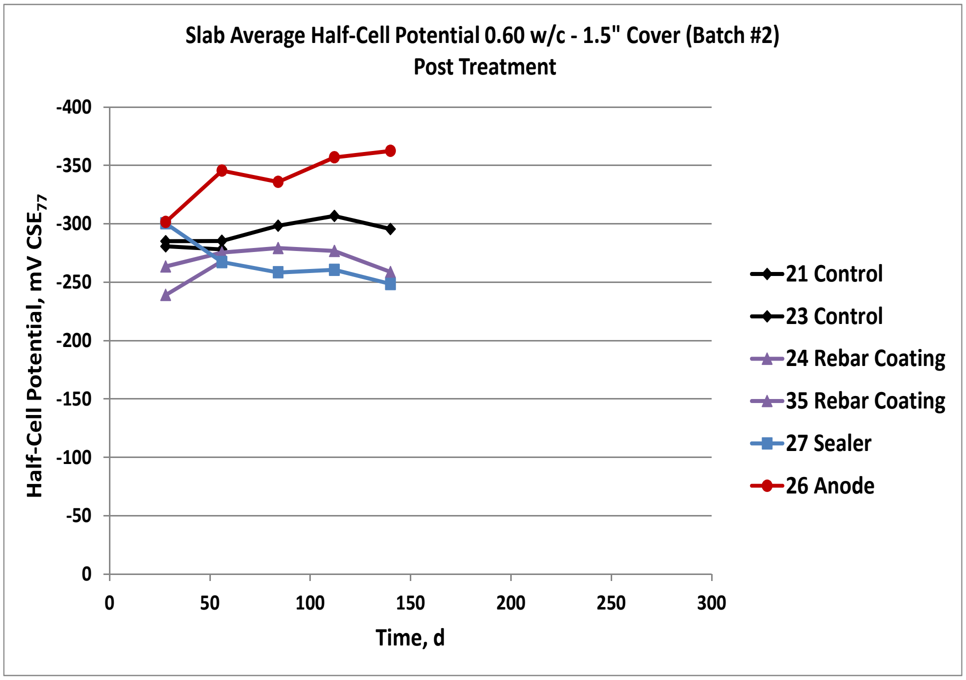


Figure 200 - Slab average half-cell potential as a function of time (Individual slabs, Batch #2, 0.60 w/c, 1.5” cover)

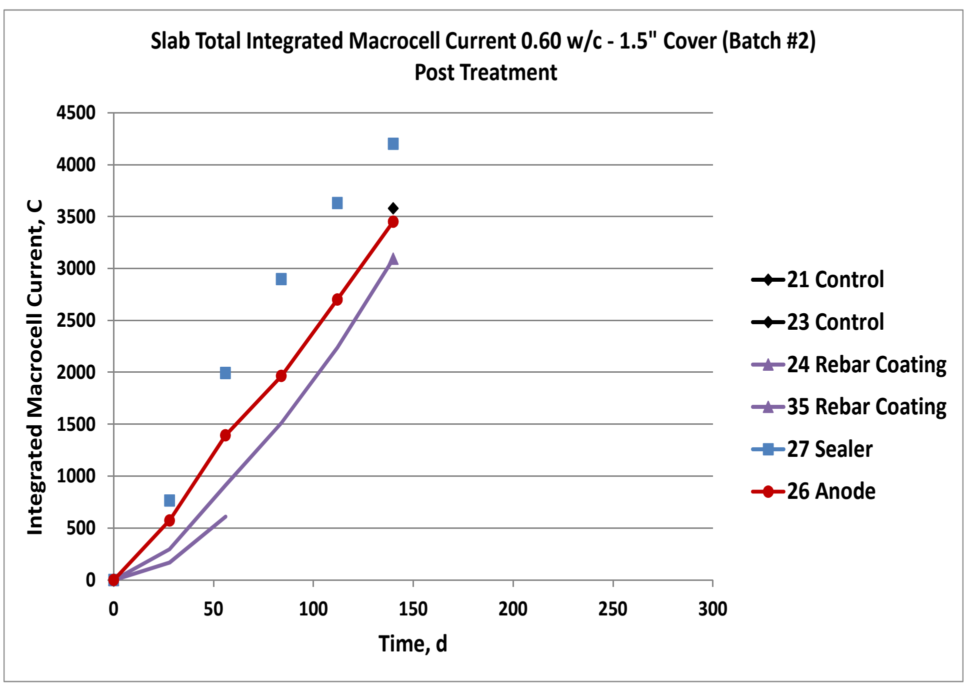
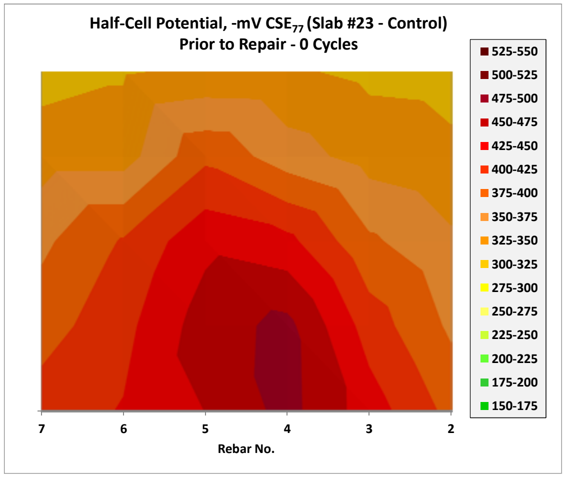
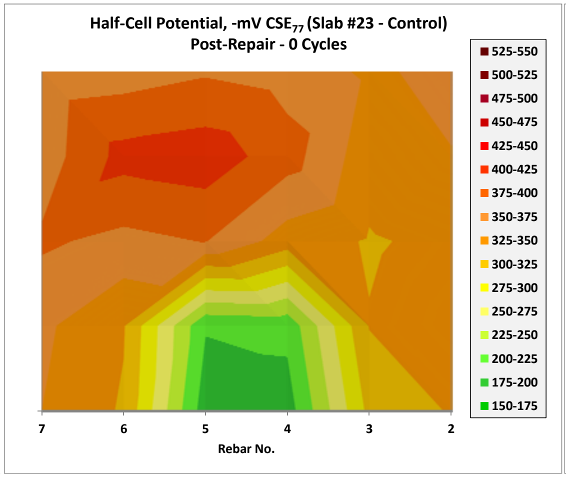
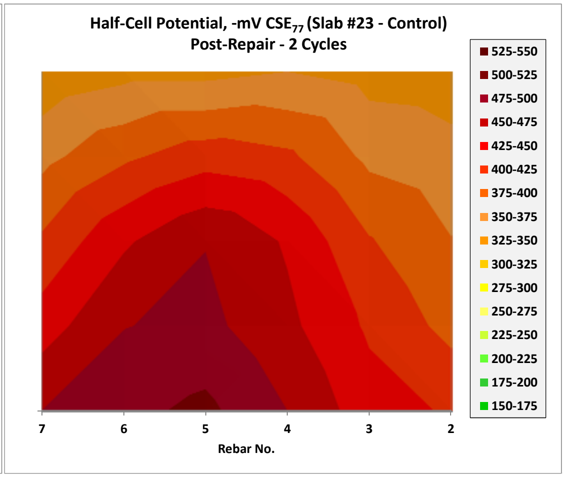
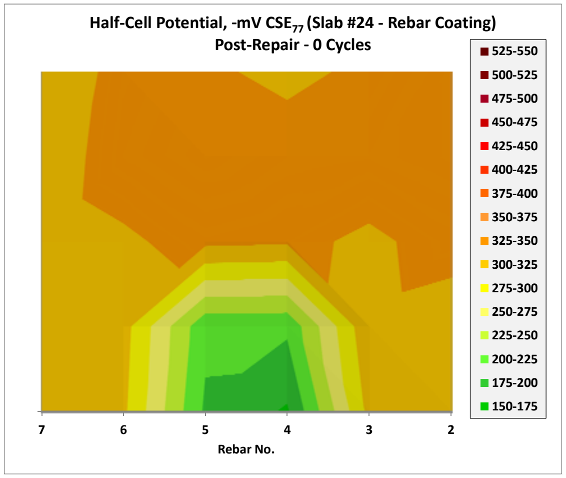


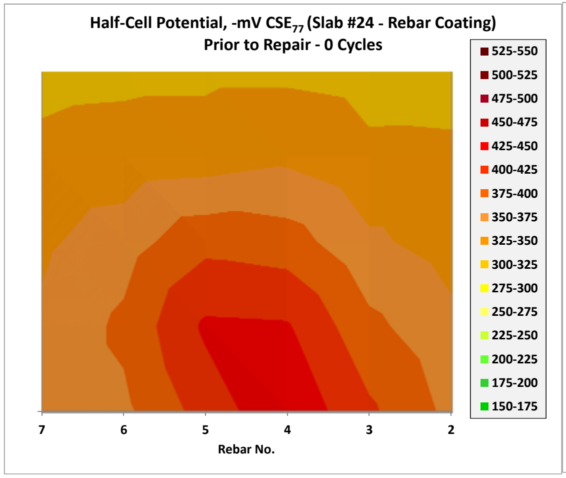
Figure 201 - Slab total integrated current as a function of time (Individual slabs, Batch #2, 0.60 w/c, 1.5” cover)

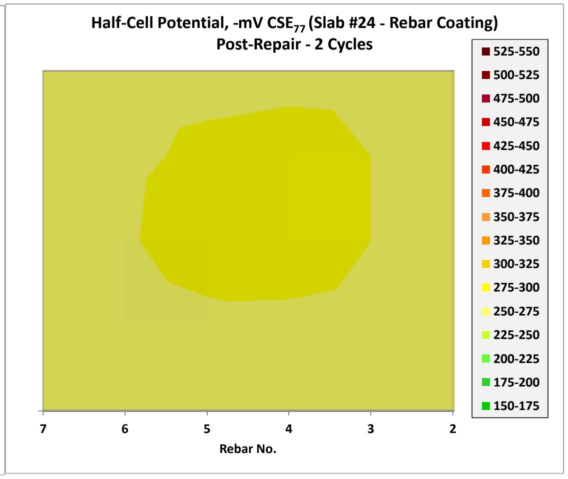

Half-Cell Potential, -mV CSE77 (Slab #23 - Control)
Prior to Repair - 0 Cycles
525-550
500-525
475-500
450-475
425-450
400-425
375-400
350-375
325-350
300-325
275-300
250-275
225-250
200-225
175-200
150-175
7 6 5 4 3 2
Rebar No.

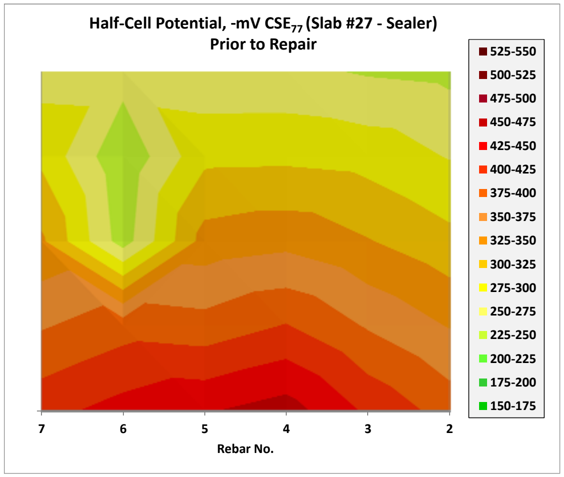

Half-Cell Potential, -mV CSE77 (Slab #23 - Control)
Post-Repair - 0 Cycles
525-550
500-525
475-500
450-475
425-450
400-425
375-400
350-375
325-350
300-325
275-300
250-275
225-250
200-225
175-200
150-175
7 6 5 4 3 2
Rebar No.

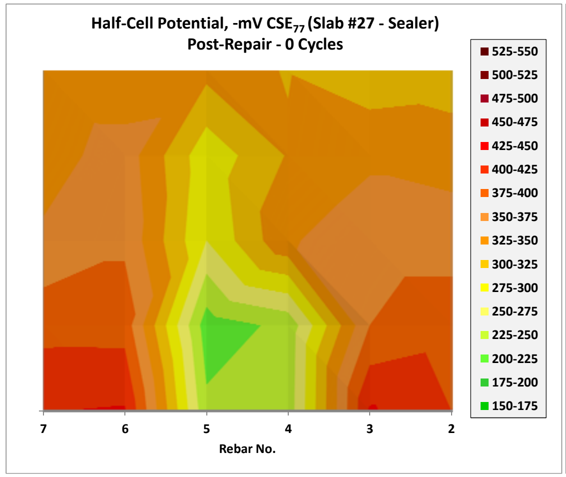

Half-Cell Potential, -mV CSE77 (Slab #23 - Control)
Post-Repair - 2 Cycles
525-550
500-525
475-500
450-475
425-450
400-425
375-400
350-375
325-350
300-325
275-300
250-275
225-250
200-225
175-200
150-175
7 6 5 4 3 2
Rebar No.

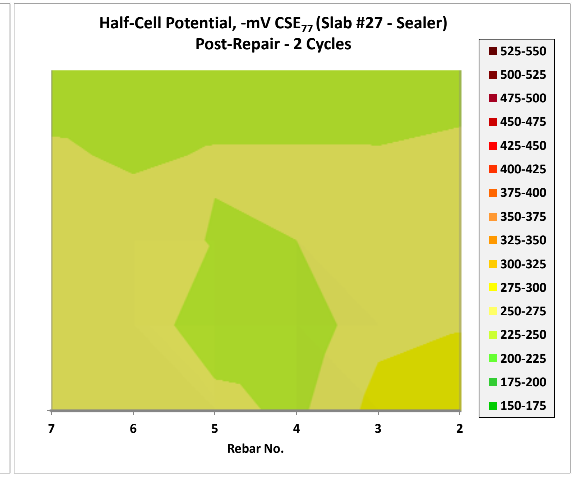

Half-Cell Potential, -mV CSE77 (Slab #24 - Rebar Coating)
Post-Repair - 0 Cycles
525-550
500-525
475-500
450-475
425-450
400-425
375-400
350-375
325-350
300-325
275-300
250-275
225-250
200-225
175-200
150-175
7 6 5 4 3 2
Rebar No.

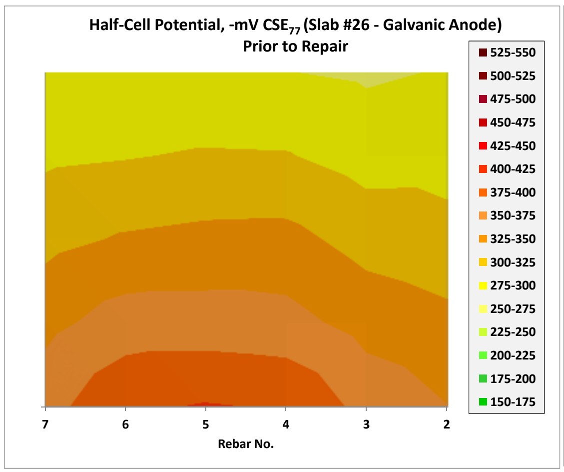

Half-Cell Potential, -mV CSE77 (Slab #24 - Rebar Coating)
Prior to Repair - 0 Cycles
525-550
500-525
475-500
450-475
425-450
400-425
375-400
350-375
325-350
300-325
275-300
250-275
225-250
200-225
175-200
150-175
7 6 5 4 3 2
Rebar No.

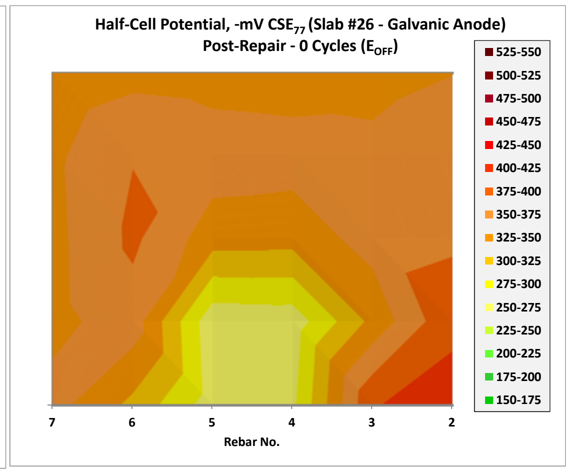

Half-Cell Potential, -mV CSE77 (Slab #24 - Rebar Coating)
Post-Repair - 2 Cycles
525-550
500-525
475-500
450-475
425-450
400-425
375-400
350-375
325-350
300-325
275-300
250-275
225-250
200-225
175-200
150-175
7 6 5 4 3 2
Rebar No.

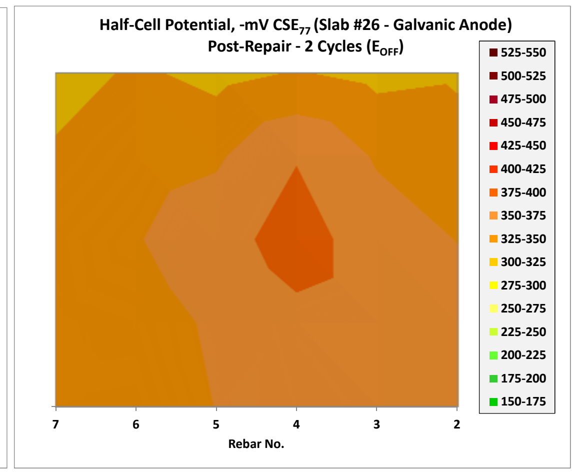

Half-Cell Potential, -mV CSE_{77} (Slab #27 - Sealer)
Prior to Repair
525-550
500-525
475-500
450-475
425-450
400-425
375-400
350-375
325-350
300-325
275-300
250-275
225-250
200-225
175-200
150-175
7
6
5
4
3
2
Rebar No.


Half-Cell Potential, -mV CSE_{77} (Slab #27 - Sealer)
Post-Repair - 0 Cycles
525-550
500-525
475-500
450-475
425-450
400-425
375-400
350-375
325-350
300-325
275-300
250-275
225-250
200-225
175-200
150-175
7
6
5
4
3
2
Rebar No.


Half-Cell Potential, -mV CSE_{77} (Slab #27 - Sealer)
Post-Repair - 2 Cycles
525-550
500-525
475-500
450-475
425-450
400-425
375-400
350-375
325-350
300-325
275-300
250-275
225-250
200-225
175-200
150-175
7
6
5
4
3
2
Rebar No.


Half-Cell Potential, -mV CSE_{77} (Slab #26 - Galvanic Anode)
Prior to Repair
525-550
500-525
475-500
450-475
425-450
400-425
375-400
350-375
325-350
300-325
275-300
250-275
225-250
200-225
175-200
150-175
7
6
5
4
3
2
Rebar No.

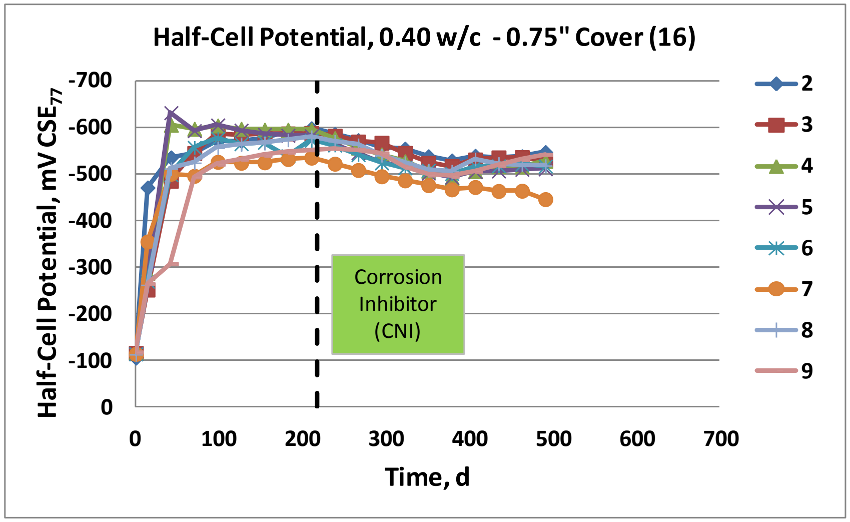

Half-Cell Potential, -mV CSE_{77} (Slab #26 - Galvanic Anode)
Post-Repair - 0 Cycles (E_{OFF})
525-550
500-525
475-500
450-475
425-450
400-425
375-400
350-375
325-350
300-325
275-300
250-275
225-250
200-225
175-200
150-175
7
6
5
4
3
2
Rebar No.

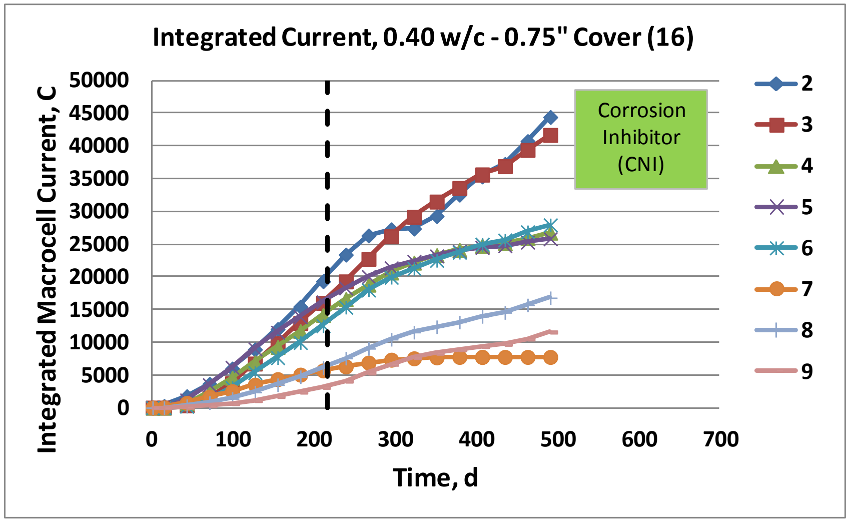

Half-Cell Potential, -mV CSE_{77} (Slab #26 - Galvanic Anode)
Post-Repair - 2 Cycles (E_{OFF})
525-550
500-525
475-500
450-475
425-450
400-425
375-400
350-375
325-350
300-325
275-300
250-275
225-250
200-225
175-200
150-175
7
6
5
4
3
2
Rebar No.

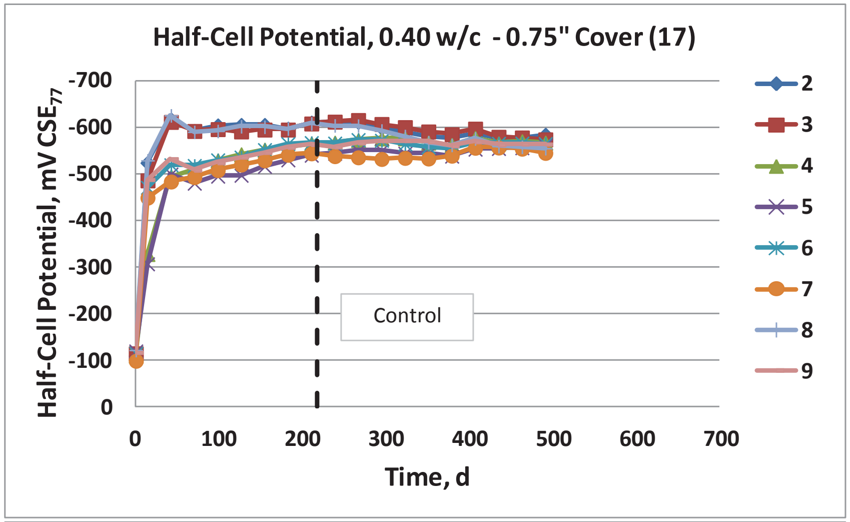
Appendix I – Individual Slab Test Results

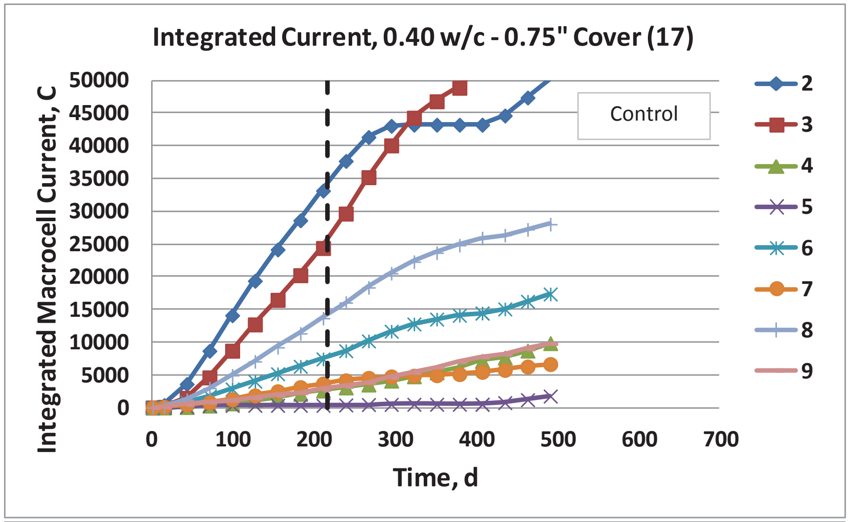
0.75-inch Cover Topical Treatment Slabs

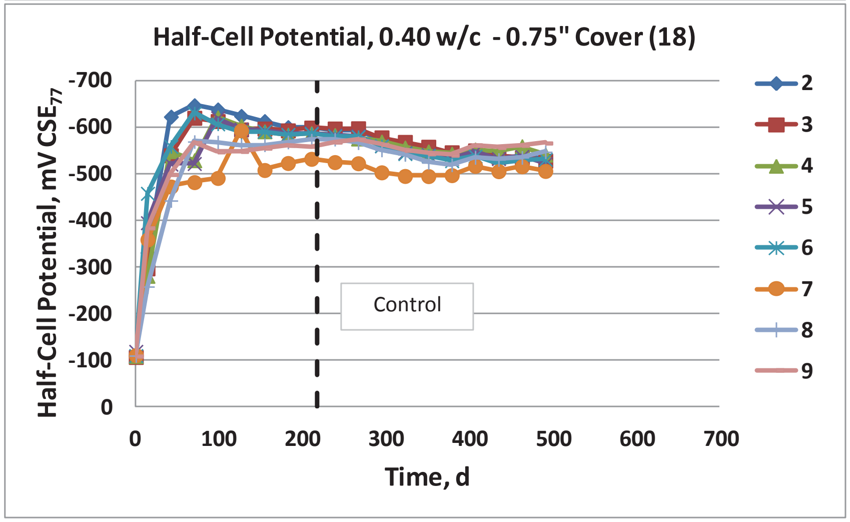
Batch #1

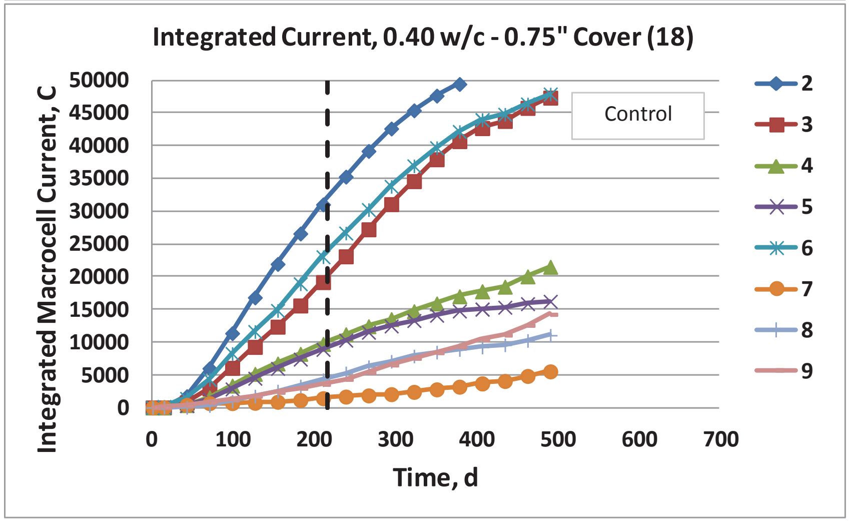


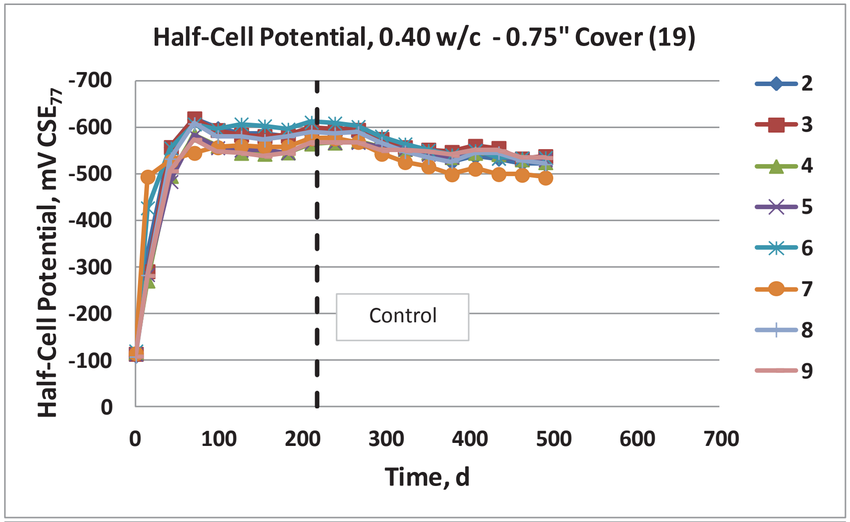


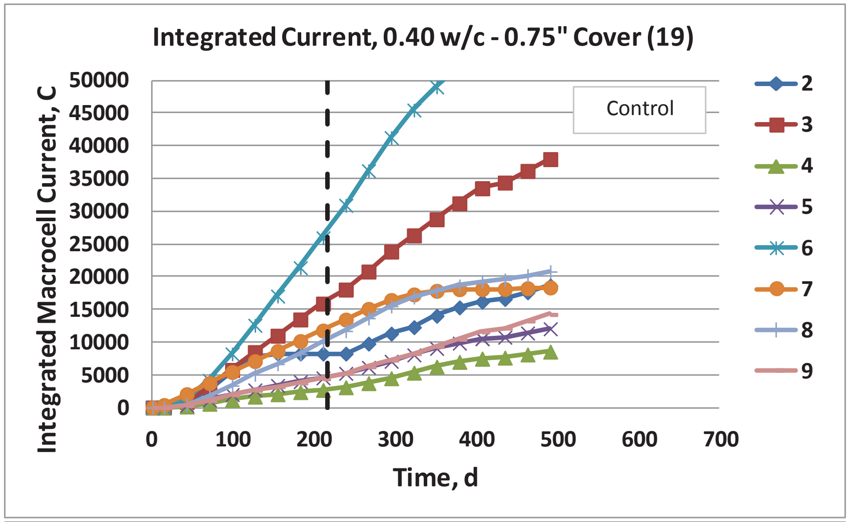

Half-Cell Potential, 0.40 w/c - 0.75" Cover (17)
Half-Cell Potential, mV CSE_{77}
Time, d
Control
2
3
4
5
6
7
8
9

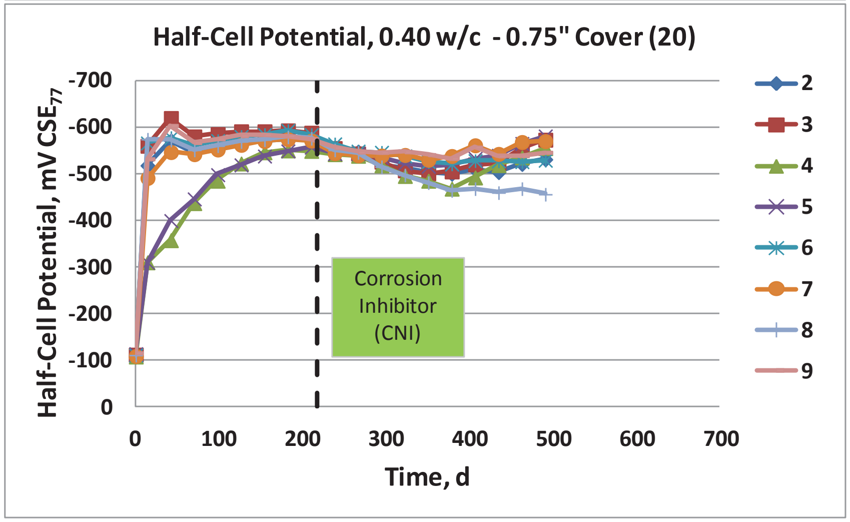

Integrated Current, 0.40 w/c - 0.75" Cover (17)
Integrated Macrocell Current, C
Time, d
Control
2
3
4
5
6
7
8
9

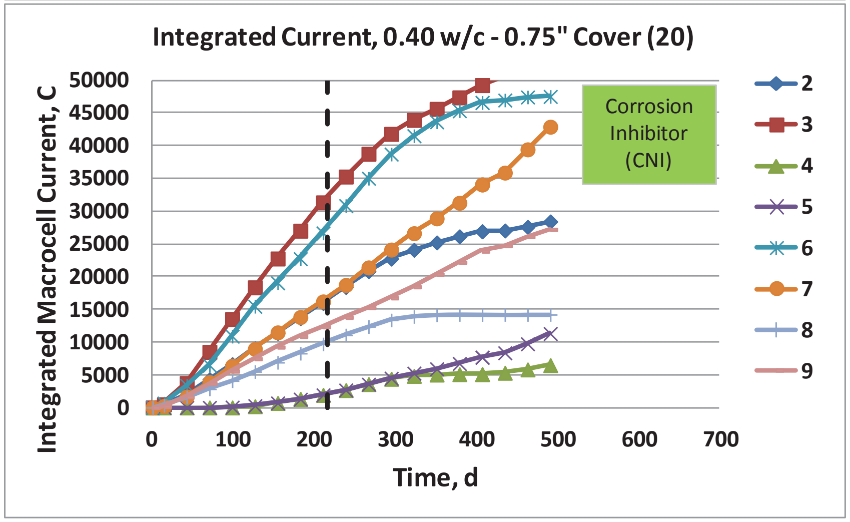

Half-Cell Potential, 0.40 w/c - 0.75" Cover (18)
Half-Cell Potential, mV CSE_{77}
Time, d
Control
2
3
4
5
6
7
8
9


Integrated Current, 0.40 w/c - 0.75" Cover (18)
Integrated Macrocell Current, C
Time, d
Control
2
3
4
5
6
7
8
9

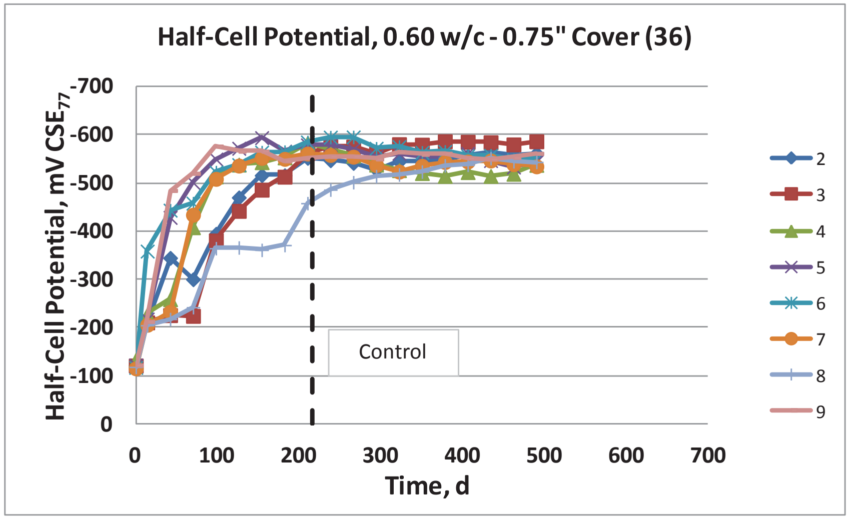

Half-Cell Potential, 0.40 w/c - 0.75" Cover (19)
Half-Cell Potential, mV CSE77
Time, d
Control
2
3
4
5
6
7
8
9

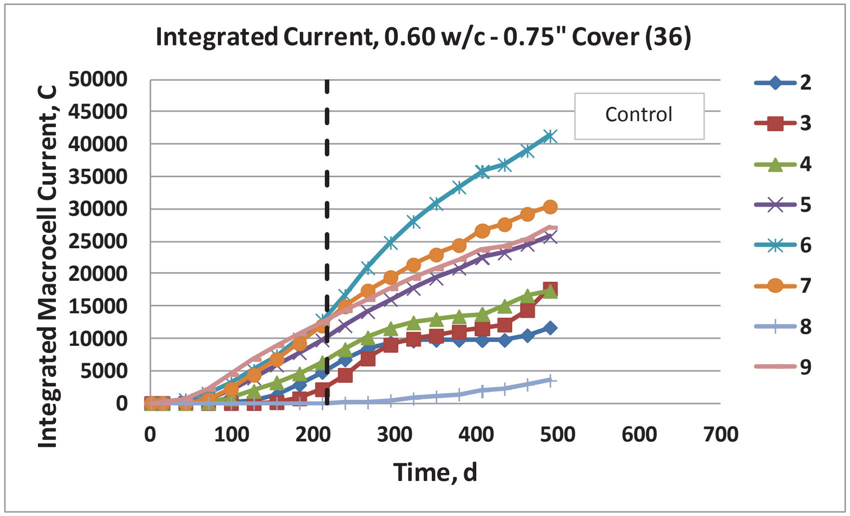

Integrated Current, 0.40 w/c - 0.75" Cover (19)
Integrated Macrocell Current, C
Time, d
Control
2
3
4
5
6
7
8
9

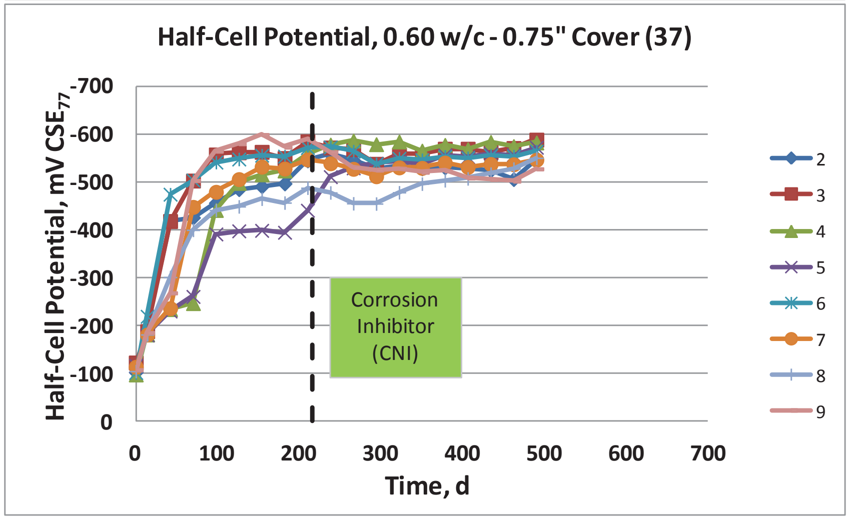

Half-Cell Potential, 0.40 w/c - 0.75" Cover (20)
Half-Cell Potential, mV CSE77
Time, d
Corrosion Inhibitor (CNI)
2
3
4
5
6
7
8
9

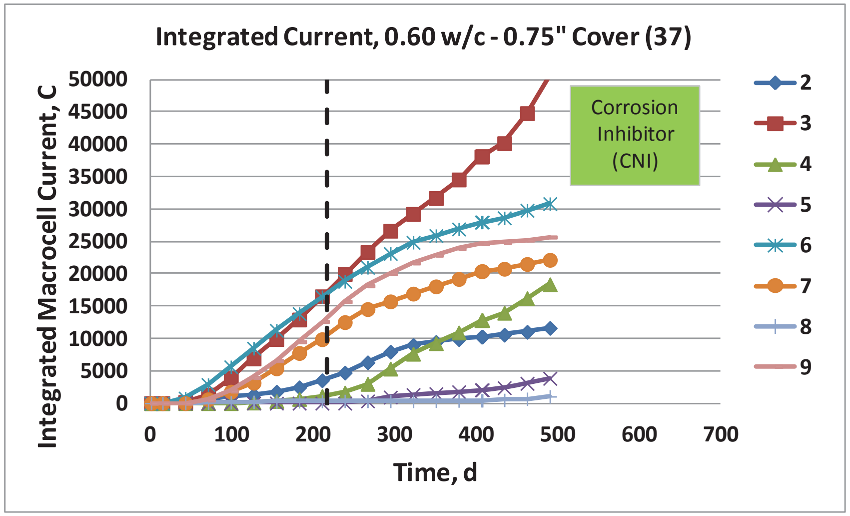

Integrated Current, 0.40 w/c - 0.75" Cover (20)
Integrated Macrocell Current, C
Time, d
Corrosion Inhibitor (CNI)
2
3
4
5
6
7
8
9

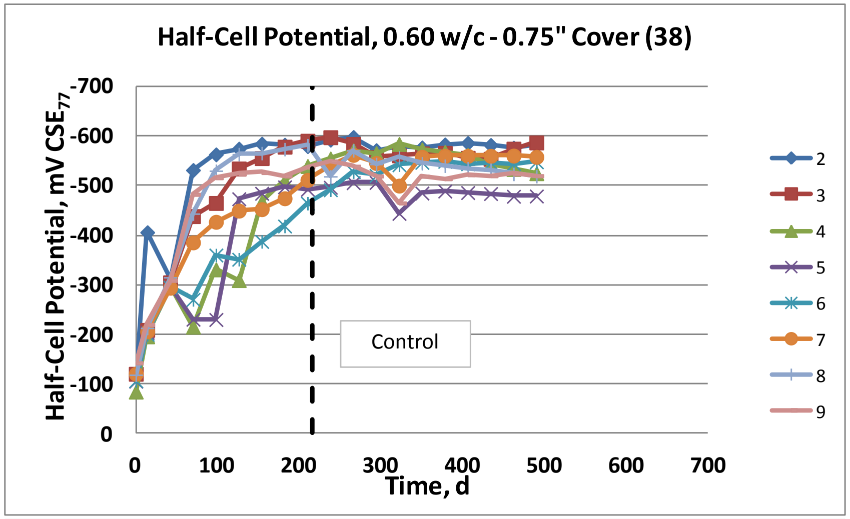
Batch #2

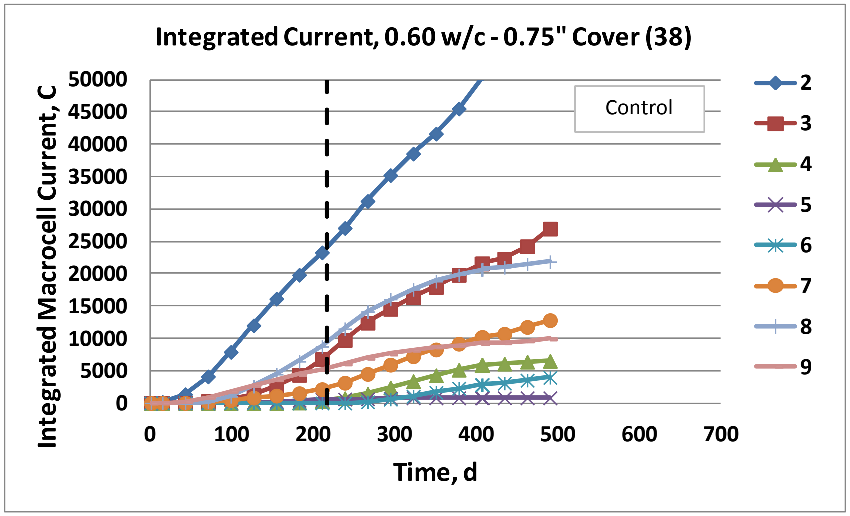

Half-Cell Potential, 0.60 w/c - 0.75" Cover (36)
Half-Cell Potential, mV CSE_{77}
Time, d
Control
2
3
4
5
6
7
8
9

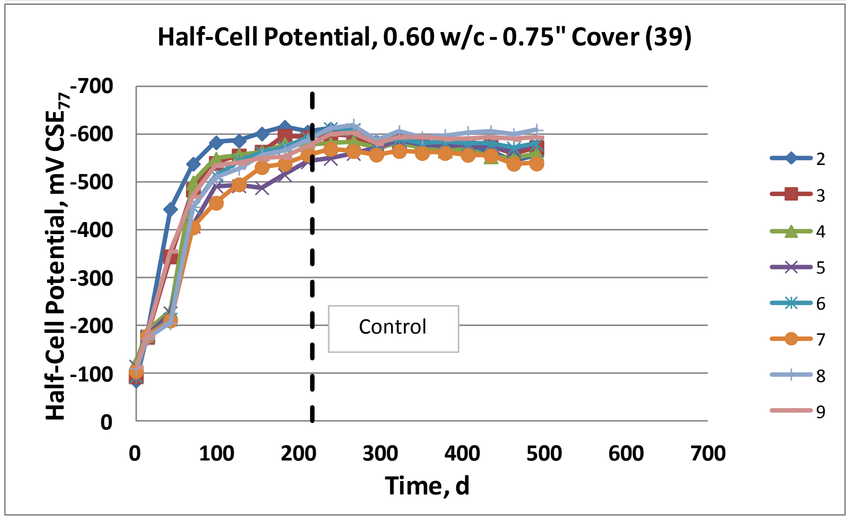

Integrated Current, 0.60 w/c - 0.75" Cover (36)
Integrated Macrocell Current, C
Time, d
Control
2
3
4
5
6
7
8
9

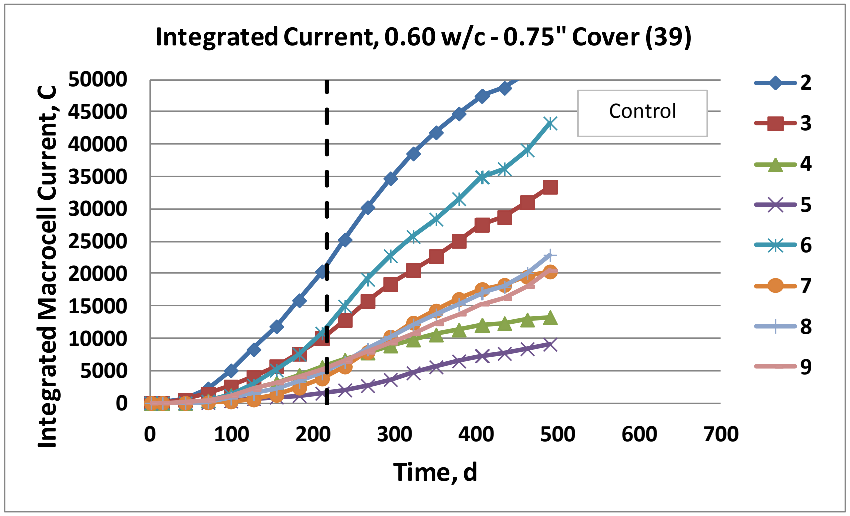

Half-Cell Potential, 0.60 w/c - 0.75" Cover (37)
Half-Cell Potential, mV CSE_{77}
Time, d
Corrosion Inhibitor (CNI)
2
3
4
5
6
7
8
9

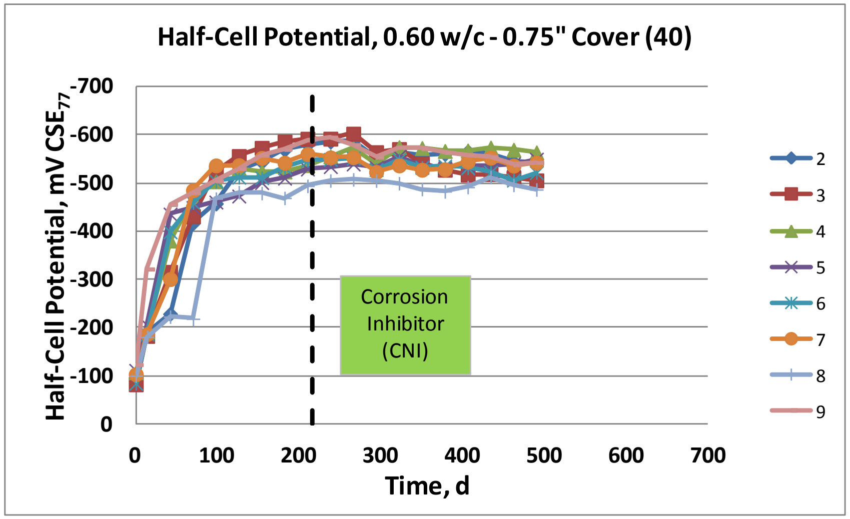

Integrated Current, 0.60 w/c - 0.75" Cover (37)
Integrated Macrocell Current, C
Time, d
Corrosion Inhibitor (CNI)
2
3
4
5
6
7
8
9

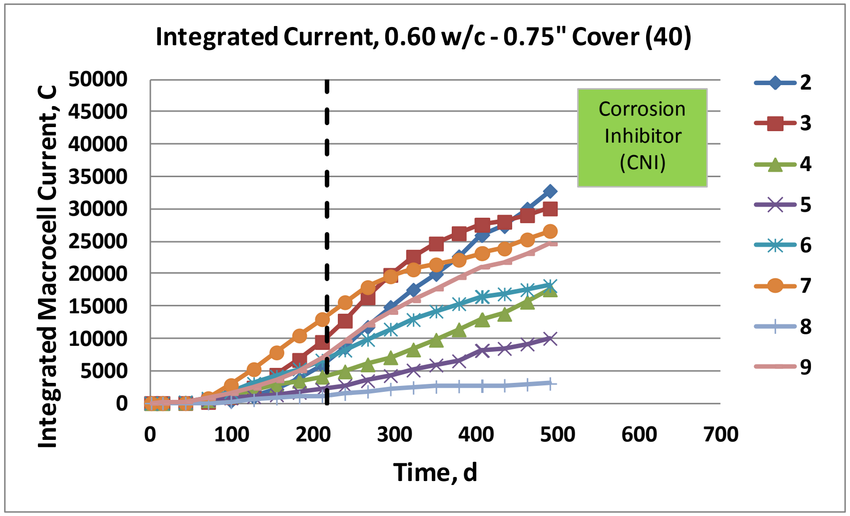

Half-Cell Potential, 0.60 w/c - 0.75" Cover (38)
Half-Cell Potential, mV CSE_{77}
Time, d
Control
2
3
4
5
6
7
8
9


Integrated Current, 0.60 w/c - 0.75" Cover (38)
Integrated Macrocell Current, C
Time, d
Control
2
3
4
5
6
7
8
9

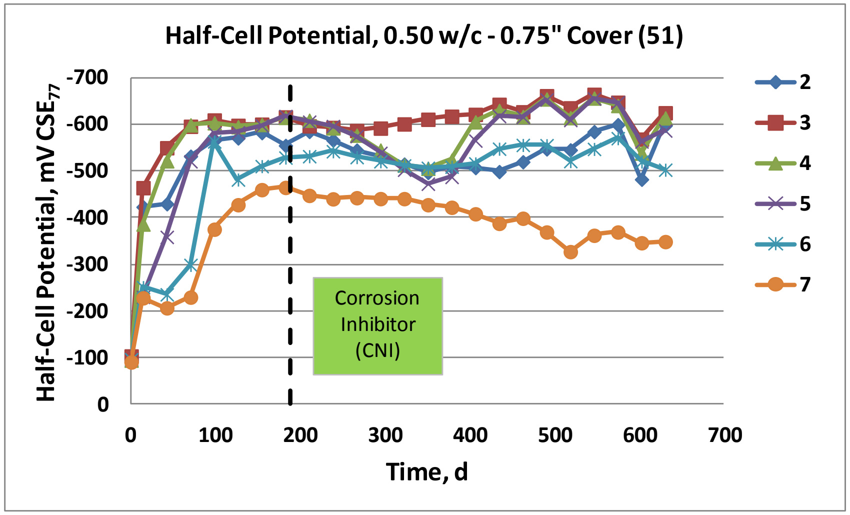

Half-Cell Potential, 0.60 w/c - 0.75" Cover (39)
Half-Cell Potential, mV CSE_{77}
Time, d
Control
2
3
4
5
6
7
8
9

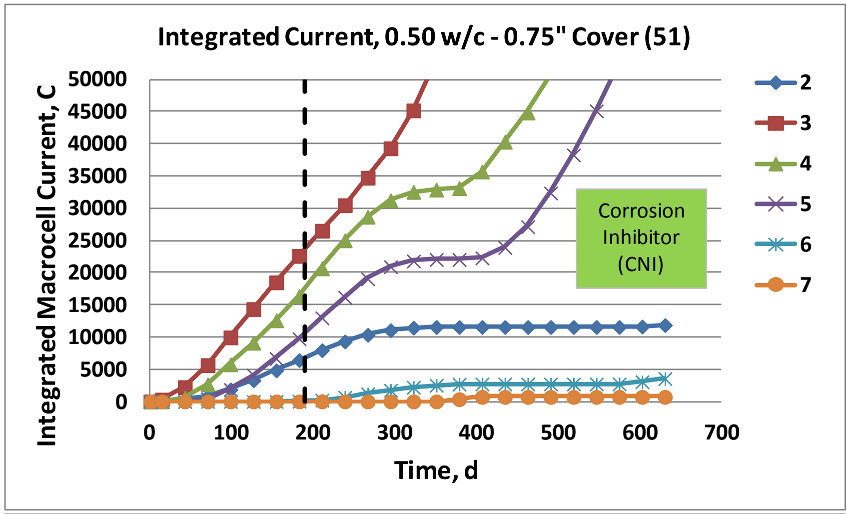

Integrated Current, 0.60 w/c - 0.75" Cover (39)
Integrated Macrocell Current, C
Time, d
Control
2
3
4
5
6
7
8
9

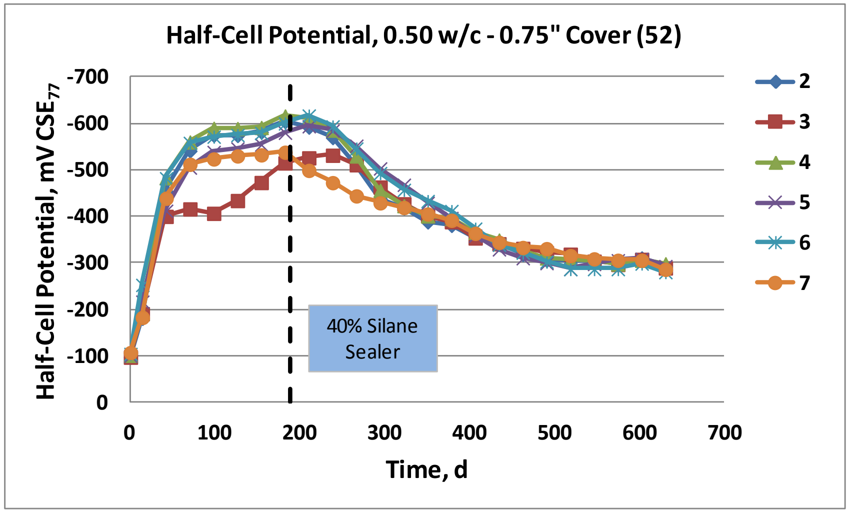

Half-Cell Potential, 0.60 w/c - 0.75" Cover (40)
Half-Cell Potential, mV CSE_{77}
Time, d
Corrosion Inhibitor (CNI)
-700
-600
-500
-400
-300
-200
-100
0
0
100
200
300
400
500
600
700
2
3
4
5
6
7
8
9

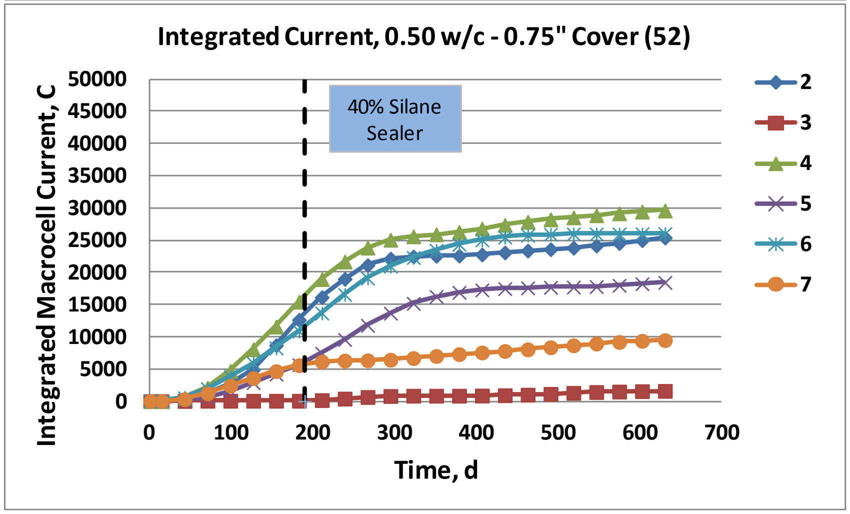

Integrated Current, 0.60 w/c - 0.75" Cover (40)
Integrated Macrocell Current, C
Time, d
Corrosion Inhibitor (CNI)
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
100
200
300
400
500
600
700
2
3
4
5
6
7
8
9

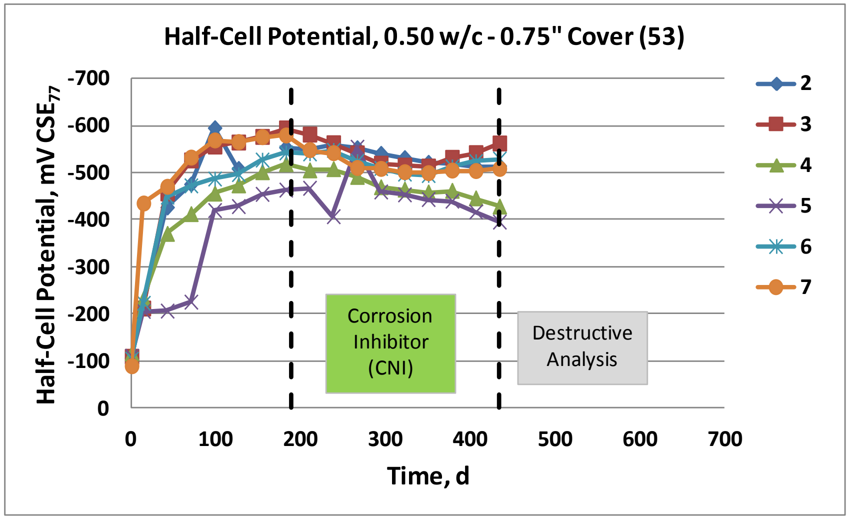
Batch #3

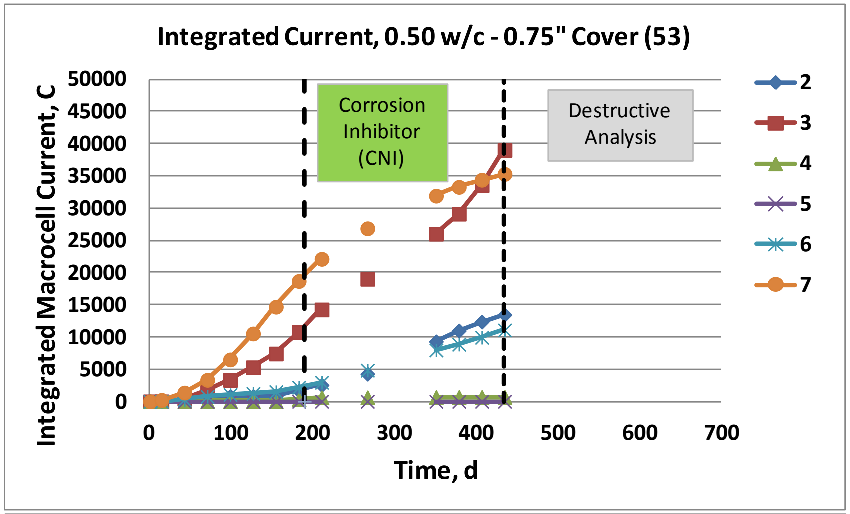

Half-Cell Potential, 0.50 w/c - 0.75" Cover (51)
Half-Cell Potential, mV CSE77
Time, d
Corrosion Inhibitor (CNI)
2
3
4
5
6
7

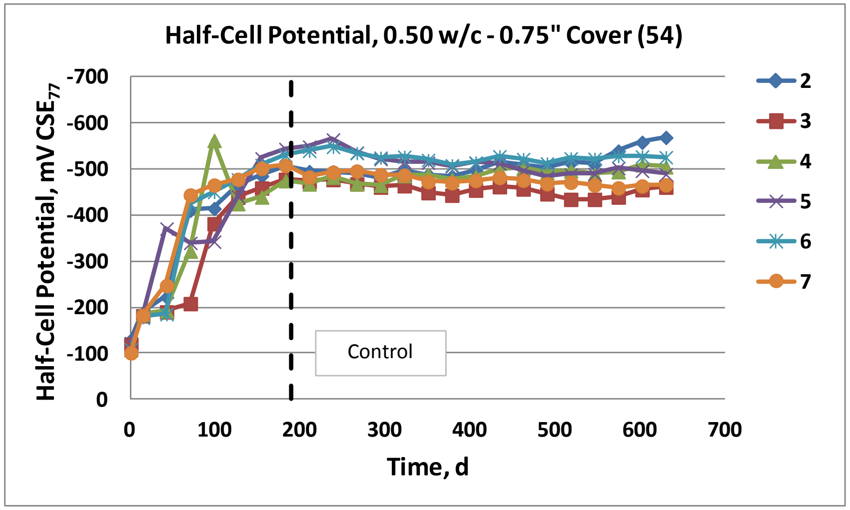

Integrated Current, 0.50 w/c - 0.75" Cover (51)
Integrated Macrocell Current, C
Time, d
Corrosion Inhibitor (CNI)
2
3
4
5
6
7

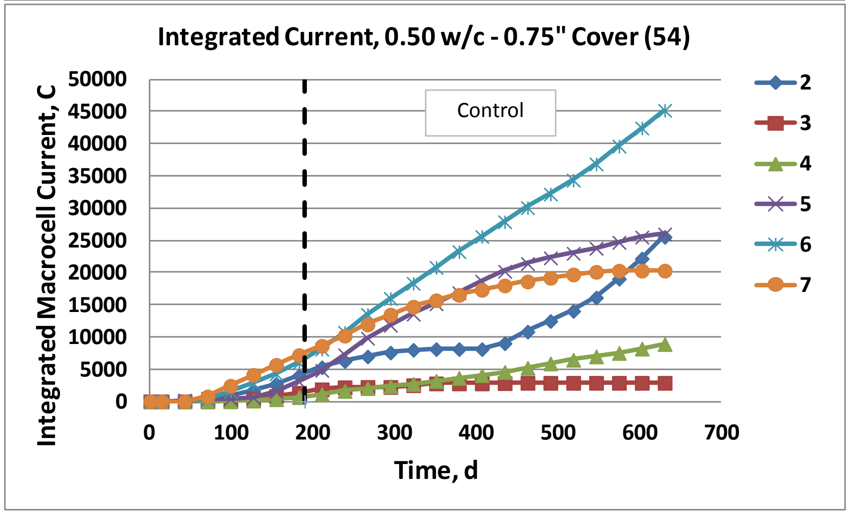

Half-Cell Potential, 0.50 w/c - 0.75" Cover (52)
Half-Cell Potential, mV CSE77
Time, d
40% Silane Sealer
2
3
4
5
6
7

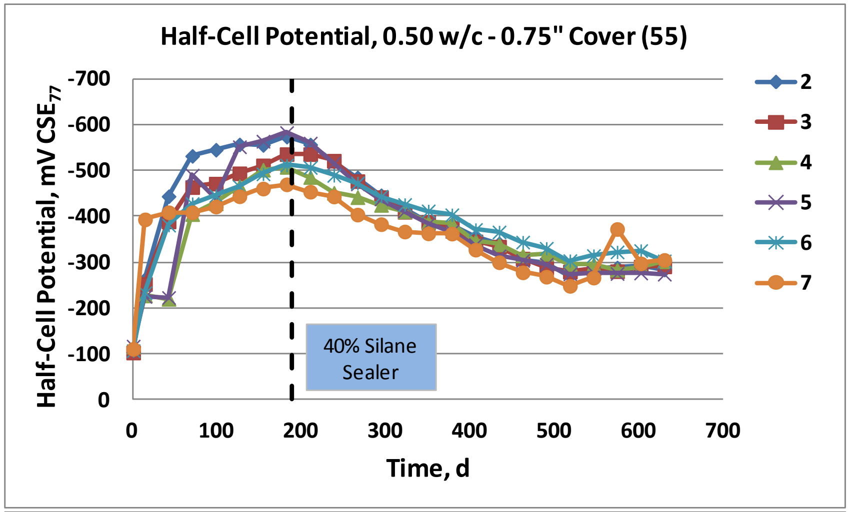

Integrated Current, 0.50 w/c - 0.75" Cover (52)
Integrated Macrocell Current, C
Time, d
40% Silane Sealer
2
3
4
5
6
7

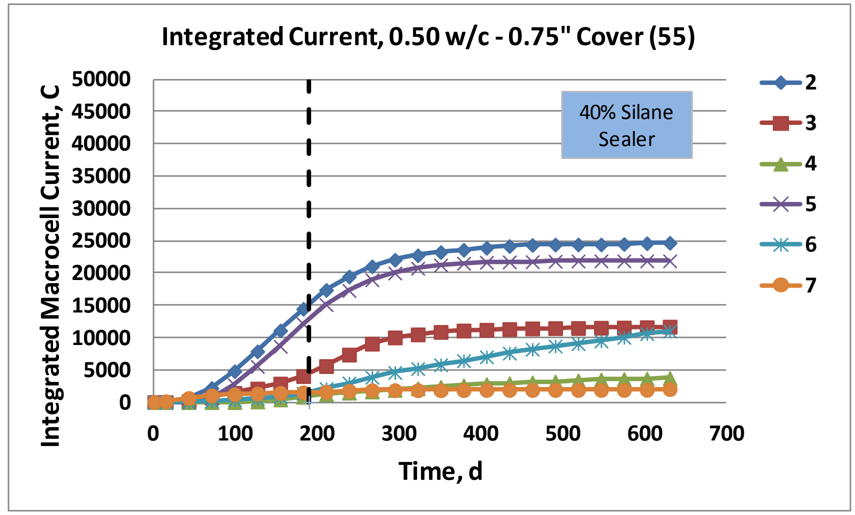

Half-Cell Potential, 0.50 w/c - 0.75" Cover (53)
Half-Cell Potential, mV CSE77
Time, d
Corrosion Inhibitor (CNI)
Destructive Analysis
2
3
4
5
6
7

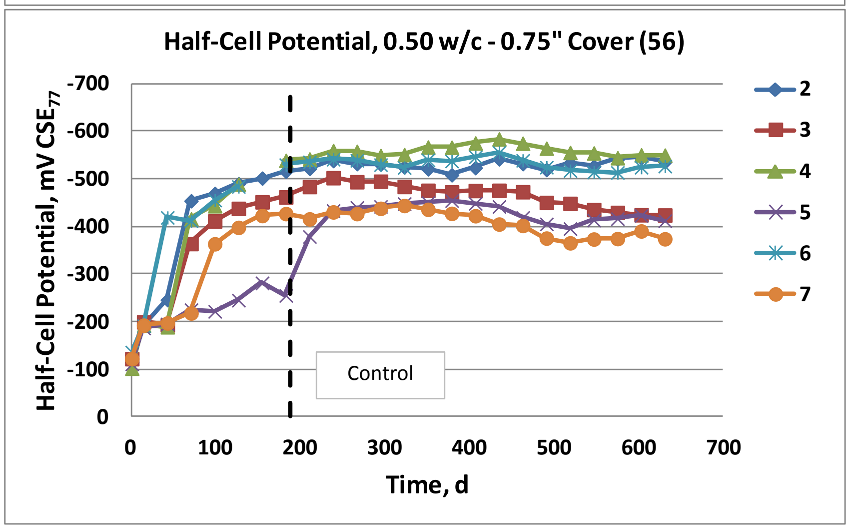

Integrated Current, 0.50 w/c - 0.75" Cover (53)
Integrated Macrocell Current, C
Time, d
Corrosion Inhibitor (CNI)
Destructive Analysis
2
3
4
5
6
7

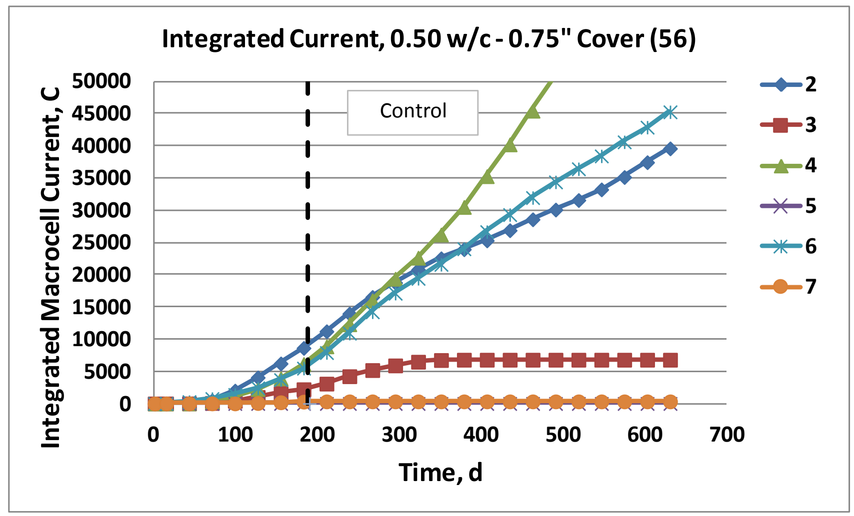

Half-Cell Potential, 0.50 w/c - 0.75" Cover (54)
Half-Cell Potential, mV CSE77
Time, d
Control
2
3
4
5
6
7

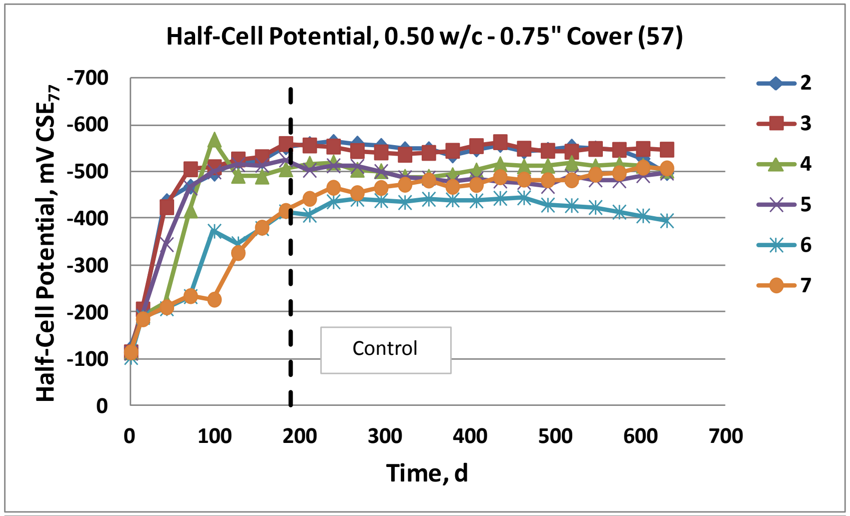

Integrated Current, 0.50 w/c - 0.75" Cover (54)
Integrated Macrocell Current, C
Time, d
Control
2
3
4
5
6
7

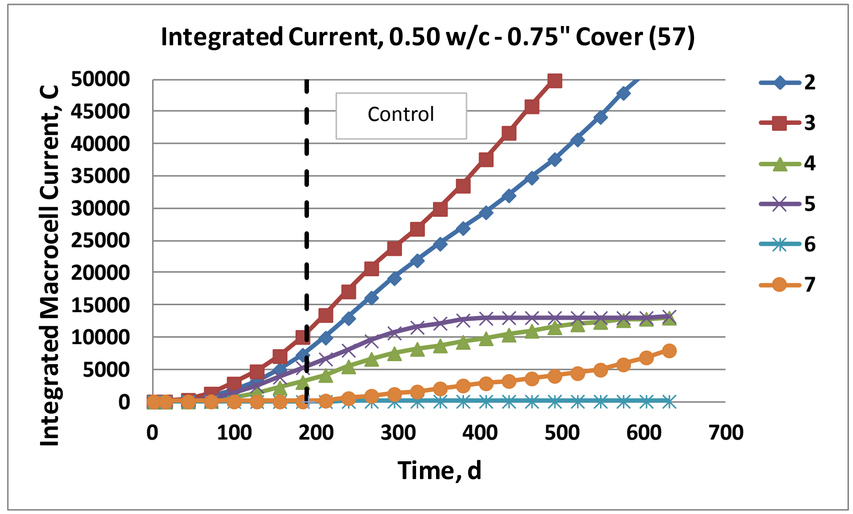

Half-Cell Potential, 0.50 w/c - 0.75" Cover (55)
Half-Cell Potential, mV CSE_{77}
-700
-600
-500
-400
-300
-200
-100
0
0
100
200
300
400
500
600
700
Time, d
40% Silane Sealer
2
3
4
5
6
7

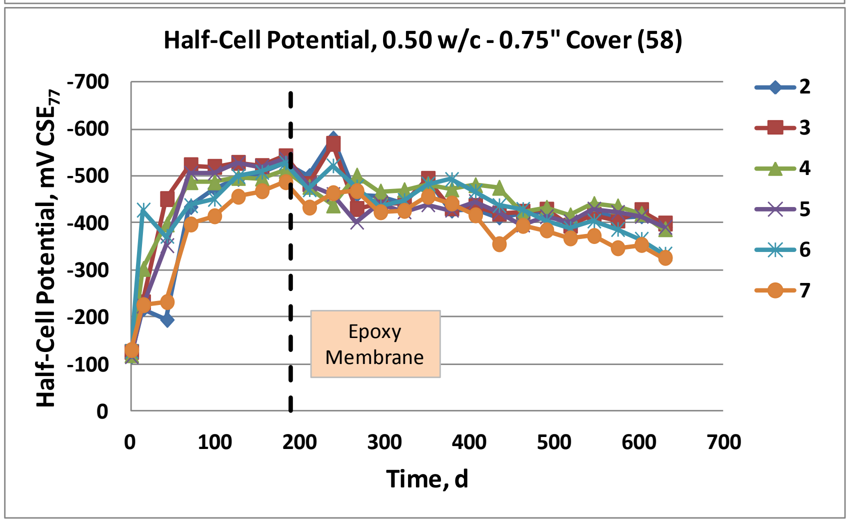

Integrated Current, 0.50 w/c - 0.75" Cover (55)
Integrated Macrocell Current, C
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
100
200
300
400
500
600
700
Time, d
40% Silane Sealer
2
3
4
5
6
7

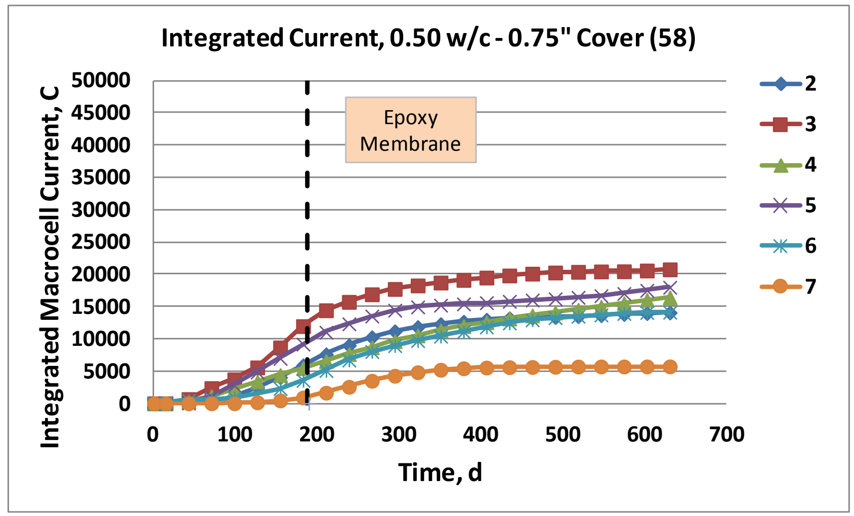

Half-Cell Potential, 0.50 w/c - 0.75" Cover (56)
Half-Cell Potential, mV CSE_{77}
-700
-600
-500
-400
-300
-200
-100
0
0
100
200
300
400
500
600
700
Time, d
Control
2
3
4
5
6
7

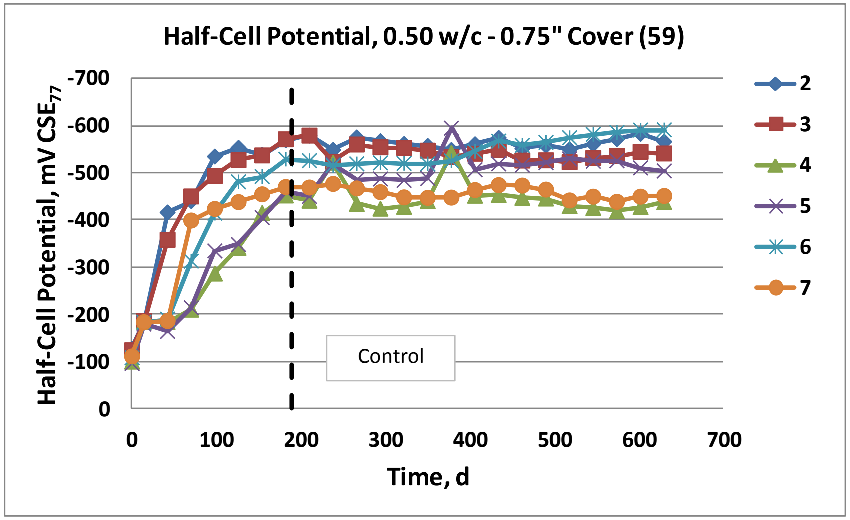

Integrated Current, 0.50 w/c - 0.75" Cover (56)
Integrated Macrocell Current, C
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
100
200
300
400
500
600
700
Time, d
Control
2
3
4
5
6
7

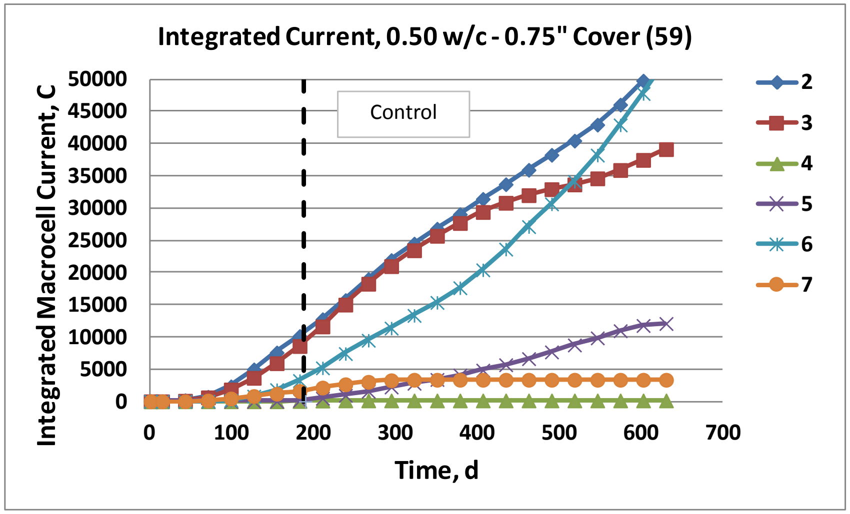

Half-Cell Potential, 0.50 w/c - 0.75" Cover (57)
Half-Cell Potential, mV CSE_{77}
Time, d
Control
2
3
4
5
6
7

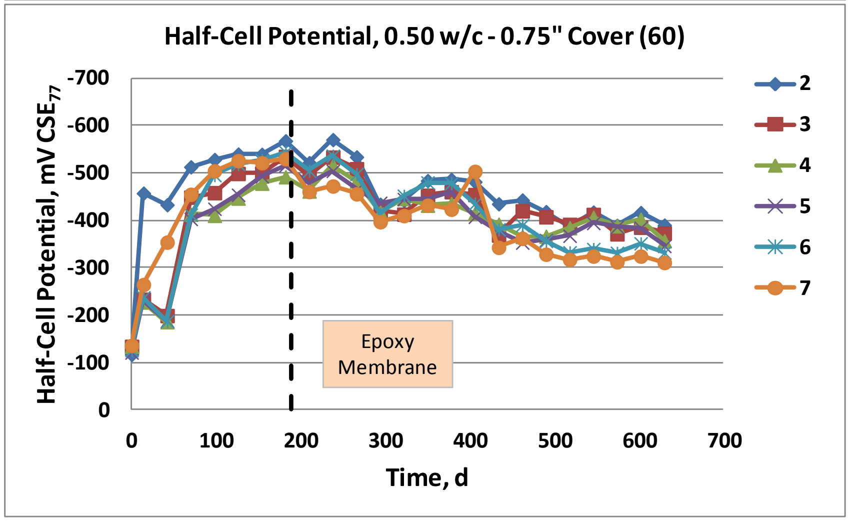

Integrated Current, 0.50 w/c - 0.75" Cover (57)
Integrated Macrocell Current, C
Time, d
Control
2
3
4
5
6
7

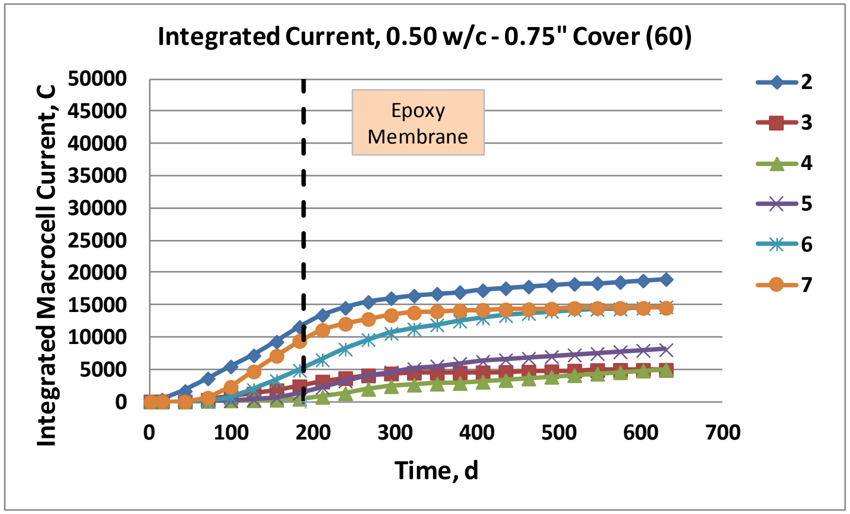

Half-Cell Potential, 0.50 w/c - 0.75" Cover (58)
Half-Cell Potential, mV CSE_{77}
Time, d
Epoxy Membrane
2
3
4
5
6
7


Integrated Current, 0.50 w/c - 0.75" Cover (58)
Integrated Macrocell Current, C
Time, d
Epoxy Membrane
2
3
4
5
6
7

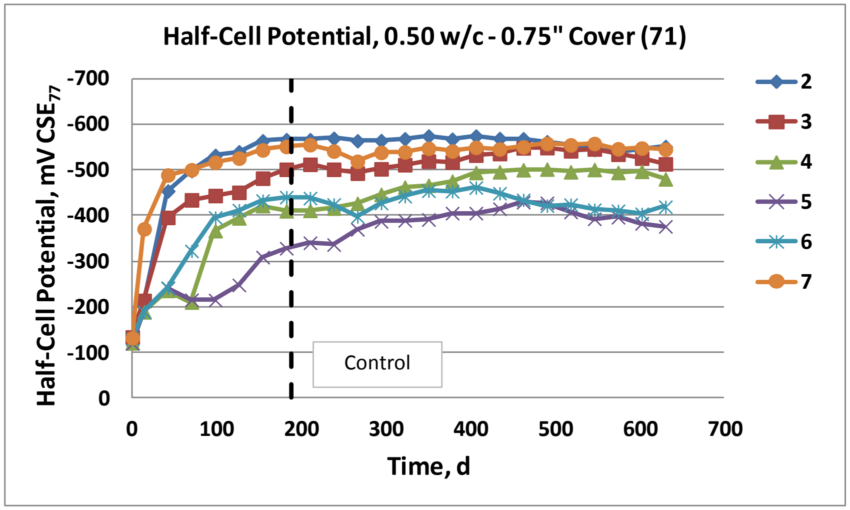

Half-Cell Potential, 0.50 w/c - 0.75" Cover (59)
Half-Cell Potential, mV CSE_{77}
Time, d
Control
2
3
4
5
6
7

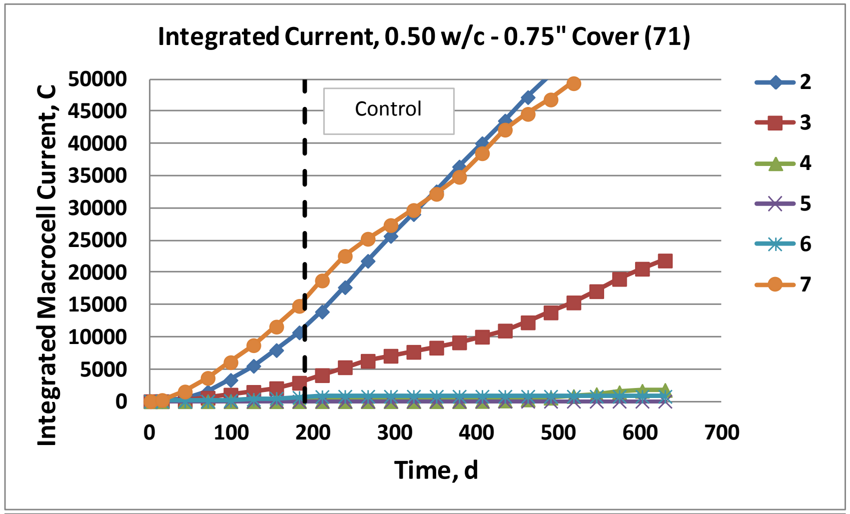

Integrated Current, 0.50 w/c - 0.75" Cover (59)
Integrated Macrocell Current, C
Time, d
Control
2
3
4
5
6
7

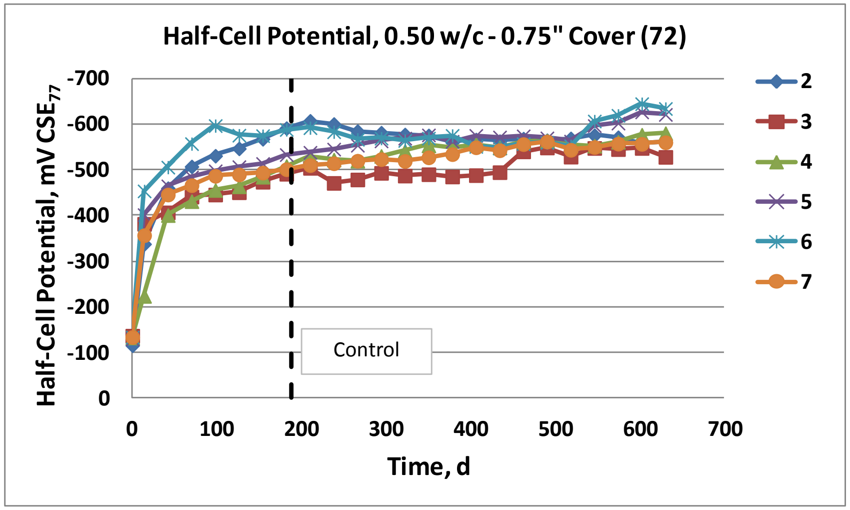

Half-Cell Potential, 0.50 w/c - 0.75" Cover (60)
Half-Cell Potential, mV CSE_{77}
Time, d
Epoxy Membrane
2
3
4
5
6
7

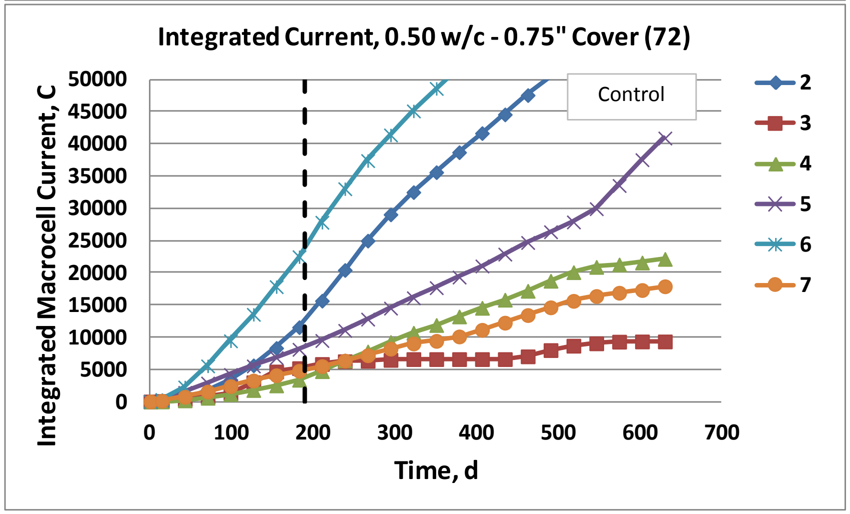

Integrated Current, 0.50 w/c - 0.75" Cover (60)
Integrated Macrocell Current, C
Time, d
Epoxy Membrane
2
3
4
5
6
7

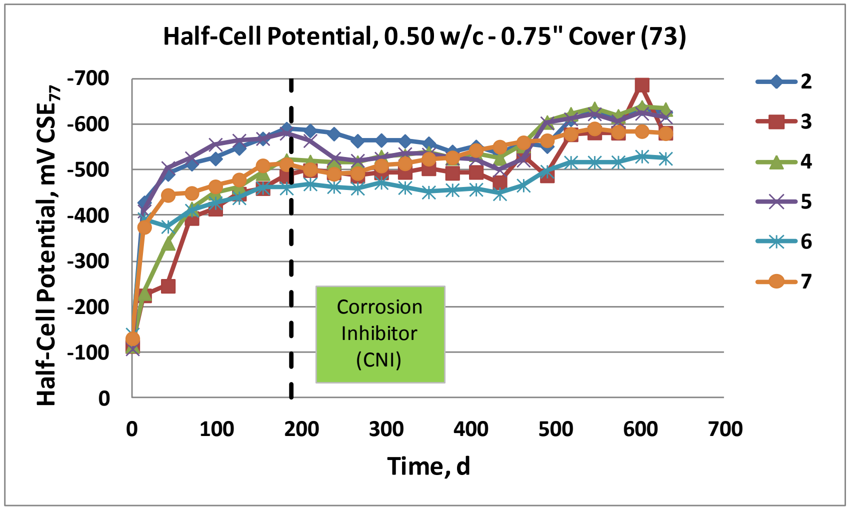
Batch #4

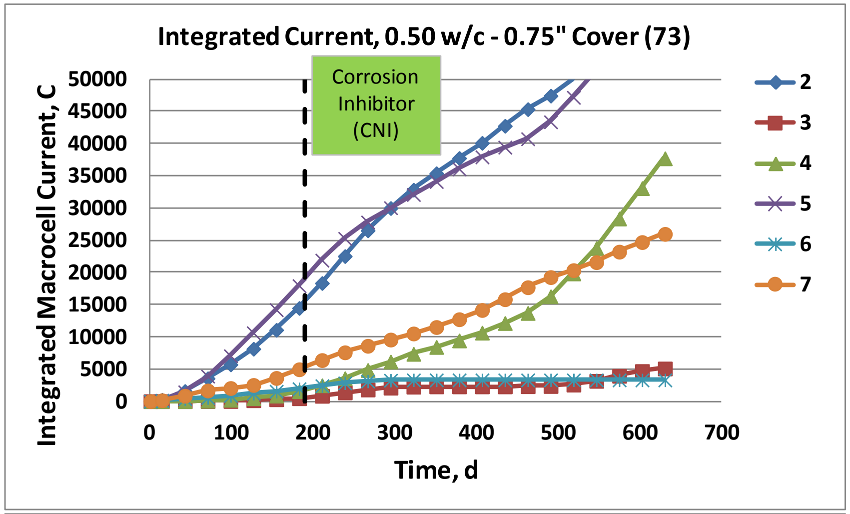

Half-Cell Potential, 0.50 w/c - 0.75" Cover (71)
Half-Cell Potential, mV CSE_{77}
Time, d
Control
2
3
4
5
6
7

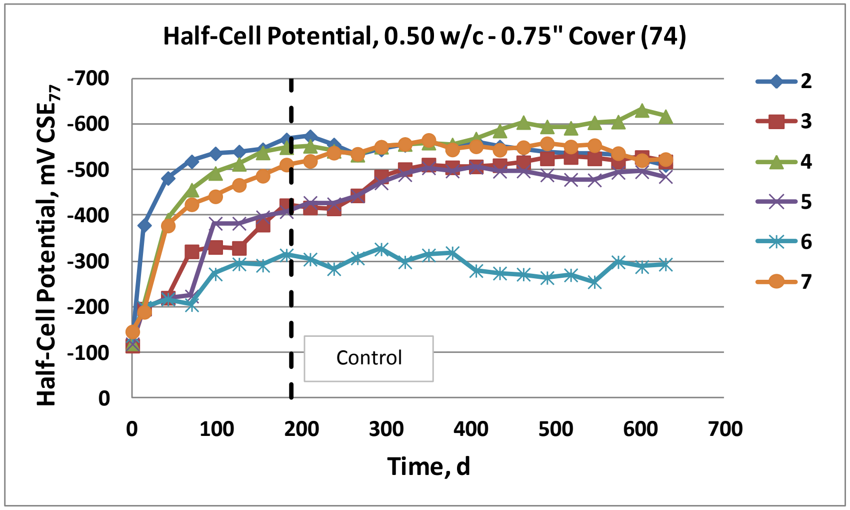

Integrated Current, 0.50 w/c - 0.75" Cover (71)
Integrated Macrocell Current, C
Time, d
Control
2
3
4
5
6
7

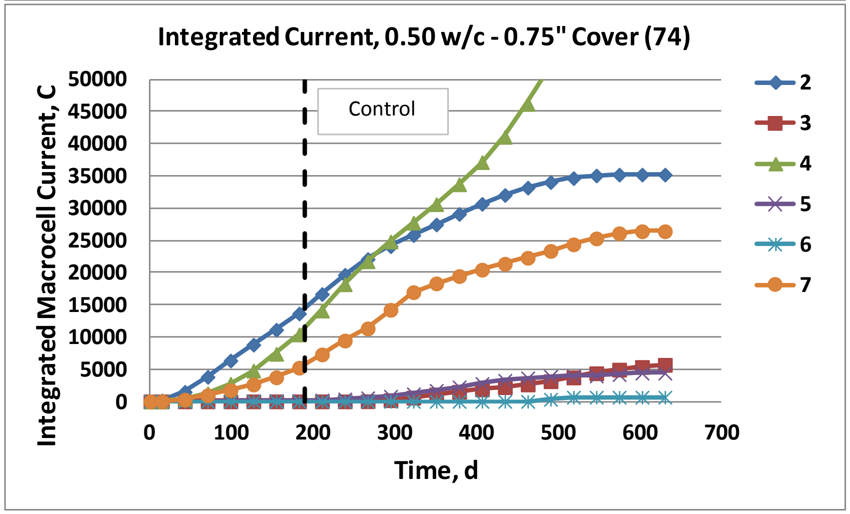

Half-Cell Potential, 0.50 w/c - 0.75" Cover (72)
Half-Cell Potential, mV CSE_{77}
Time, d
Control
2
3
4
5
6
7

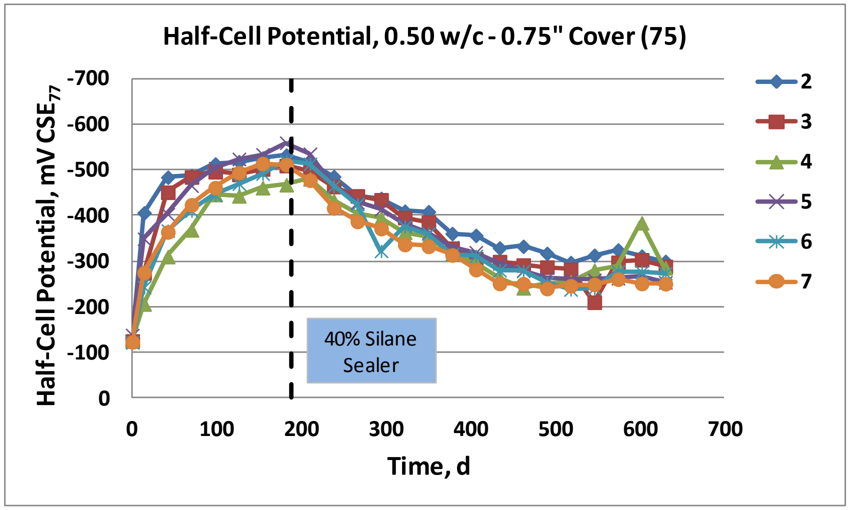

Integrated Current, 0.50 w/c - 0.75" Cover (72)
Integrated Macrocell Current, C
Time, d
Control
2
3
4
5
6
7

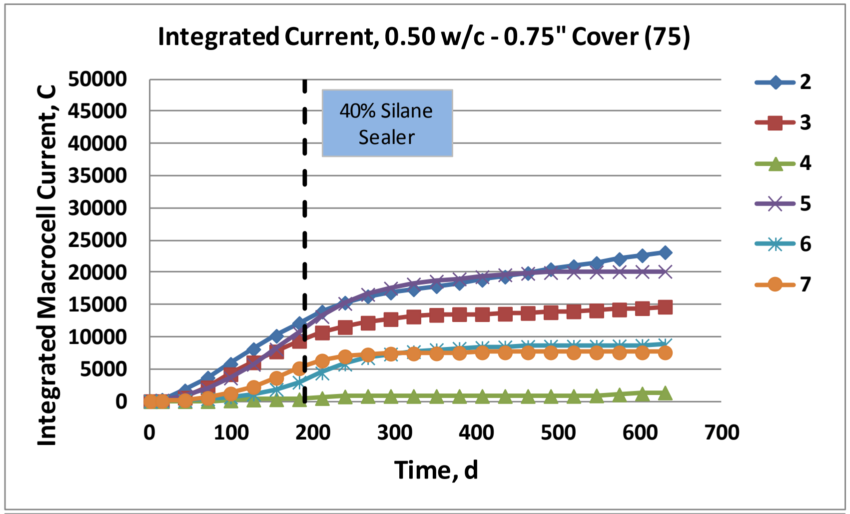

Half-Cell Potential, 0.50 w/c - 0.75" Cover (73)
Half-Cell Potential, mV CSE77
Time, d
Corrosion Inhibitor (CNI)
2
3
4
5
6
7

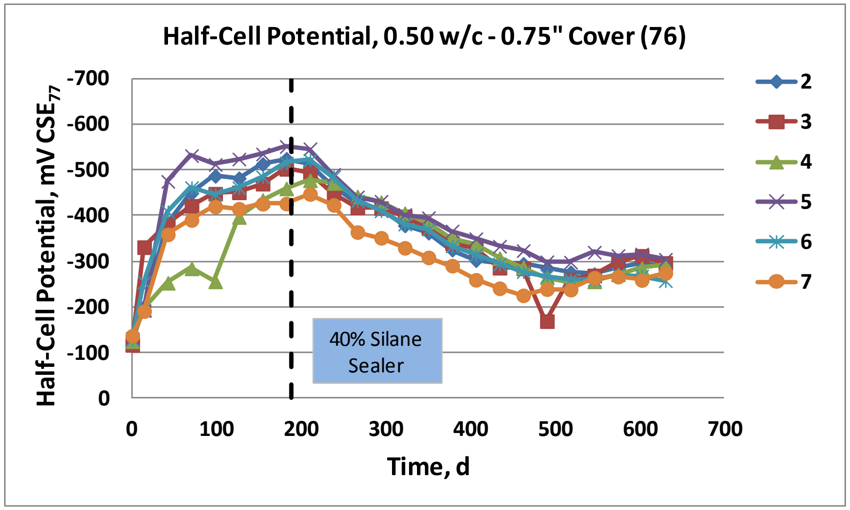

Integrated Current, 0.50 w/c - 0.75" Cover (73)
Integrated Macrocell Current, C
Time, d
Corrosion Inhibitor (CNI)
2
3
4
5
6
7

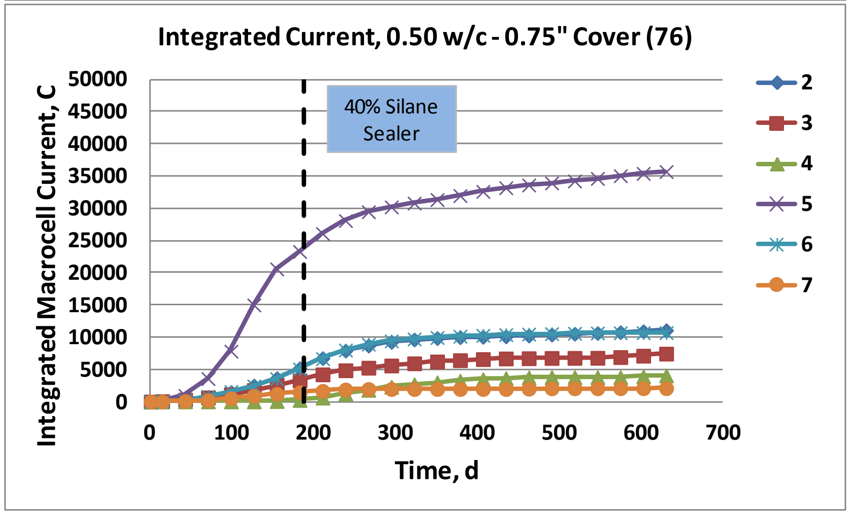

Half-Cell Potential, 0.50 w/c - 0.75" Cover (74)
Half-Cell Potential, mV CSE77
Time, d
Control
2
3
4
5
6
7

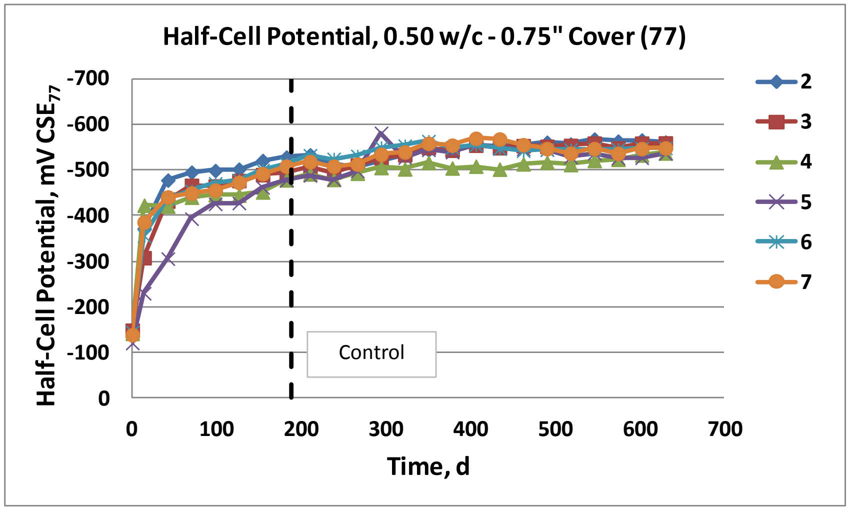

Integrated Current, 0.50 w/c - 0.75" Cover (74)
Integrated Macrocell Current, C
Time, d
Control
2
3
4
5
6
7

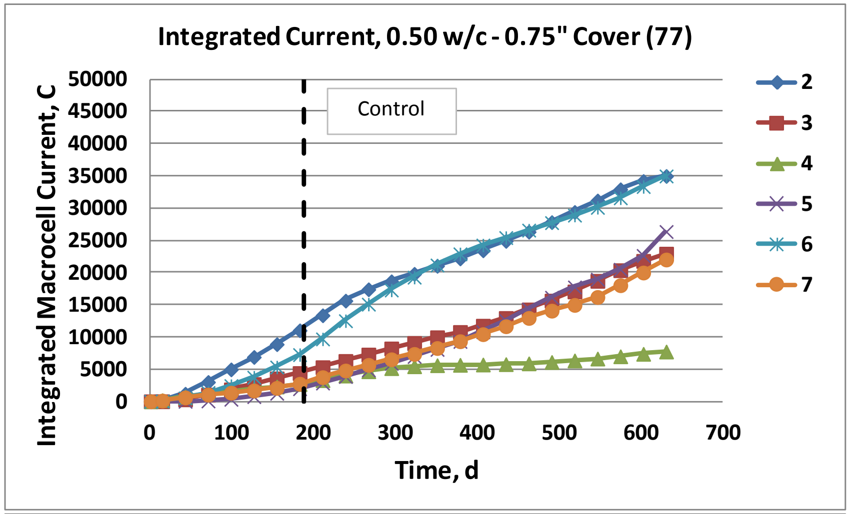

Half-Cell Potential, 0.50 w/c - 0.75" Cover (75)
Half-Cell Potential, mV CSE77
-700
-600
-500
-400
-300
-200
-100
0
0
100
200
300
400
500
600
700
Time, d
40% Silane Sealer
2
3
4
5
6
7

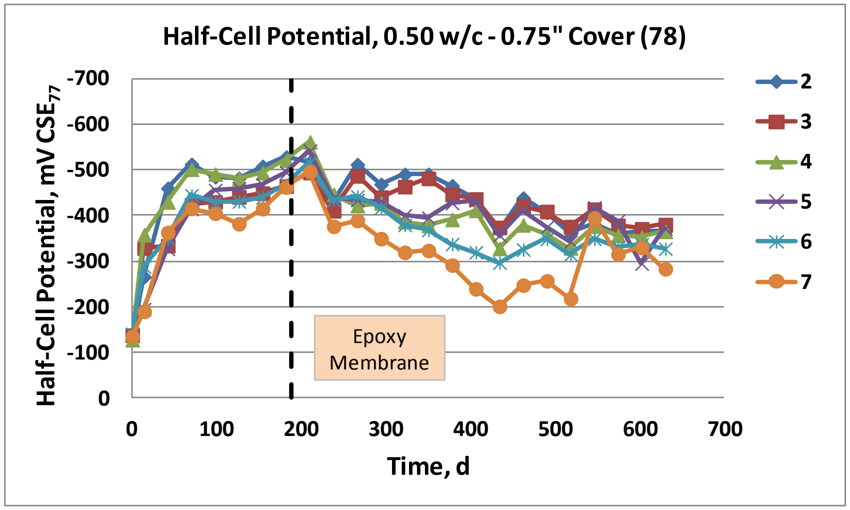

Integrated Current, 0.50 w/c - 0.75" Cover (75)
Integrated Macrocell Current, C
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
100
200
300
400
500
600
700
Time, d
40% Silane Sealer
2
3
4
5
6
7

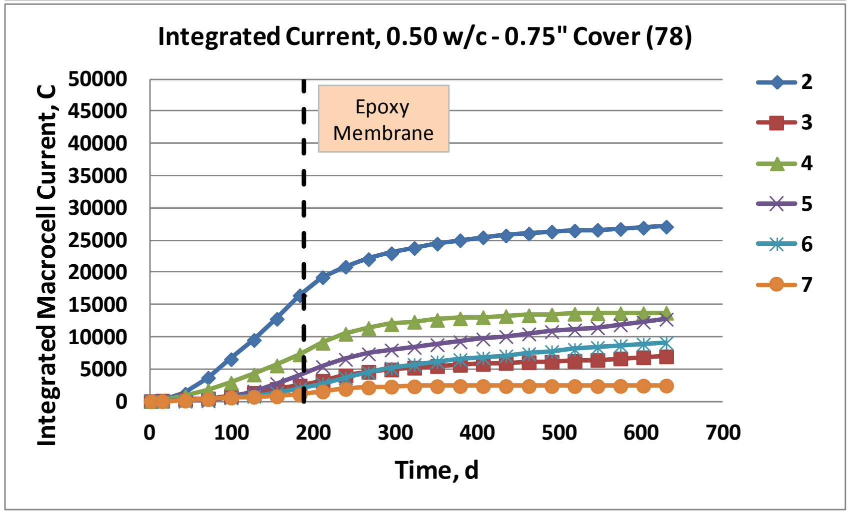

Half-Cell Potential, 0.50 w/c - 0.75" Cover (76)
Half-Cell Potential, mV CSE77
-700
-600
-500
-400
-300
-200
-100
0
0
100
200
300
400
500
600
700
Time, d
40% Silane Sealer
2
3
4
5
6
7

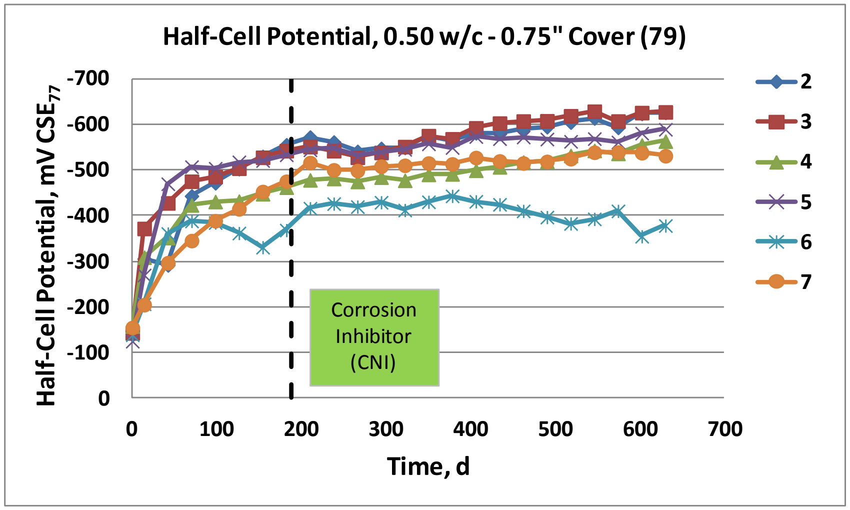

Integrated Current, 0.50 w/c - 0.75" Cover (76)
Integrated Macrocell Current, C
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
100
200
300
400
500
600
700
Time, d
40% Silane Sealer
2
3
4
5
6
7

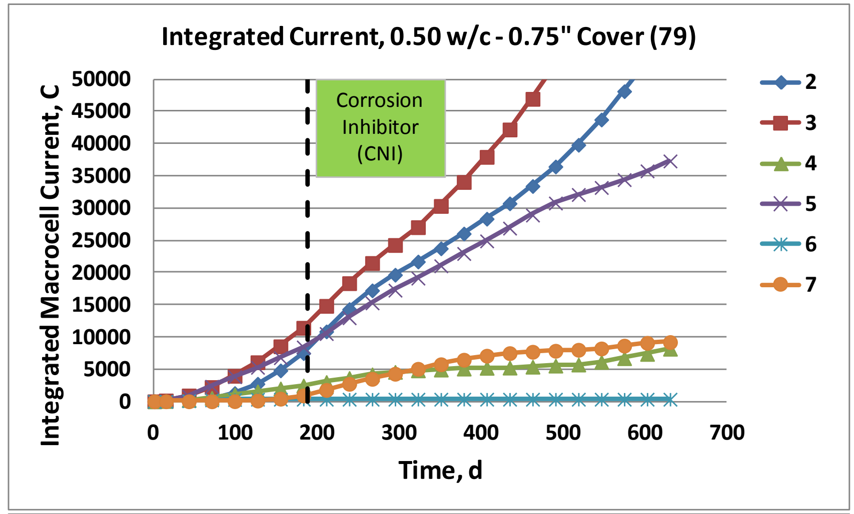

Half-Cell Potential, 0.50 w/c - 0.75" Cover (77)
Half-Cell Potential, mV CSE77
Time, d
Control
2
3
4
5
6
7

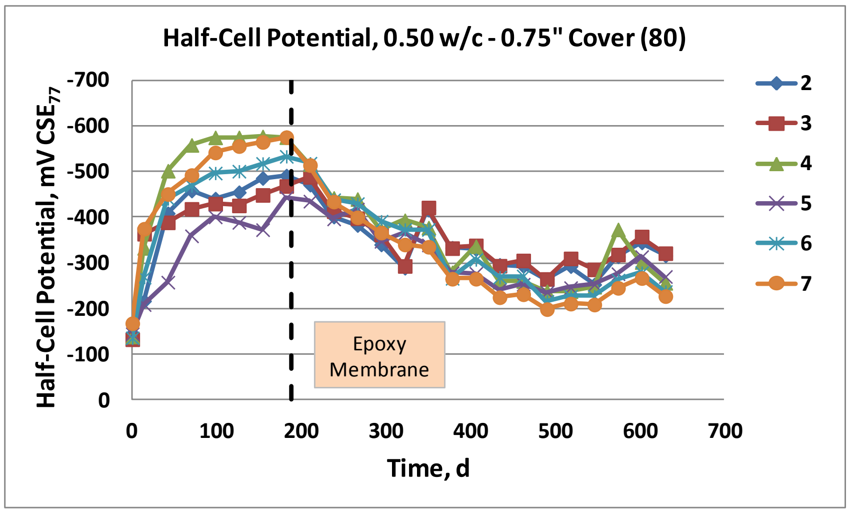

Integrated Current, 0.50 w/c - 0.75" Cover (77)
Integrated Macrocell Current, C
Time, d
Control
2
3
4
5
6
7

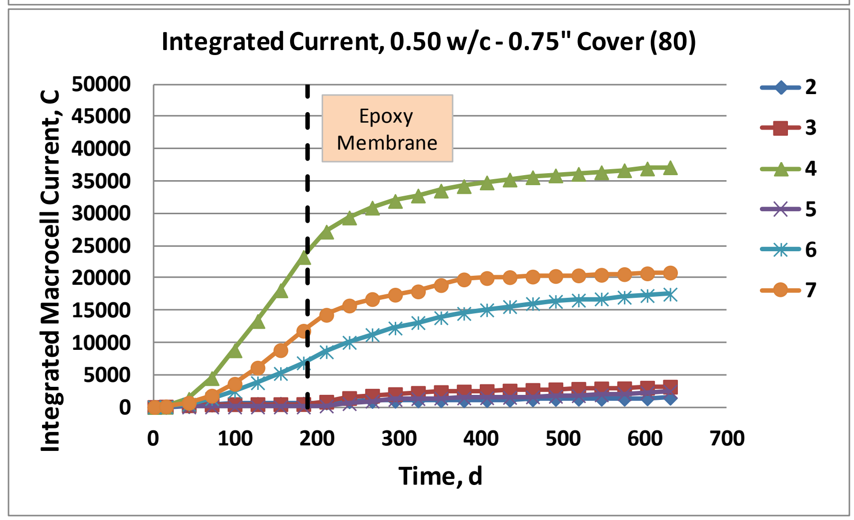

Half-Cell Potential, 0.50 w/c - 0.75" Cover (78)
Half-Cell Potential, mV CSE77
Time, d
Epoxy Membrane
2
3
4
5
6
7


Integrated Current, 0.50 w/c - 0.75" Cover (78)
Integrated Macrocell Current, C
Time, d
Epoxy Membrane
2
3
4
5
6
7

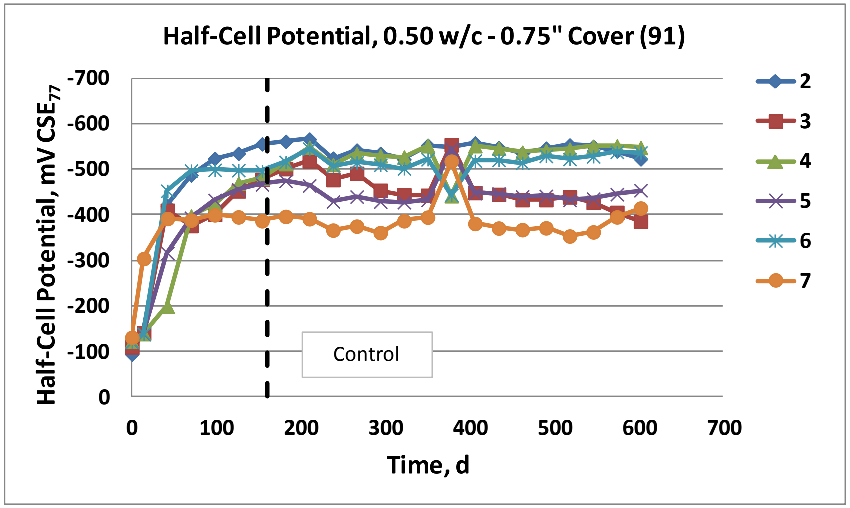

Half-Cell Potential, 0.50 w/c - 0.75" Cover (79)
Half-Cell Potential, mV CSE_{77}
-700
-600
-500
-400
-300
-200
-100
0
0
100
200
300
400
500
600
700
Time, d
Corrosion Inhibitor (CNI)
2
3
4
5
6
7

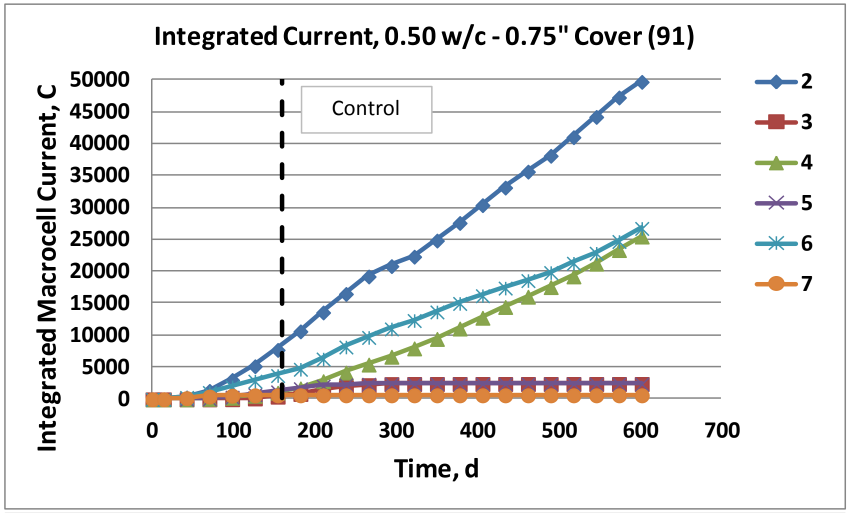

Integrated Current, 0.50 w/c - 0.75" Cover (79)
Integrated Macrocell Current, C
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
100
200
300
400
500
600
700
Time, d
Corrosion Inhibitor (CNI)
2
3
4
5
6
7

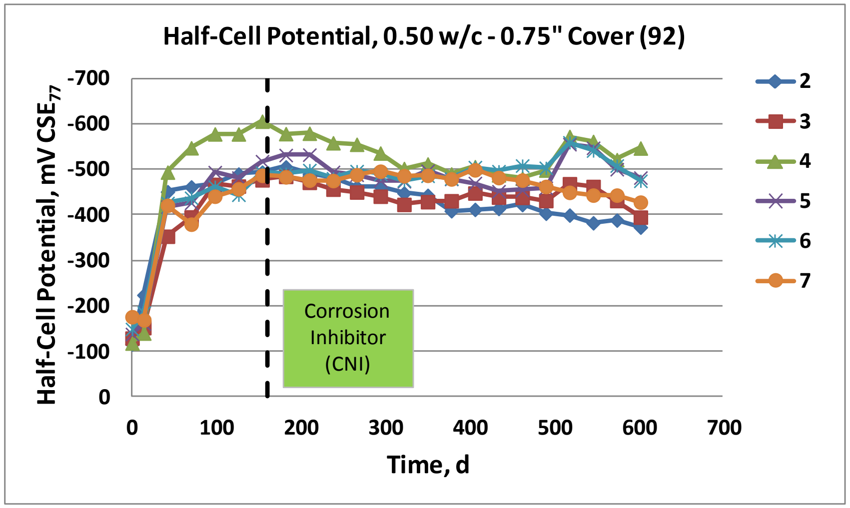

Half-Cell Potential, 0.50 w/c - 0.75" Cover (80)
Half-Cell Potential, mV CSE_{77}
-700
-600
-500
-400
-300
-200
-100
0
0
100
200
300
400
500
600
700
Time, d
Epoxy Membrane
2
3
4
5
6
7

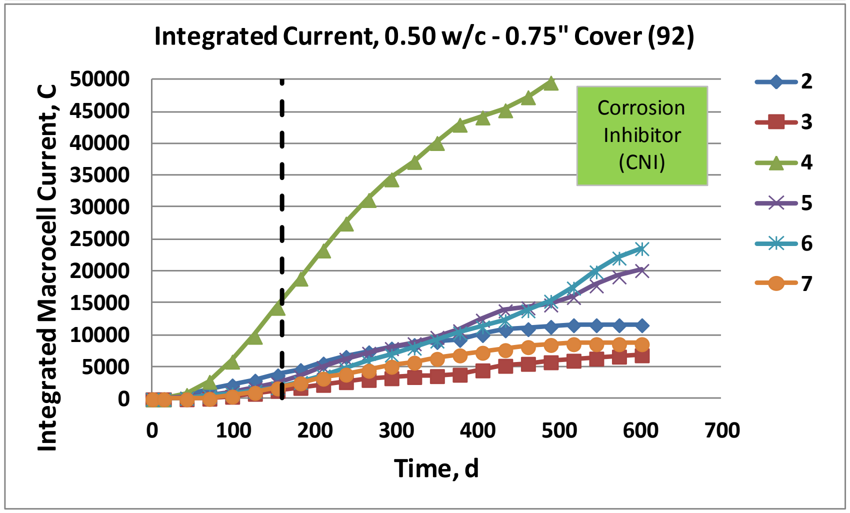

Integrated Current, 0.50 w/c - 0.75" Cover (80)
Integrated Macrocell Current, C
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
100
200
300
400
500
600
700
Time, d
Epoxy Membrane
2
3
4
5
6
7

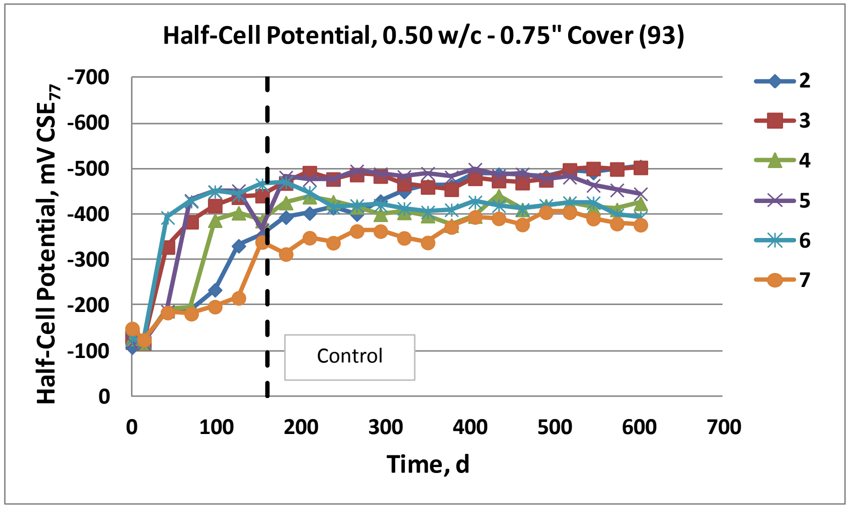
Batch #5

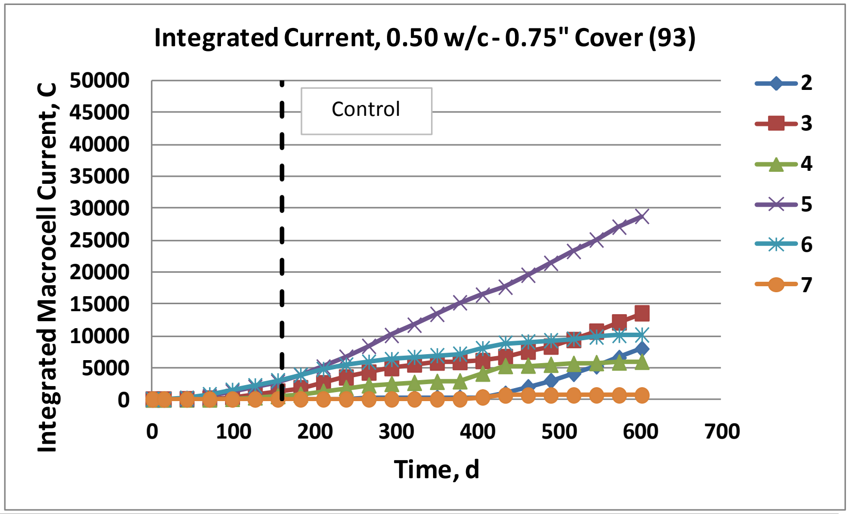

Half-Cell Potential, 0.50 w/c - 0.75" Cover (91)
Half-Cell Potential, mV CSE_{77}
Time, d
Control
2
3
4
5
6
7

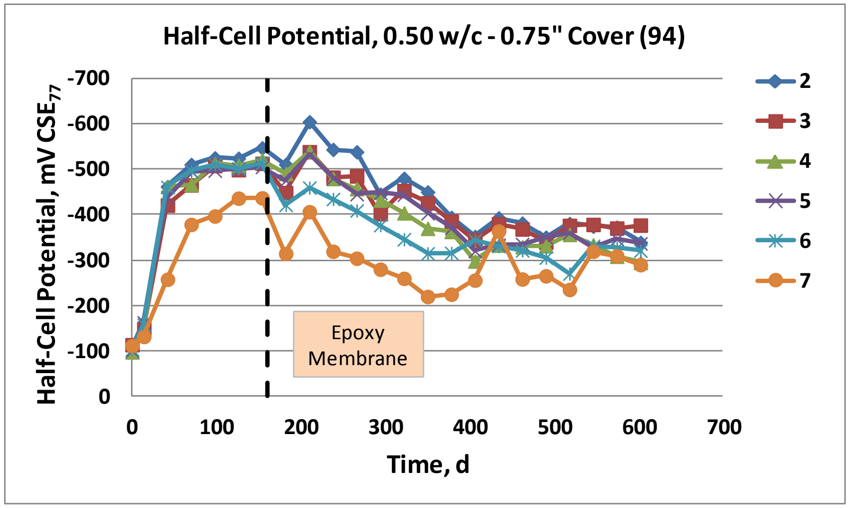

Integrated Current, 0.50 w/c - 0.75" Cover (91)
Integrated Macrocell Current, C
Time, d
Control
2
3
4
5
6
7

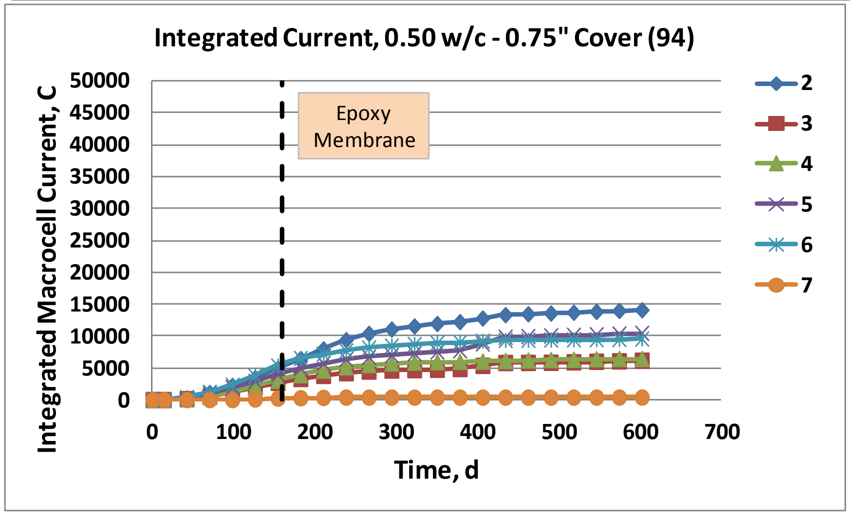

Half-Cell Potential, 0.50 w/c - 0.75" Cover (92)
Half-Cell Potential, mV CSE_{77}
Time, d
Corrosion Inhibitor (CNI)
2
3
4
5
6
7

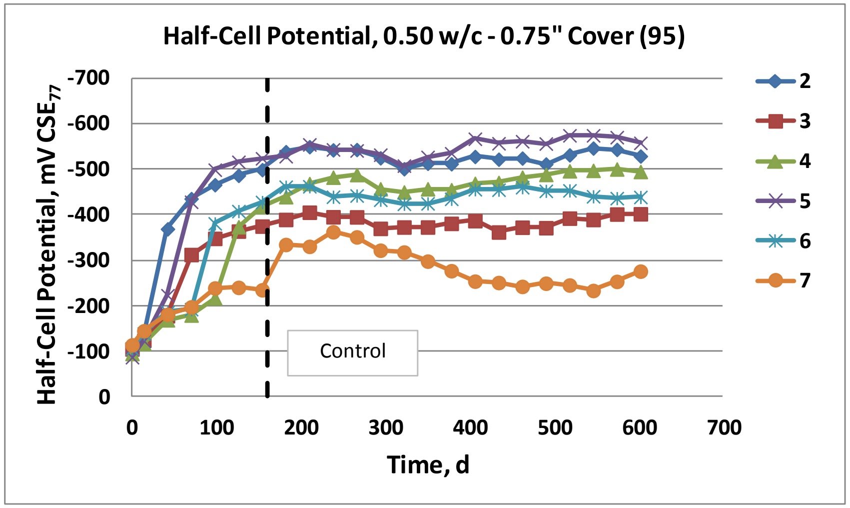

Integrated Current, 0.50 w/c - 0.75" Cover (92)
Integrated Macrocell Current, C
Time, d
Corrosion Inhibitor (CNI)
2
3
4
5
6
7

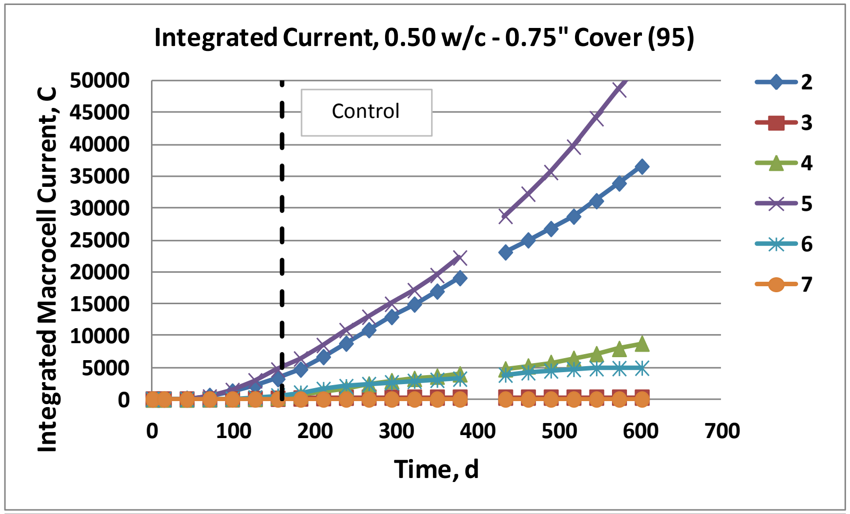

Half-Cell Potential, 0.50 w/c - 0.75" Cover (93)
Half-Cell Potential, mV CSE_{77}
-700
-600
-500
-400
-300
-200
-100
0
0
100
200
300
400
500
600
700
Time, d
Control
2
3
4
5
6
7

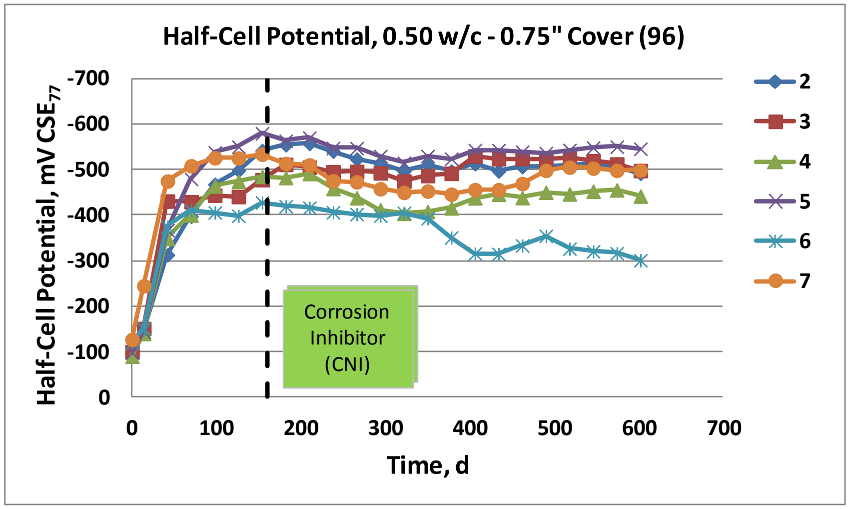

Integrated Current, 0.50 w/c - 0.75" Cover (93)
Integrated Macrocell Current, C
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
100
200
300
400
500
600
700
Time, d
Control
2
3
4
5
6
7

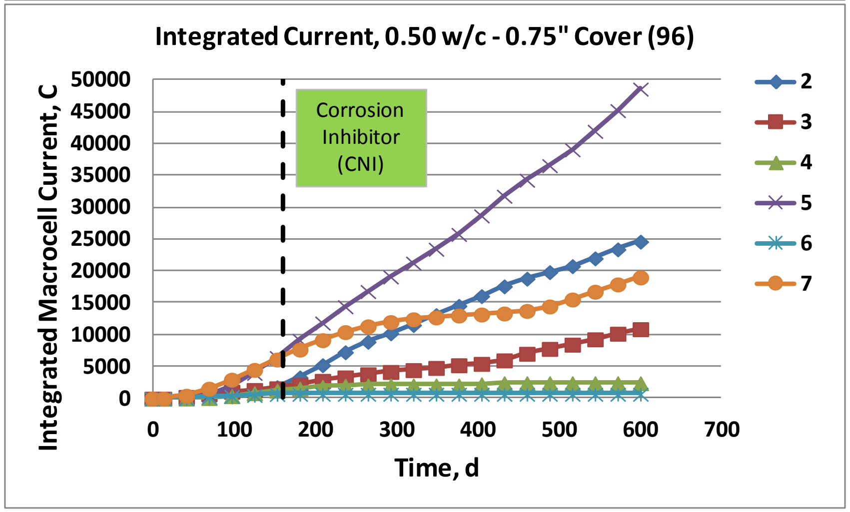

Half-Cell Potential, 0.50 w/c - 0.75" Cover (94)
Half-Cell Potential, mV CSE_{77}
-700
-600
-500
-400
-300
-200
-100
0
0
100
200
300
400
500
600
700
Time, d
Epoxy Membrane
2
3
4
5
6
7

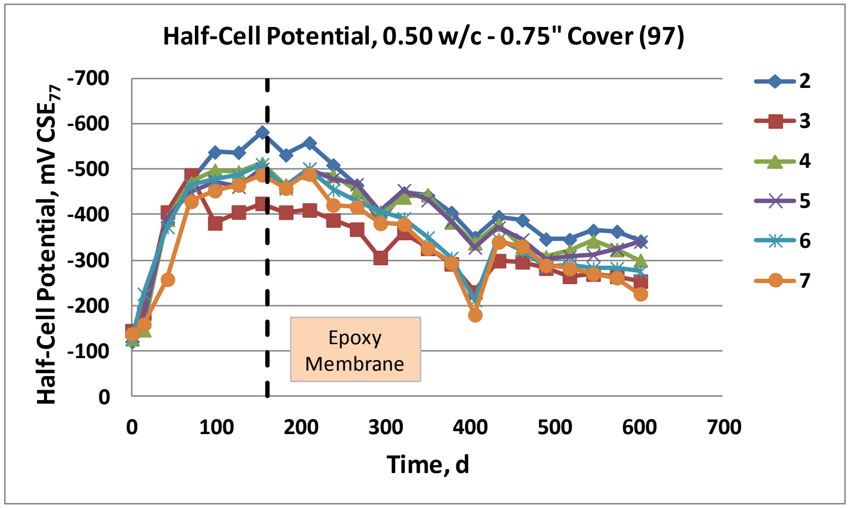

Integrated Current, 0.50 w/c - 0.75" Cover (94)
Integrated Macrocell Current, C
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
100
200
300
400
500
600
700
Time, d
Epoxy Membrane
2
3
4
5
6
7

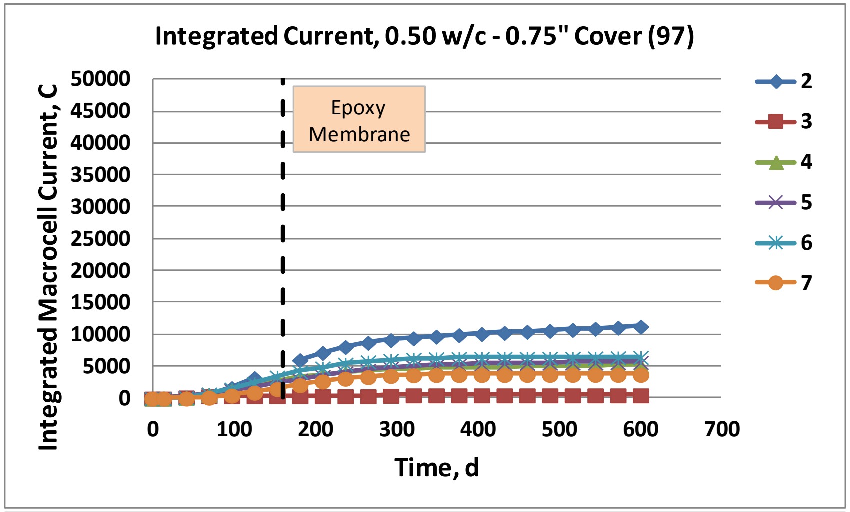

Half-Cell Potential, 0.50 w/c - 0.75" Cover (95)
Half-Cell Potential, mV CSE_{77}
Time, d
Control
2
3
4
5
6
7

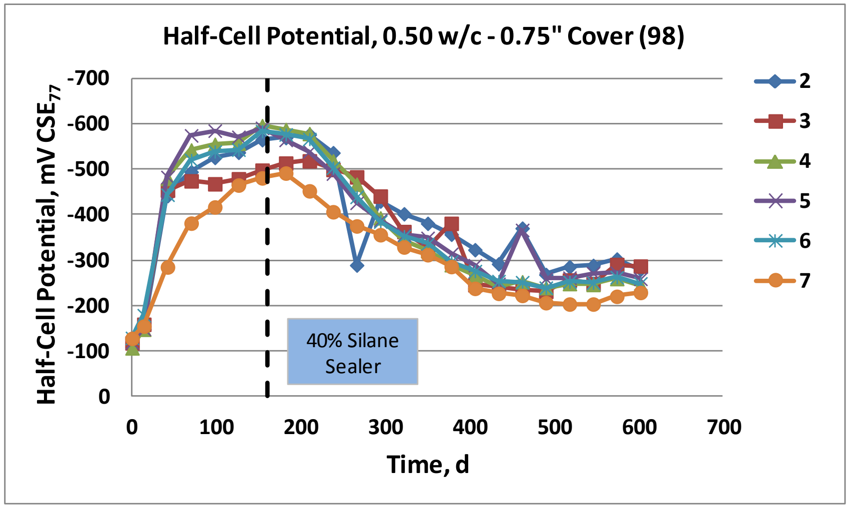

Integrated Current, 0.50 w/c - 0.75" Cover (95)
Integrated Macrocell Current, C
Time, d
Control
2
3
4
5
6
7

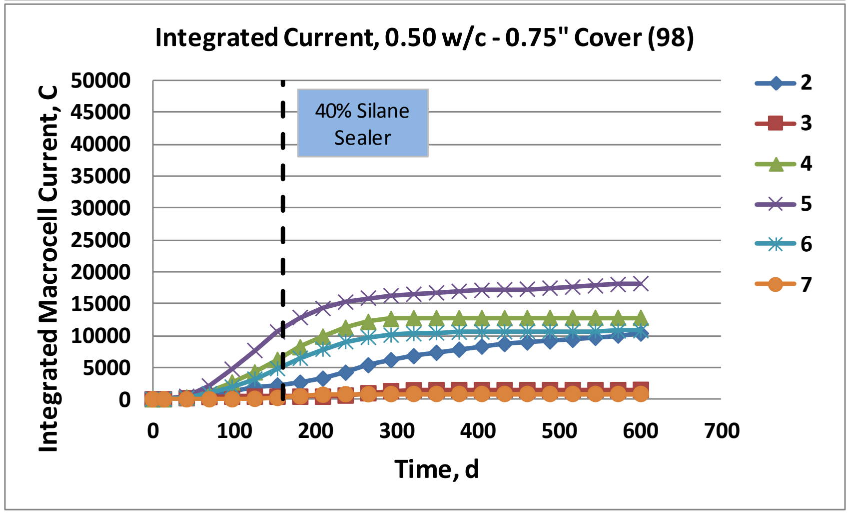

Half-Cell Potential, 0.50 w/c - 0.75" Cover (96)
Half-Cell Potential, mV CSE_{77}
Time, d
Corrosion Inhibitor (CNI)
2
3
4
5
6
7

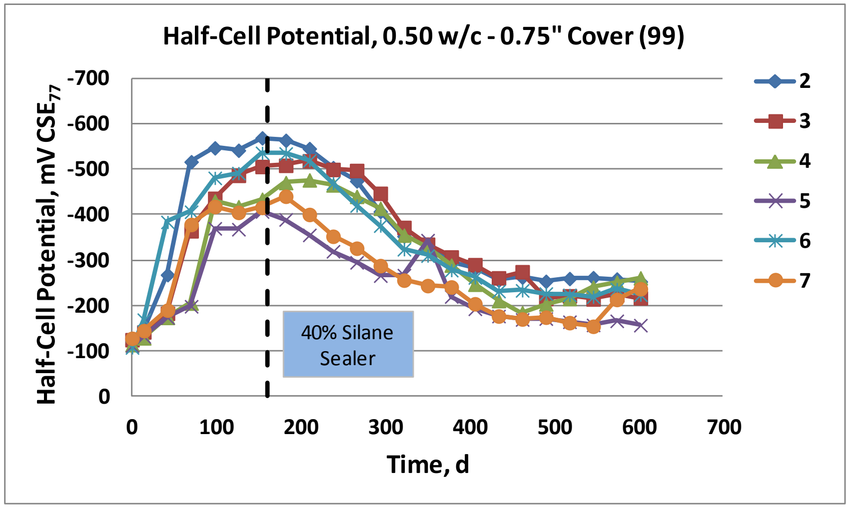

Integrated Current, 0.50 w/c - 0.75" Cover (96)
Integrated Macrocell Current, C
Time, d
Corrosion Inhibitor (CNI)
2
3
4
5
6
7

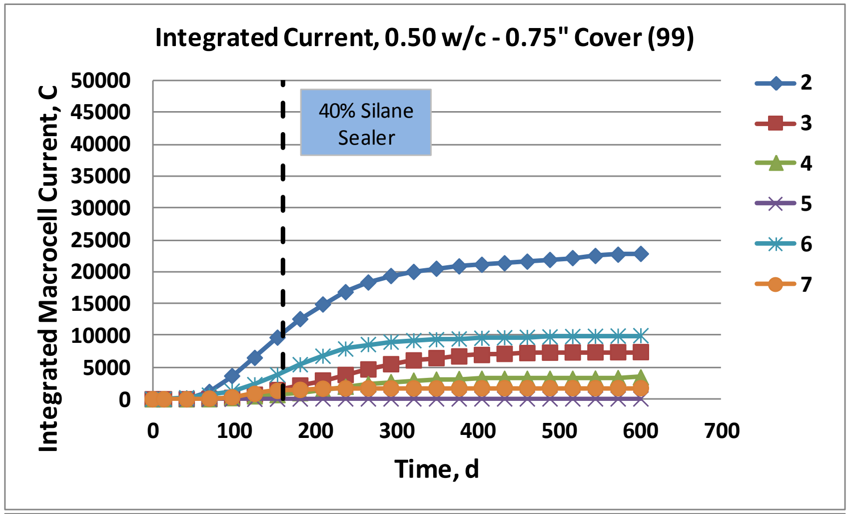

Half-Cell Potential, 0.50 w/c - 0.75" Cover (97)
Half-Cell Potential, mV CSE77
Time, d
Epoxy Membrane
2
3
4
5
6
7

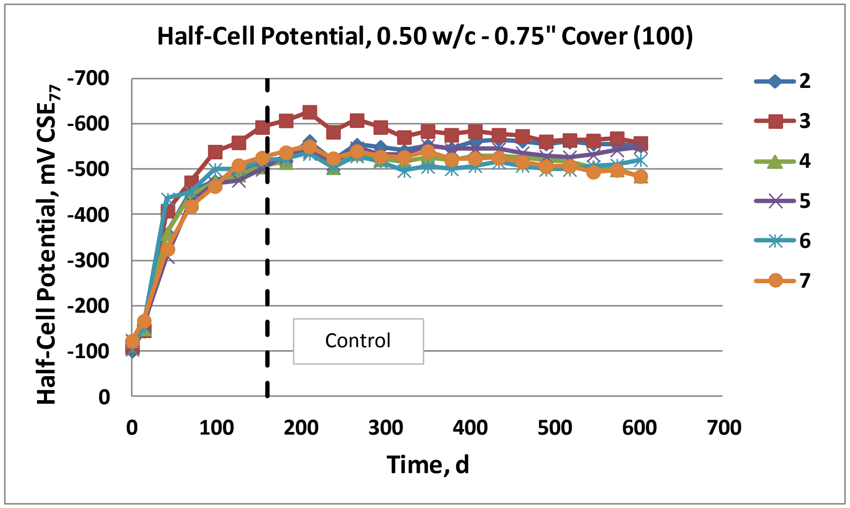

Integrated Current, 0.50 w/c - 0.75" Cover (97)
Integrated Macrocell Current, C
Time, d
Epoxy Membrane
2
3
4
5
6
7

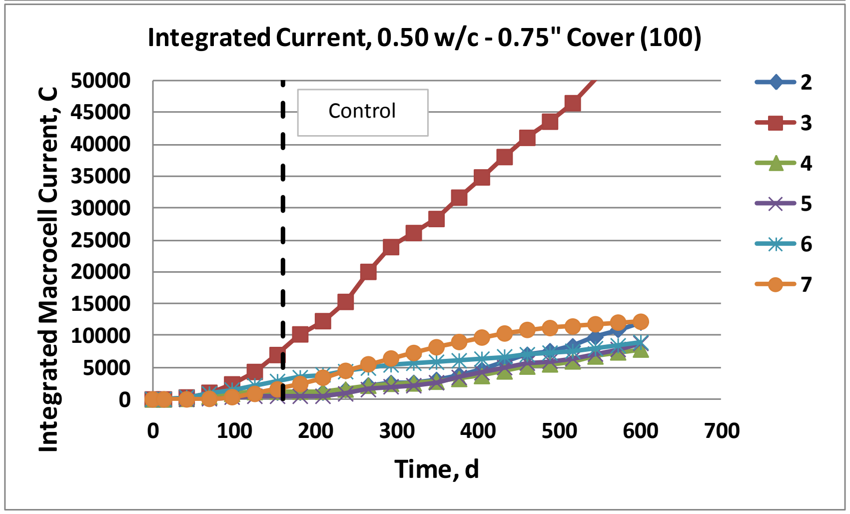

Half-Cell Potential, 0.50 w/c - 0.75" Cover (98)
Half-Cell Potential, mV CSE77
Time, d
40% Silane Sealer
2
3
4
5
6
7


Integrated Current, 0.50 w/c - 0.75" Cover (98)
Integrated Macrocell Current, C
Time, d
40% Silane Sealer
2
3
4
5
6
7


Half-Cell Potential, 0.50 w/c - 0.75" Cover (99)
Half-Cell Potential, mV CSE77
-700
-600
-500
-400
-300
-200
-100
0
0
100
200
300
400
500
600
700
Time, d
40% Silane Sealer
2
3
4
5
6
7

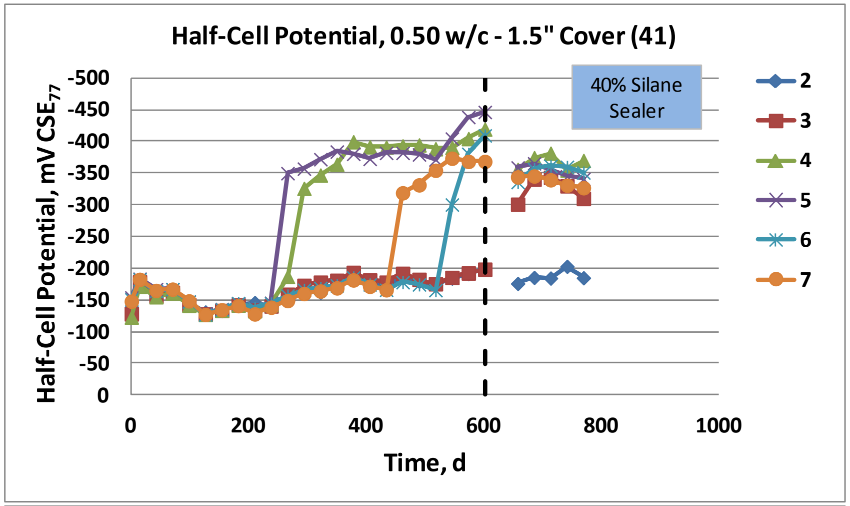

Integrated Current, 0.50 w/c - 0.75" Cover (99)
Integrated Macrocell Current, C
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
100
200
300
400
500
600
700
Time, d
40% Silane Sealer
2
3
4
5
6
7

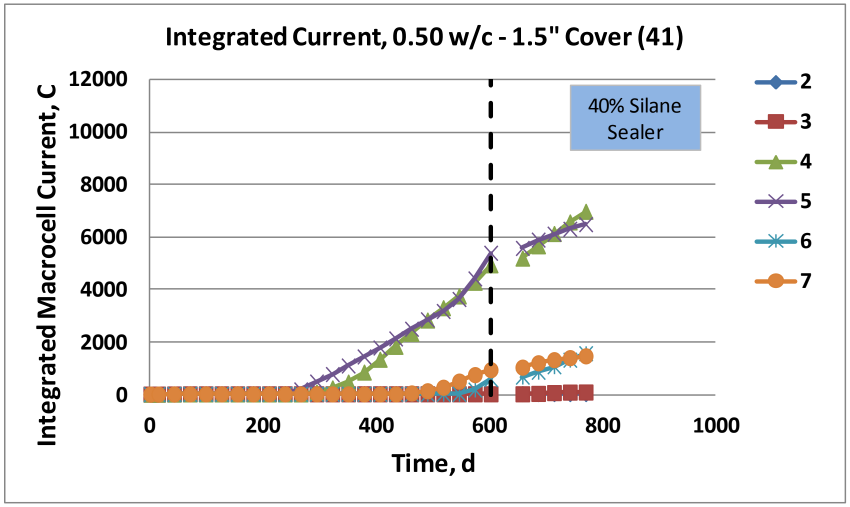

Half-Cell Potential, 0.50 w/c - 0.75" Cover (100)
Half-Cell Potential, mV CSE77
-700
-600
-500
-400
-300
-200
-100
0
0
100
200
300
400
500
600
700
Time, d
Control
2
3
4
5
6
7

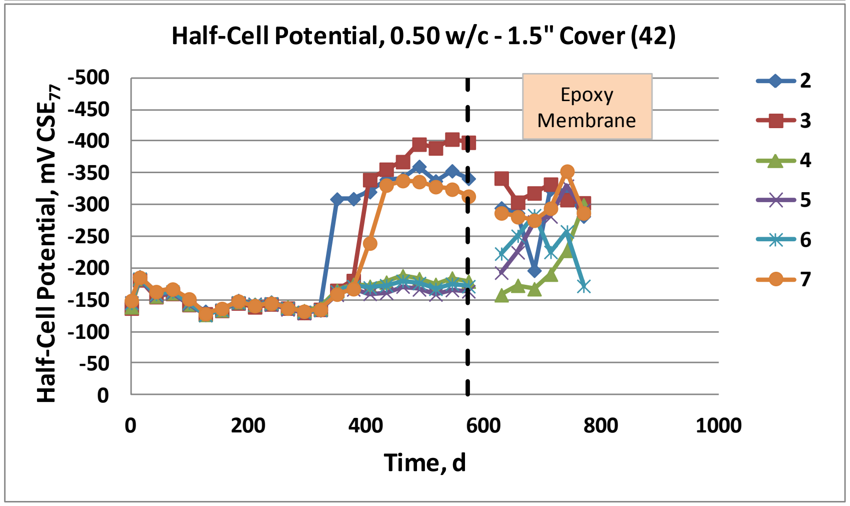

Integrated Current, 0.50 w/c - 0.75" Cover (100)
Integrated Macrocell Current, C
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
100
200
300
400
500
600
700
Time, d
Control
2
3
4
5
6
7

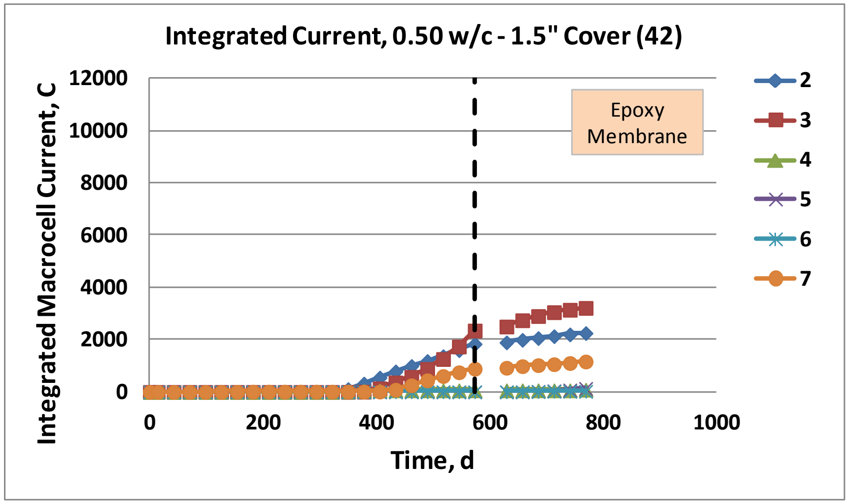
1.5-inch Cover Topical Treatment Slabs

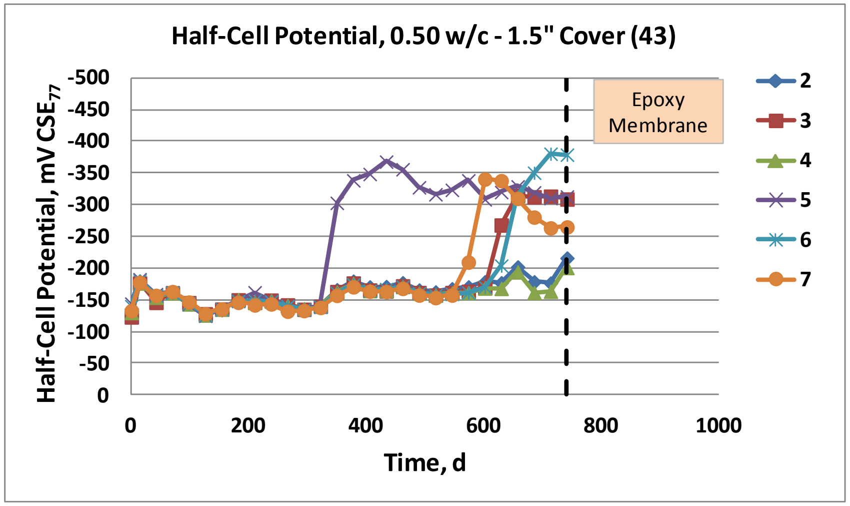
Batch #3

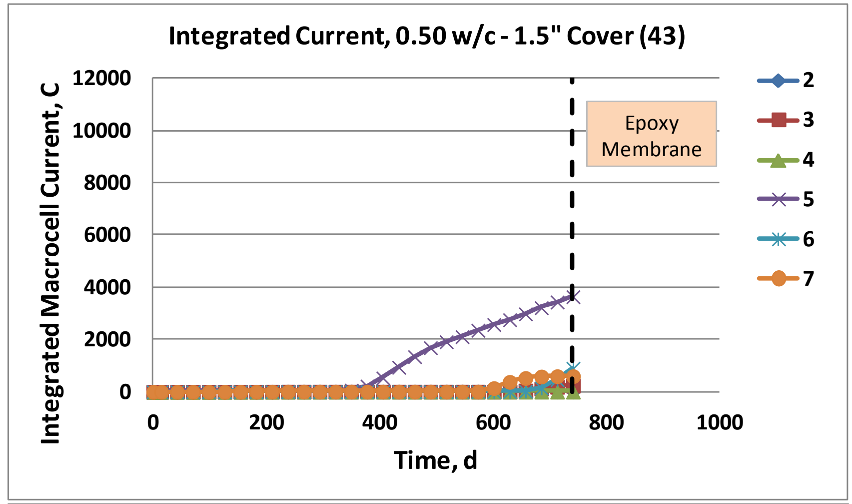


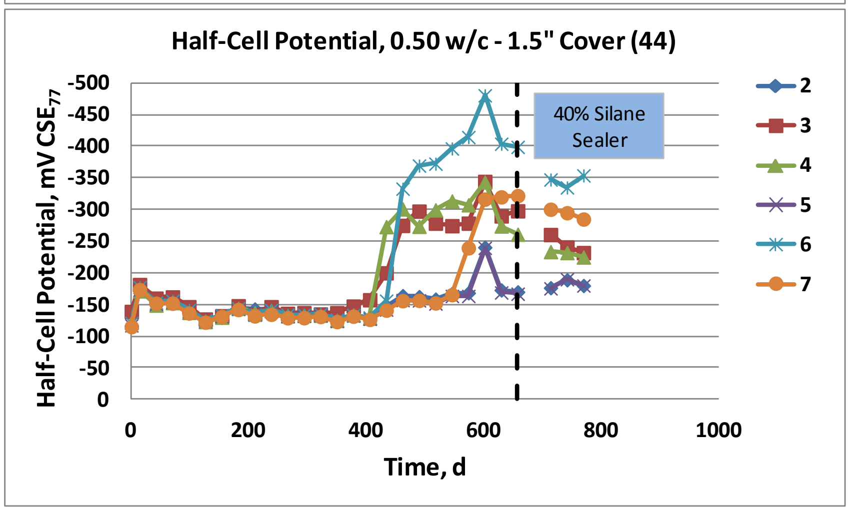


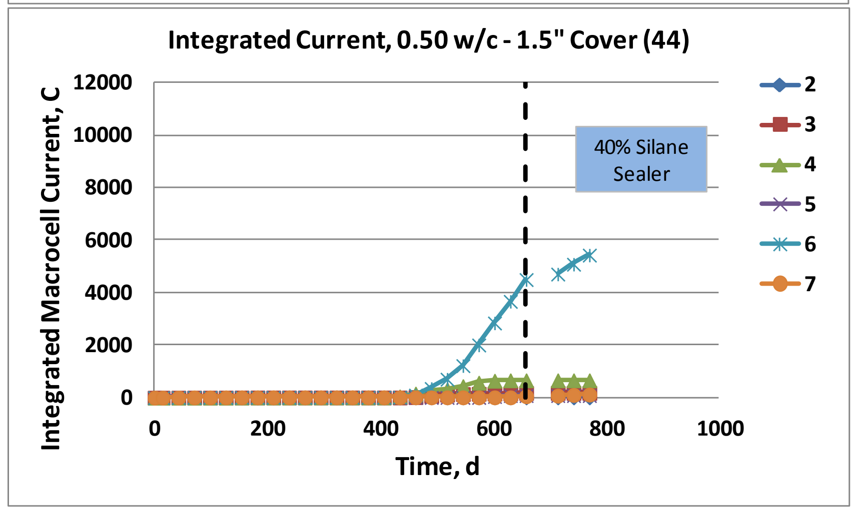


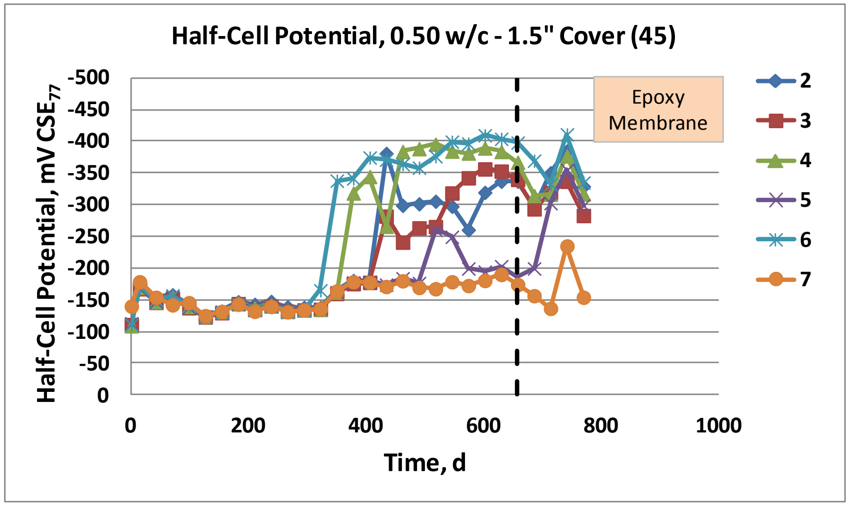


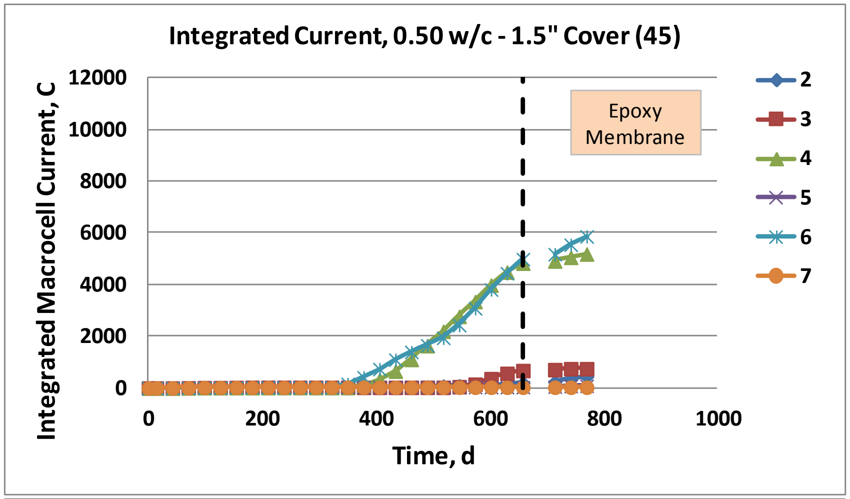

Half-Cell Potential, 0.50 w/c - 1.5" Cover (43)
Epoxy Membrane
Half-Cell Potential, mV CSE_{77}
Time, d
-500
-450
-400
-350
-300
-250
-200
-150
-100
-50
0
0
200
400
600
800
1000
2
3
4
5
6
7

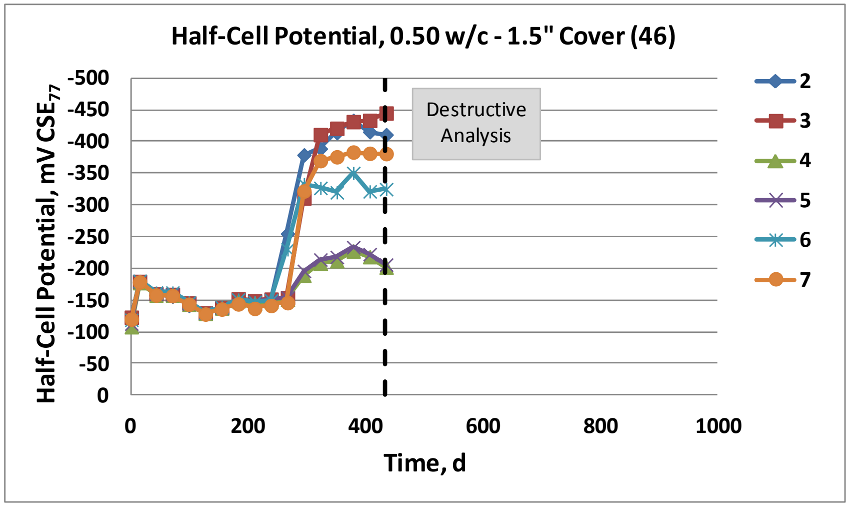

Integrated Current, 0.50 w/c - 1.5" Cover (43)
Epoxy Membrane
Integrated Macrocell Current, C
Time, d
12000
10000
8000
6000
4000
2000
0
0
200
400
600
800
1000
2
3
4
5
6
7

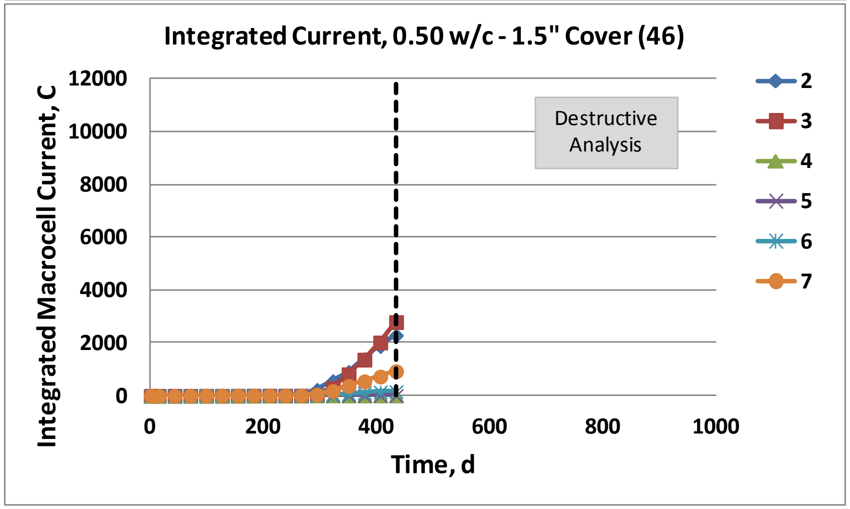

Half-Cell Potential, 0.50 w/c - 1.5" Cover (44)
40% Silane Sealer
Half-Cell Potential, mV CSE_{77}
Time, d
-500
-450
-400
-350
-300
-250
-200
-150
-100
-50
0
0
200
400
600
800
1000
2
3
4
5
6
7

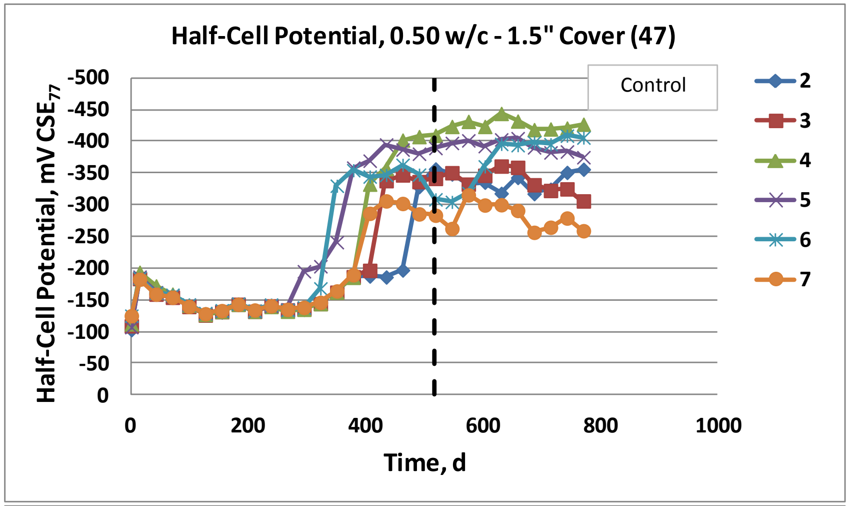

Integrated Current, 0.50 w/c - 1.5" Cover (44)
40% Silane Sealer
Integrated Macrocell Current, C
Time, d
12000
10000
8000
6000
4000
2000
0
0
200
400
600
800
1000
2
3
4
5
6
7

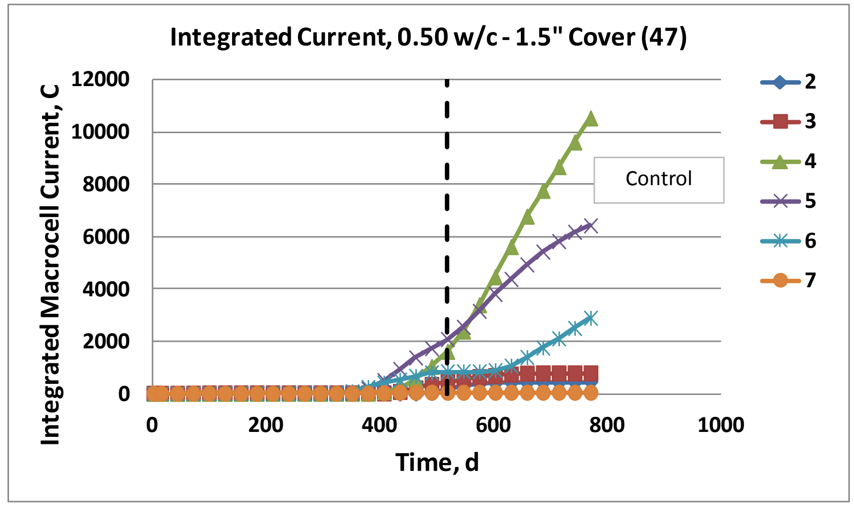

Half-Cell Potential, 0.50 w/c - 1.5" Cover (45)
Half-Cell Potential, mV CSE77
Time, d
Epoxy Membrane
2
3
4
5
6
7

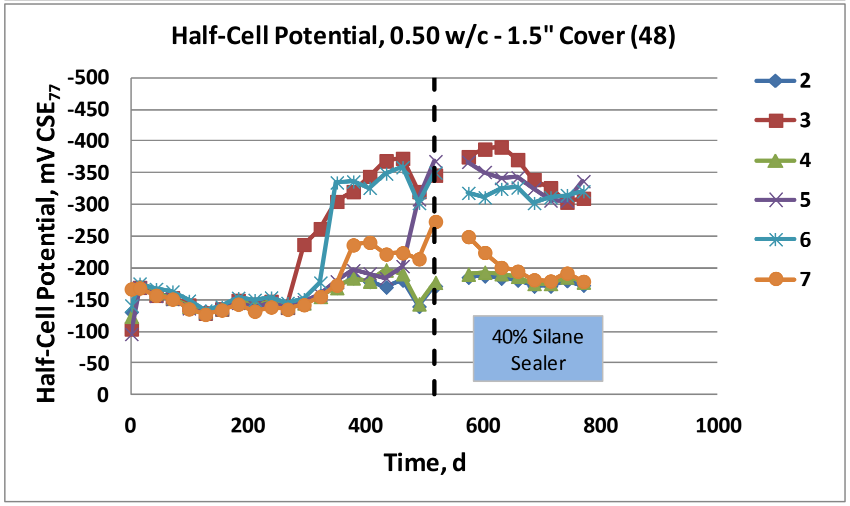

Integrated Current, 0.50 w/c - 1.5" Cover (45)
Integrated Macrocell Current, C
Time, d
Epoxy Membrane
2
3
4
5
6
7

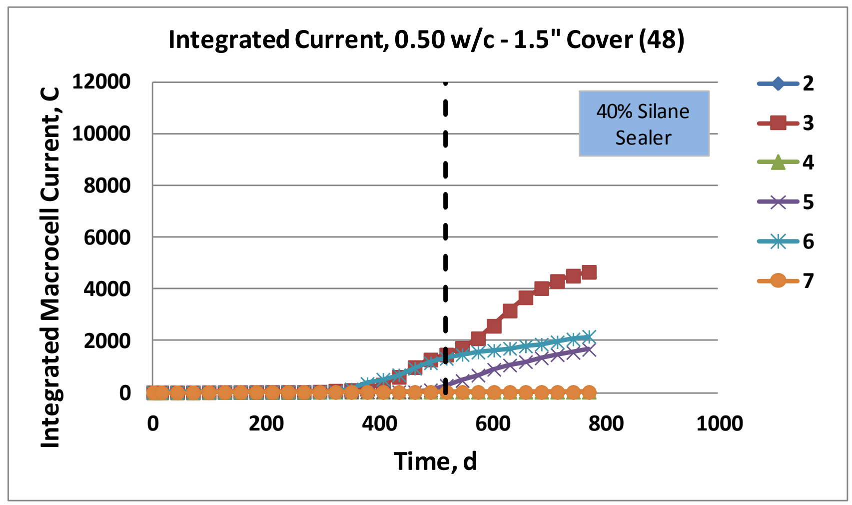

Half-Cell Potential, 0.50 w/c - 1.5" Cover (46)
Half-Cell Potential, mV CSE77
Time, d
Destructive Analysis
2
3
4
5
6
7

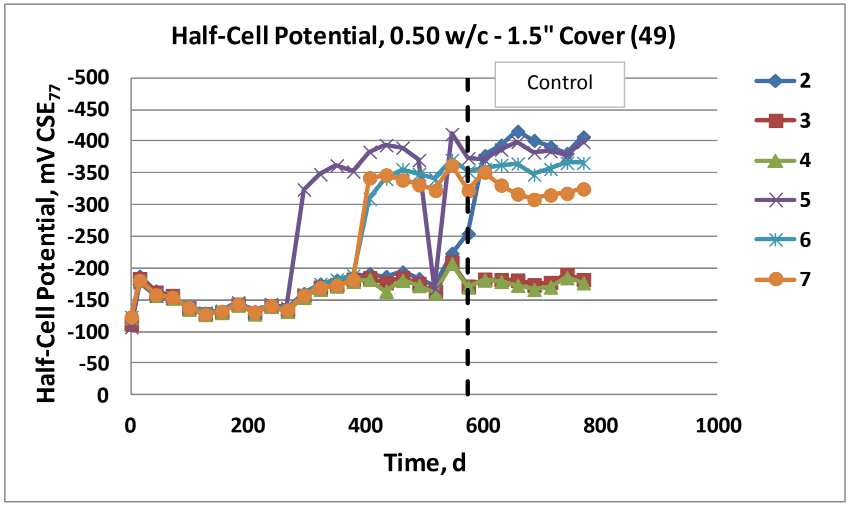

Integrated Current, 0.50 w/c - 1.5" Cover (46)
Integrated Macrocell Current, C
Time, d
Destructive Analysis
2
3
4
5
6
7

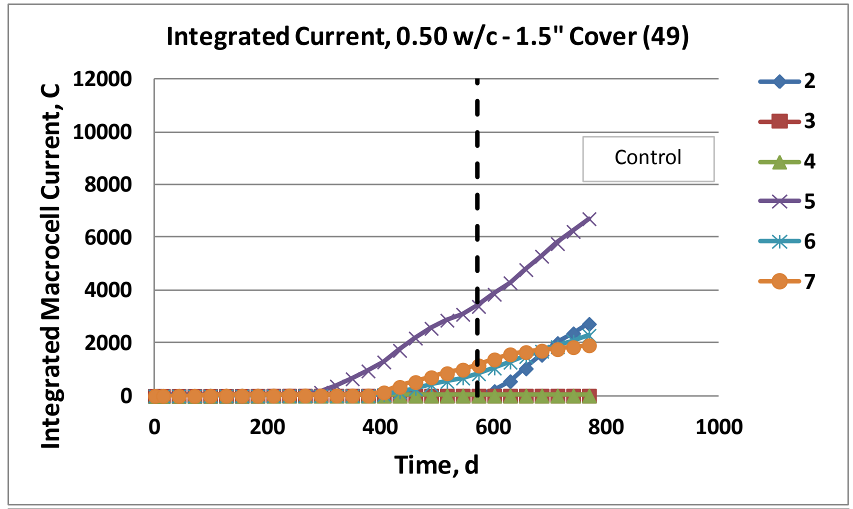

Half-Cell Potential, 0.50 w/c - 1.5" Cover (47)
Control
Half-Cell Potential, mV CSE_{77}
Time, d
2
3
4
5
6
7

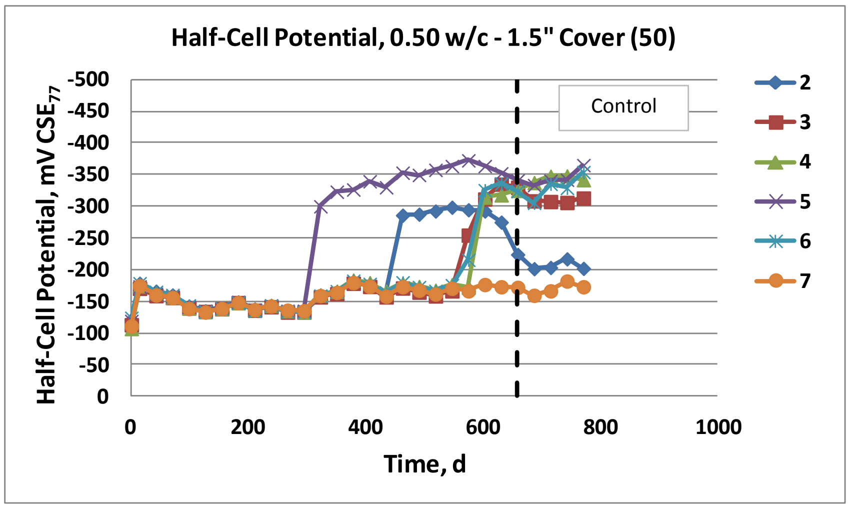

Integrated Current, 0.50 w/c - 1.5" Cover (47)
Control
Integrated Macrocell Current, C
Time, d
2
3
4
5
6
7

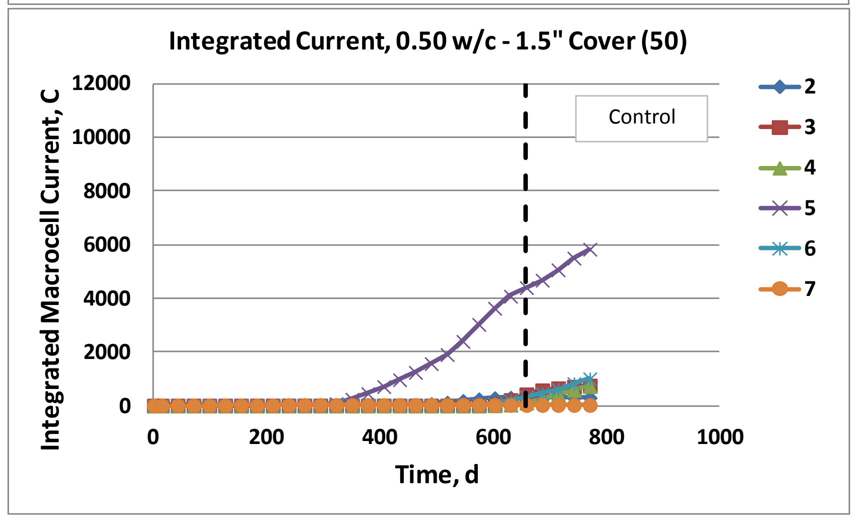

Half-Cell Potential, 0.50 w/c - 1.5" Cover (48)
40% Silane Sealer
Half-Cell Potential, mV CSE_{77}
Time, d
2
3
4
5
6
7


Integrated Current, 0.50 w/c - 1.5" Cover (48)
40% Silane Sealer
Integrated Macrocell Current, C
Time, d
2
3
4
5
6
7

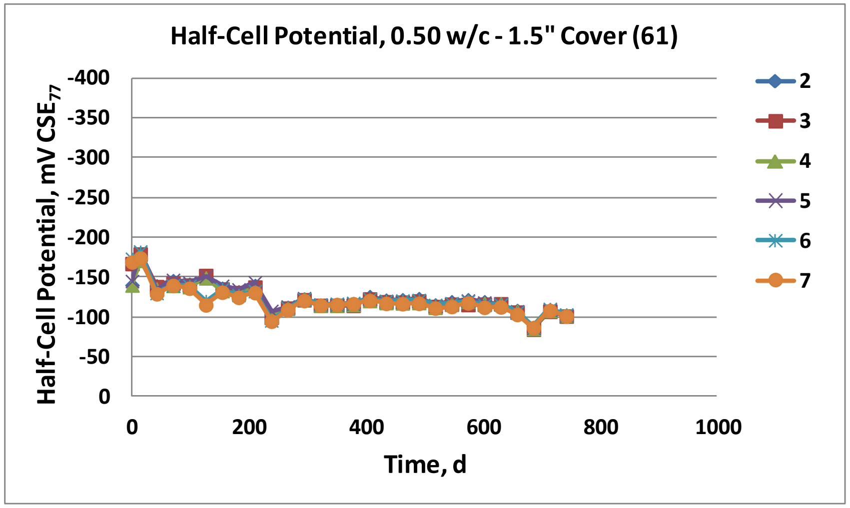

Half-Cell Potential, 0.50 w/c - 1.5" Cover (49)
Control
Half-Cell Potential, mV CSE_{77}
-500
-450
-400
-350
-300
-250
-200
-150
-100
-50
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

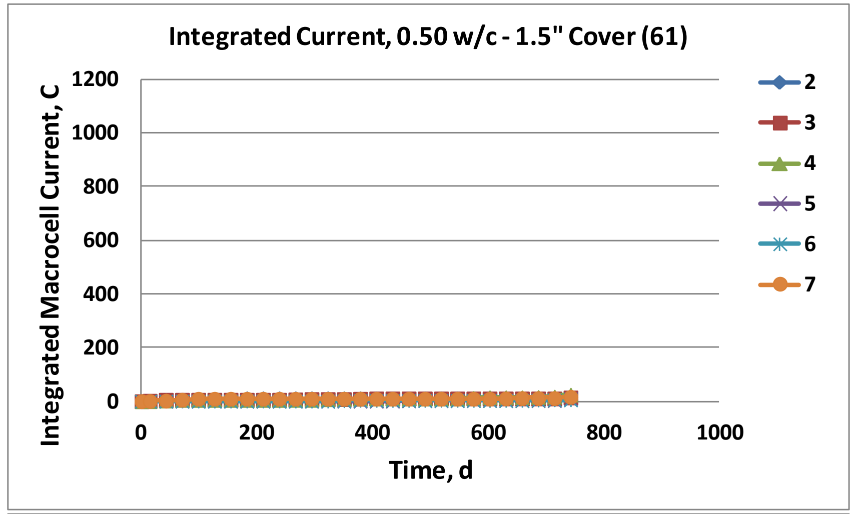

Integrated Current, 0.50 w/c - 1.5" Cover (49)
Control
Integrated Macrocell Current, C
12000
10000
8000
6000
4000
2000
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

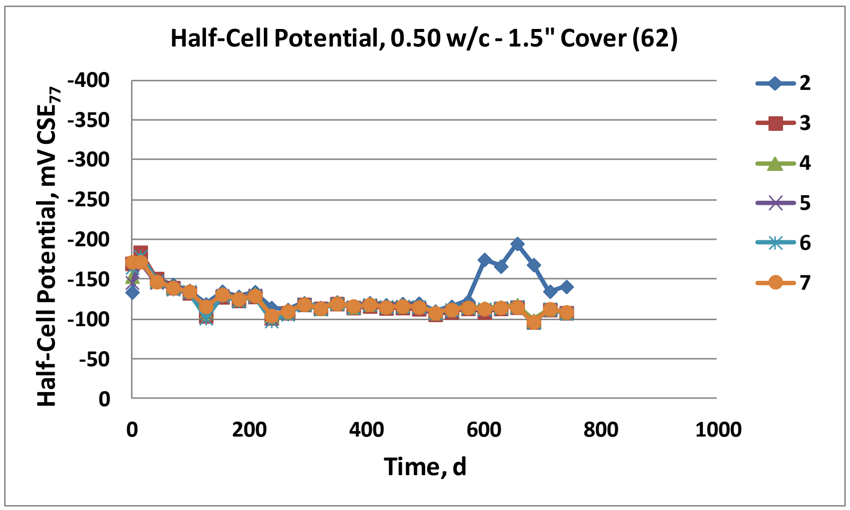

Half-Cell Potential, 0.50 w/c - 1.5" Cover (50)
Control
Half-Cell Potential, mV CSE_{77}
-500
-450
-400
-350
-300
-250
-200
-150
-100
-50
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

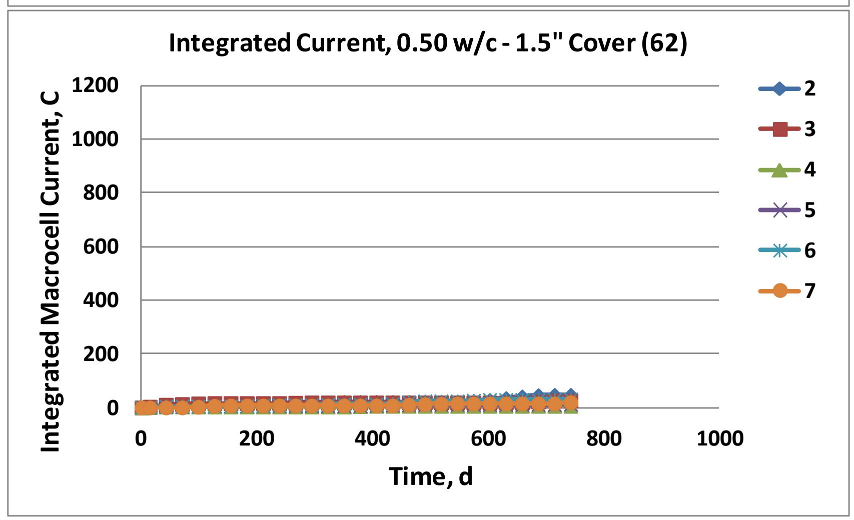

Integrated Current, 0.50 w/c - 1.5" Cover (50)
Control
Integrated Macrocell Current, C
12000
10000
8000
6000
4000
2000
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

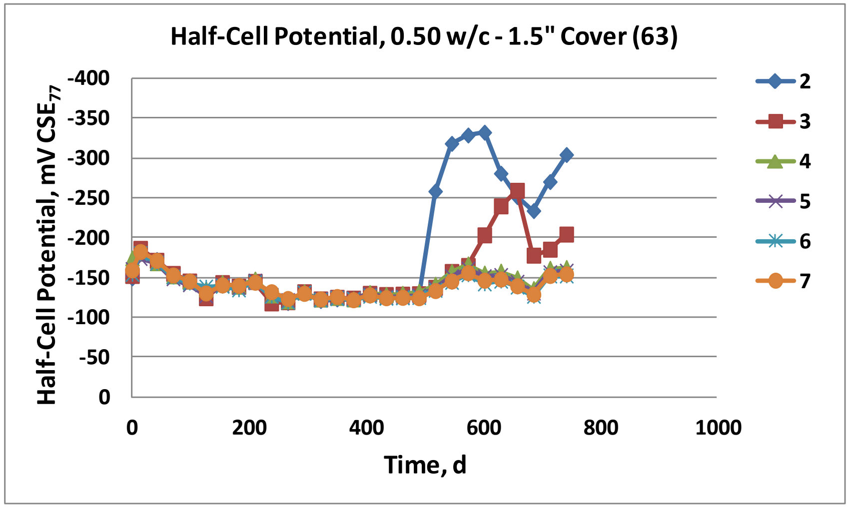
Batch #4

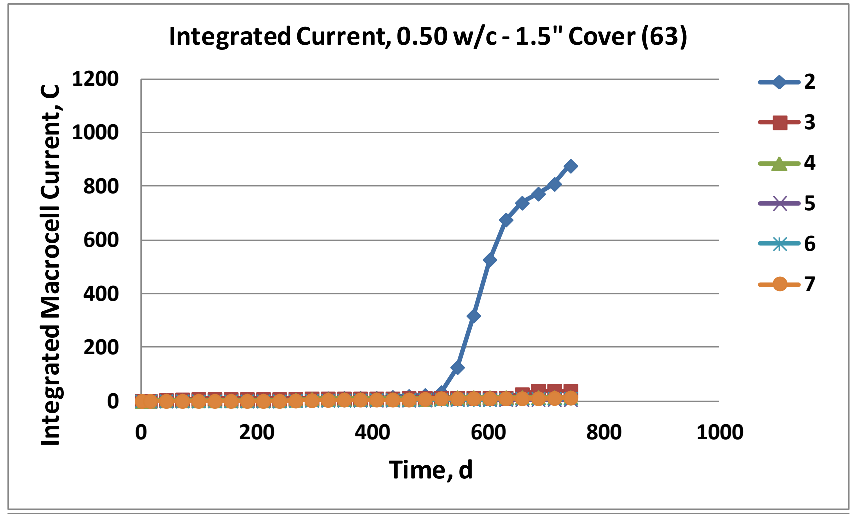

Half-Cell Potential, 0.50 w/c - 1.5" Cover (61)
Half-Cell Potential, mV CSE_{77}
-400
-350
-300
-250
-200
-150
-100
-50
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

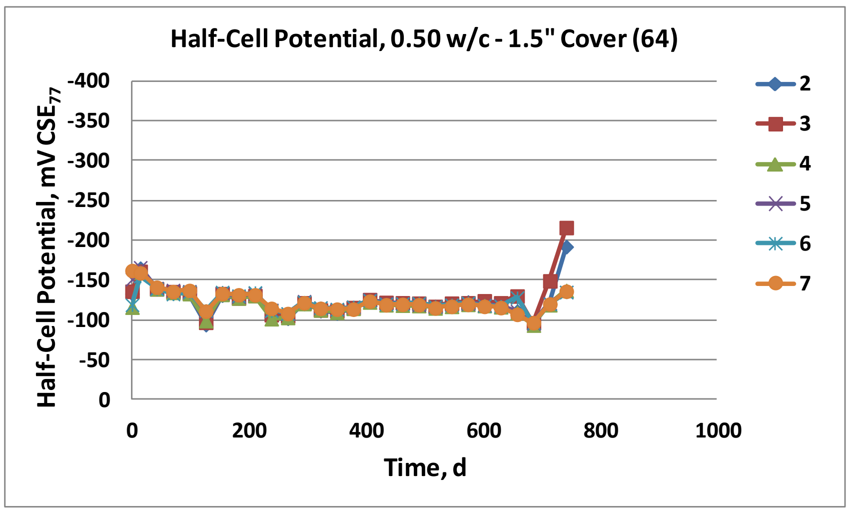

Integrated Current, 0.50 w/c - 1.5" Cover (61)
Integrated Macrocell Current, C
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

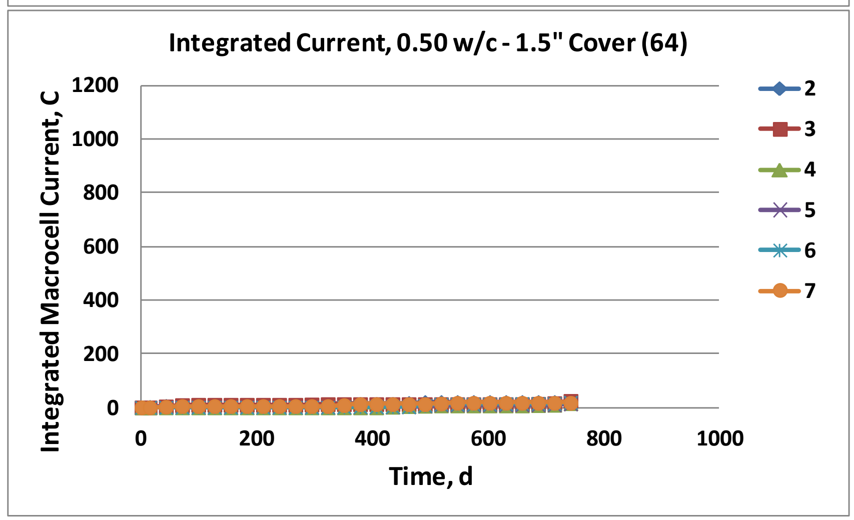

Half-Cell Potential, 0.50 w/c - 1.5" Cover (62)
Half-Cell Potential, mV CSE_{77}
-400
-350
-300
-250
-200
-150
-100
-50
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

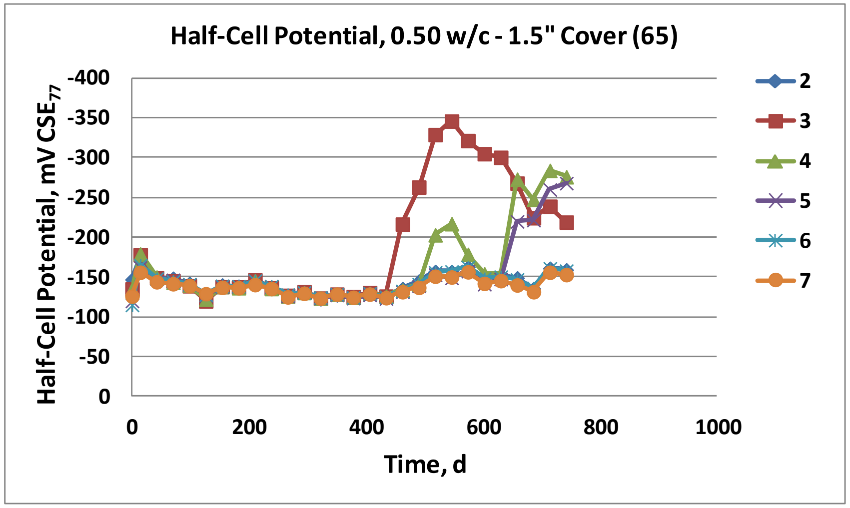

Integrated Current, 0.50 w/c - 1.5" Cover (62)
Integrated Macrocell Current, C
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

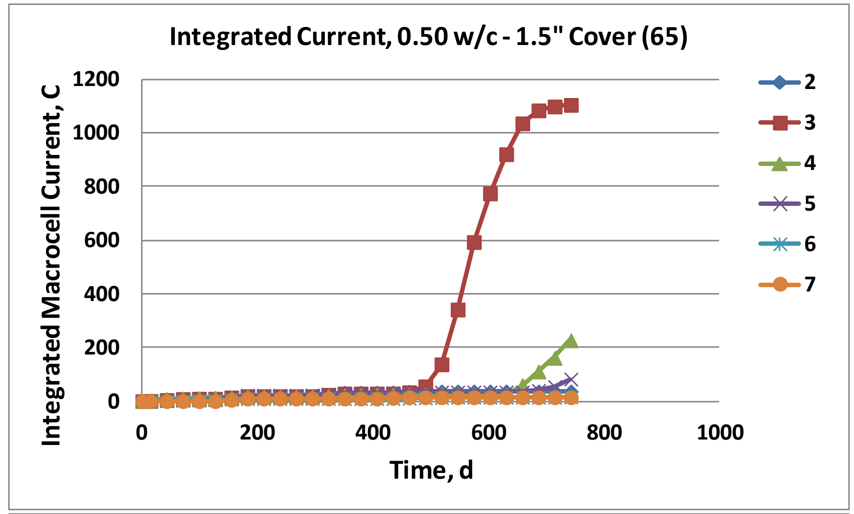

Half-Cell Potential, 0.50 w/c - 1.5" Cover (63)
Half-Cell Potential, mV CSE_{77}
-400
-350
-300
-250
-200
-150
-100
-50
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

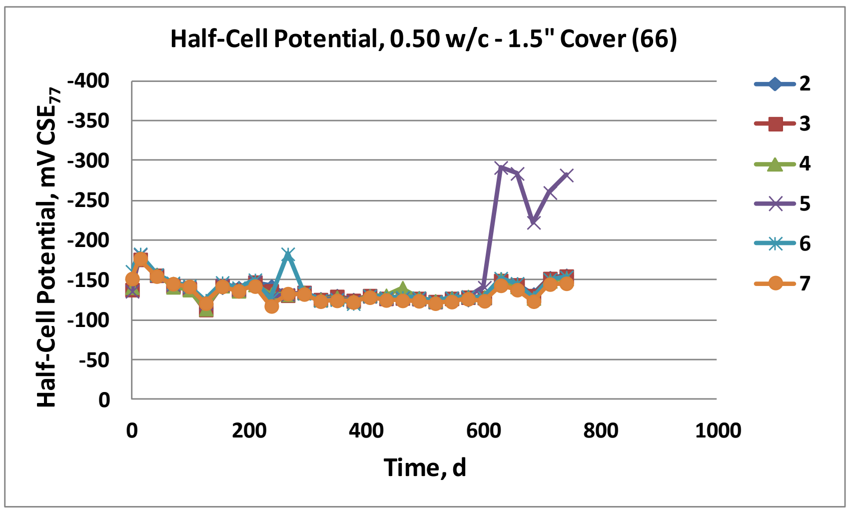

Integrated Current, 0.50 w/c - 1.5" Cover (63)
Integrated Macrocell Current, C
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

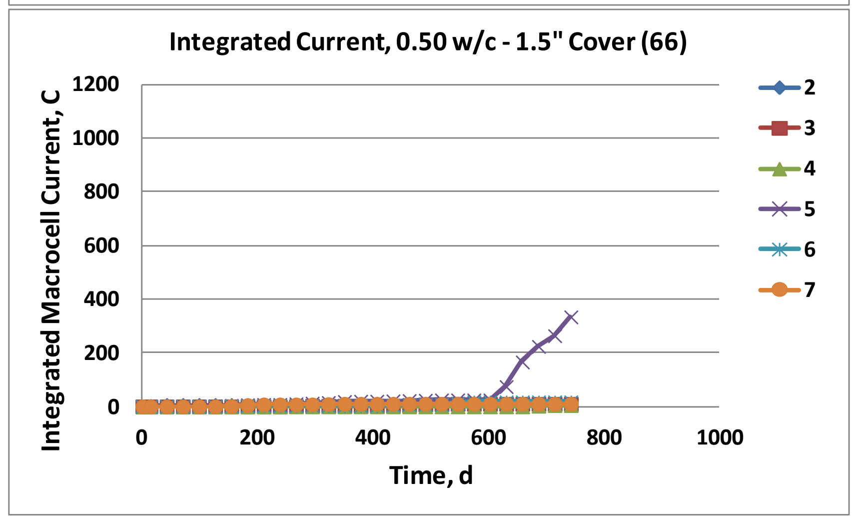

Half-Cell Potential, 0.50 w/c - 1.5" Cover (64)
Half-Cell Potential, mV CSE_{77}
-400
-350
-300
-250
-200
-150
-100
-50
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

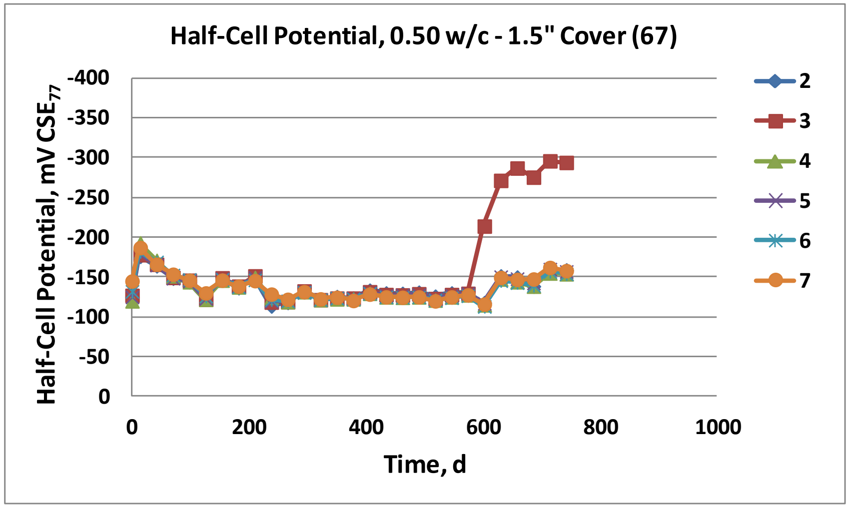

Integrated Current, 0.50 w/c - 1.5" Cover (64)
Integrated Macrocell Current, C
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

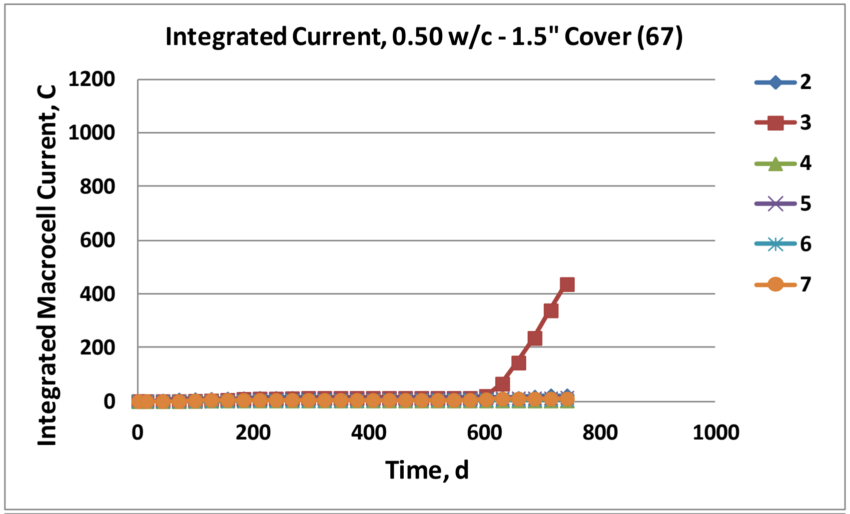

Half-Cell Potential, 0.50 w/c - 1.5" Cover (65)
Half-Cell Potential, mV CSE77
-400
-350
-300
-250
-200
-150
-100
-50
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

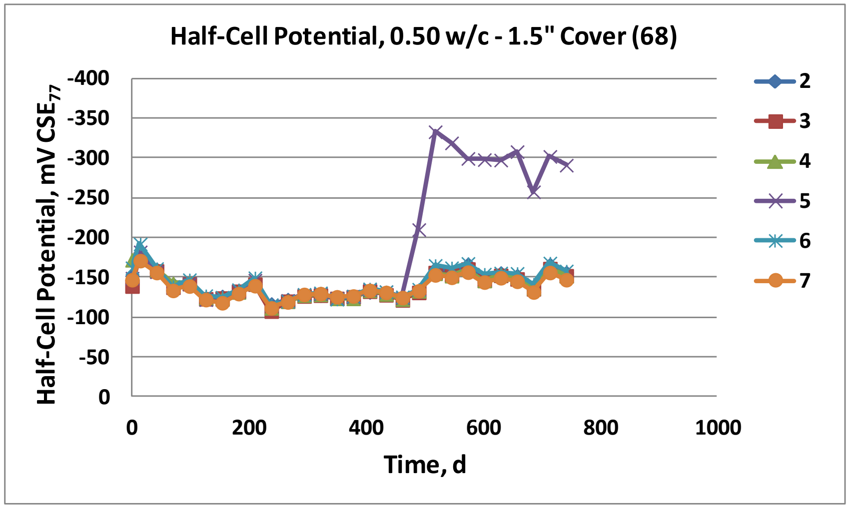

Integrated Current, 0.50 w/c - 1.5" Cover (65)
Integrated Macrocell Current, C
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

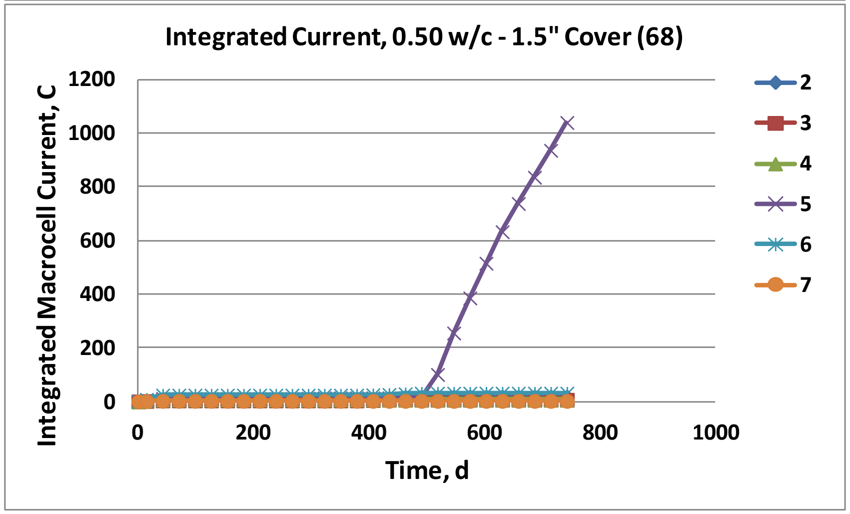

Half-Cell Potential, 0.50 w/c - 1.5" Cover (66)
Half-Cell Potential, mV CSE77
-400
-350
-300
-250
-200
-150
-100
-50
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

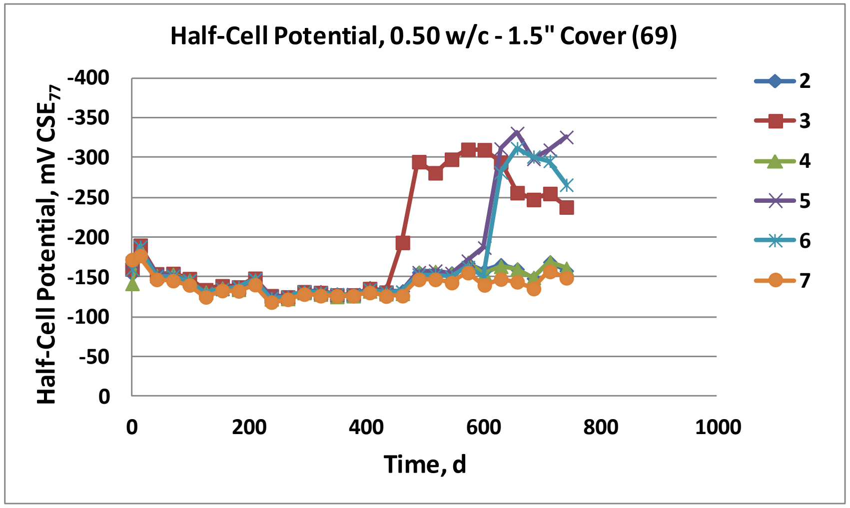

Integrated Current, 0.50 w/c - 1.5" Cover (66)
Integrated Macrocell Current, C
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

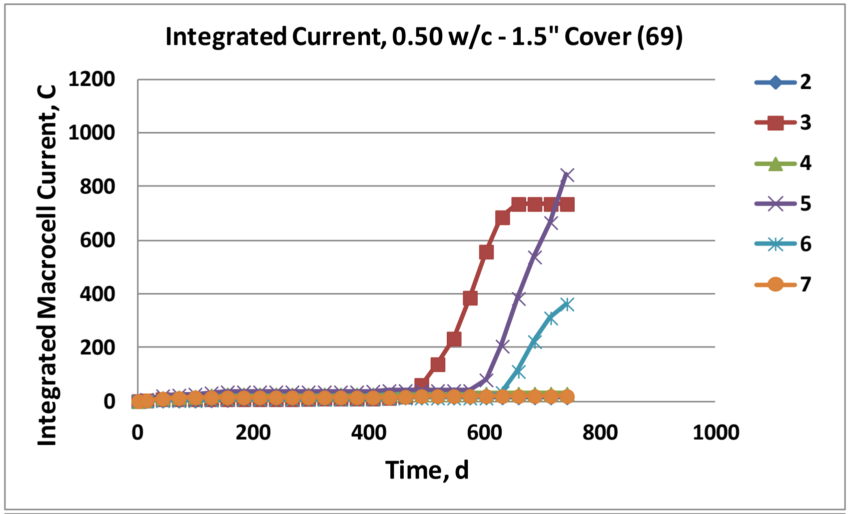

Half-Cell Potential, 0.50 w/c - 1.5" Cover (67)
Half-Cell Potential, mV CSE77
-400
-350
-300
-250
-200
-150
-100
-50
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

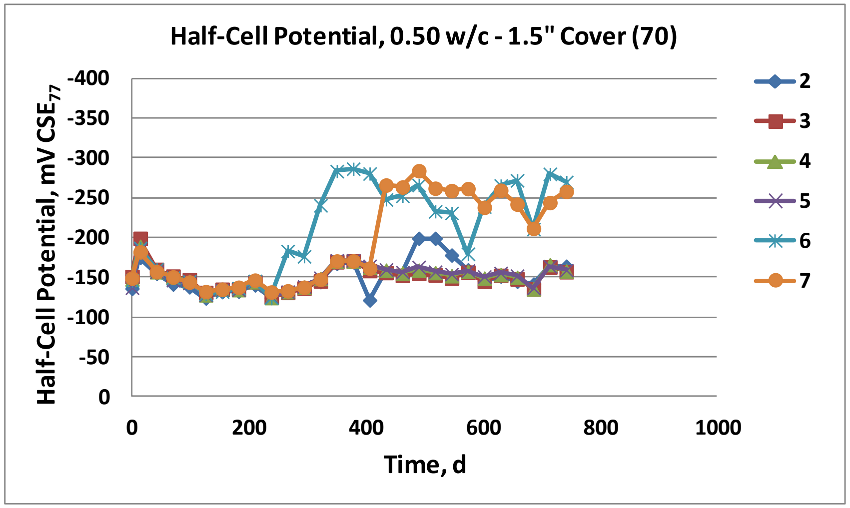

Integrated Current, 0.50 w/c - 1.5" Cover (67)
Integrated Macrocell Current, C
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

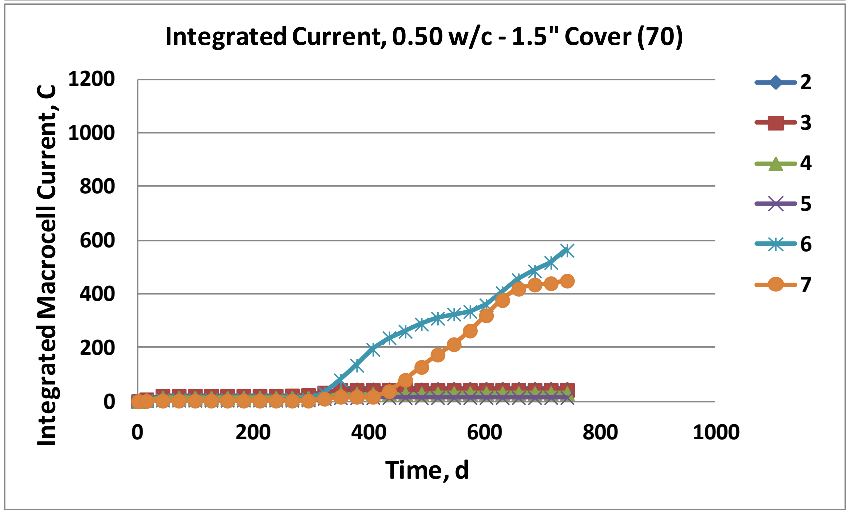

Half-Cell Potential, 0.50 w/c - 1.5" Cover (68)
Half-Cell Potential, mV CSE77
-400
-350
-300
-250
-200
-150
-100
-50
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7


Integrated Current, 0.50 w/c - 1.5" Cover (68)
Integrated Macrocell Current, C
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

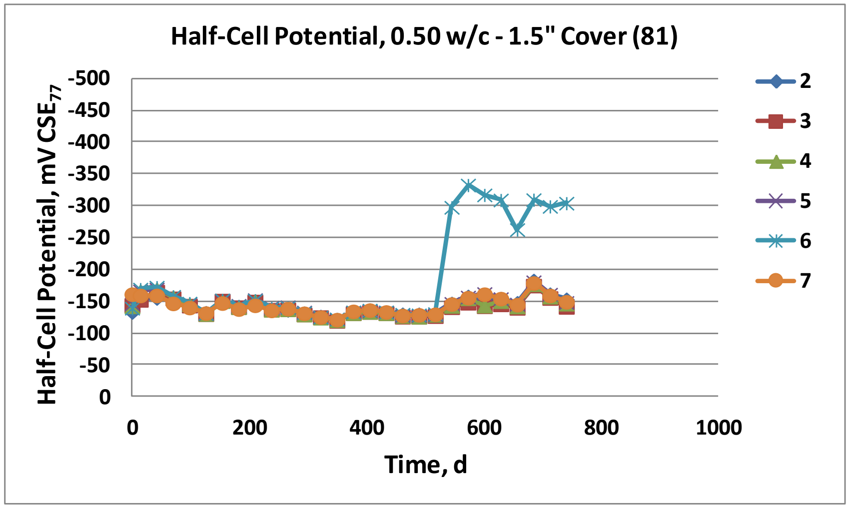

Half-Cell Potential, 0.50 w/c - 1.5" Cover (69)
Half-Cell Potential, mV CSE77
-400
-350
-300
-250
-200
-150
-100
-50
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

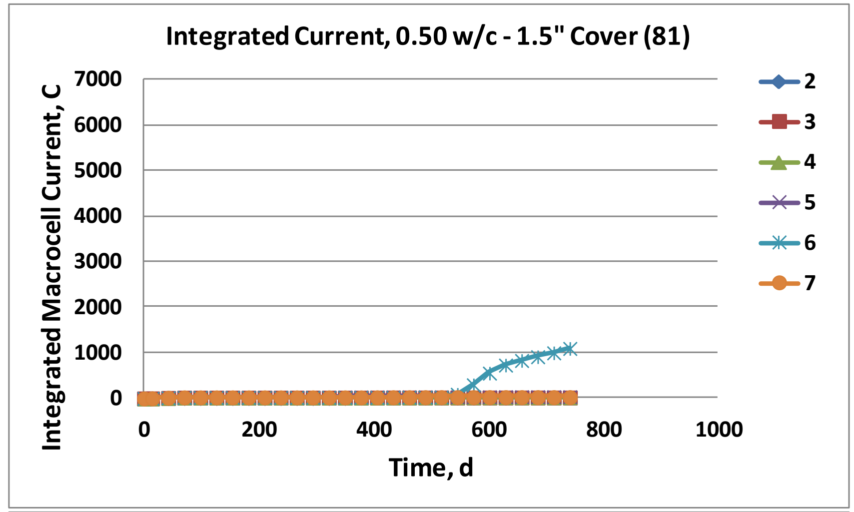

Integrated Current, 0.50 w/c - 1.5" Cover (69)
Integrated Macrocell Current, C
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

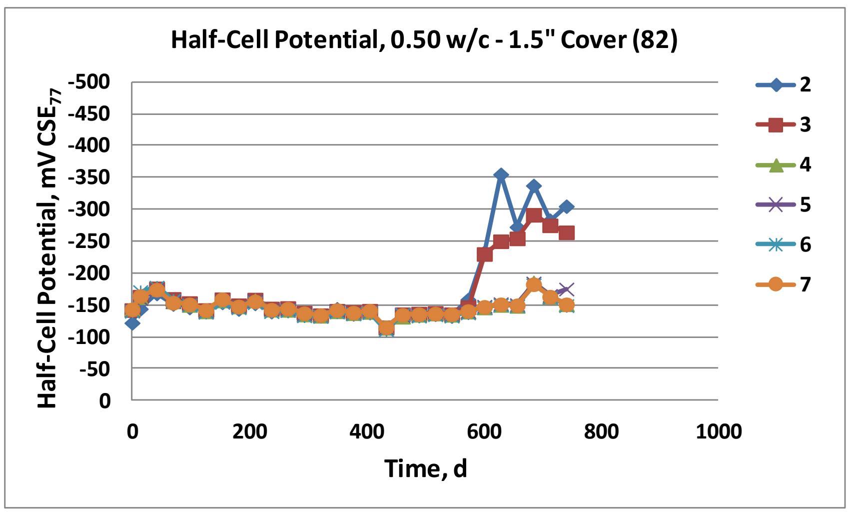

Half-Cell Potential, 0.50 w/c - 1.5" Cover (70)
Half-Cell Potential, mV CSE77
-400
-350
-300
-250
-200
-150
-100
-50
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

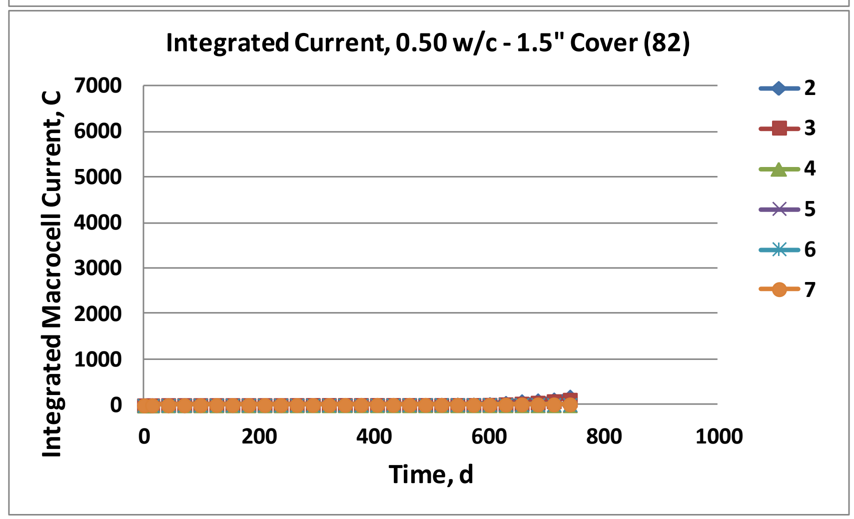

Integrated Current, 0.50 w/c - 1.5" Cover (70)
Integrated Macrocell Current, C
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

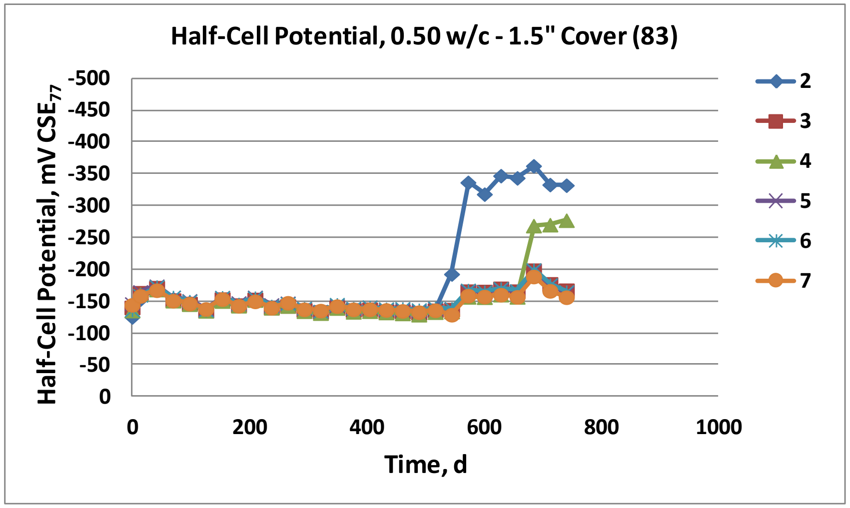
Batch #5

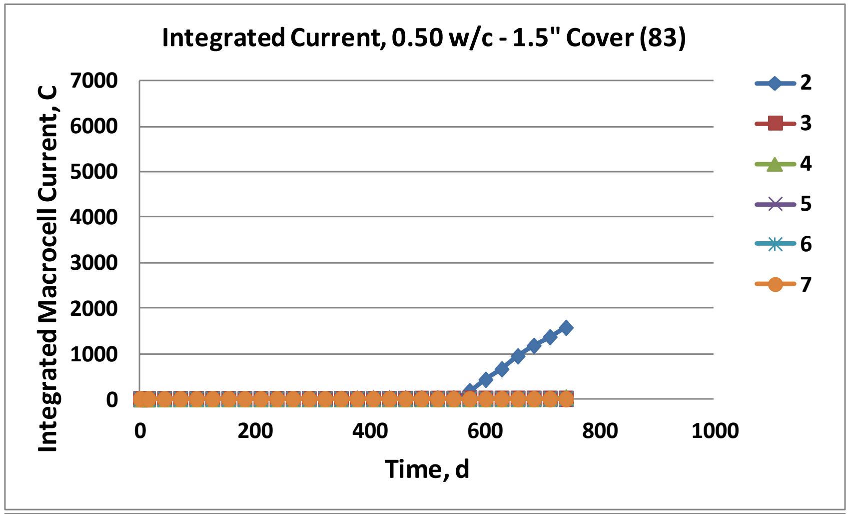

Half-Cell Potential, 0.50 w/c - 1.5" Cover (81)
Half-Cell Potential, mV CSE77
-500
-450
-400
-350
-300
-250
-200
-150
-100
-50
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

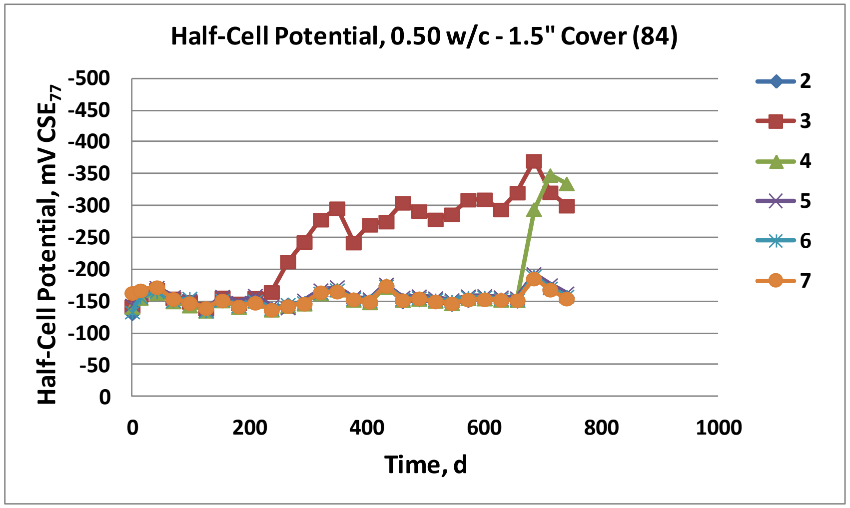

Integrated Current, 0.50 w/c - 1.5" Cover (81)
Integrated Macrocell Current, C
7000
6000
5000
4000
3000
2000
1000
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

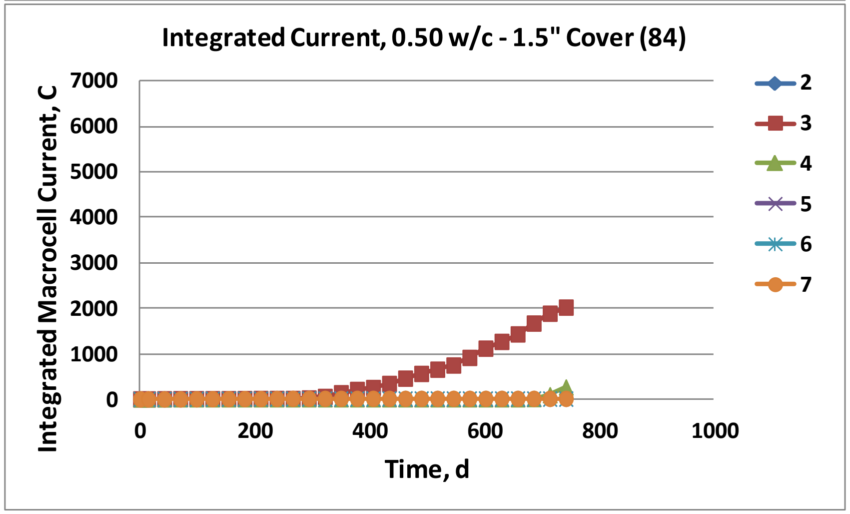

Half-Cell Potential, 0.50 w/c - 1.5" Cover (82)
Half-Cell Potential, mV CSE77
-500
-450
-400
-350
-300
-250
-200
-150
-100
-50
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

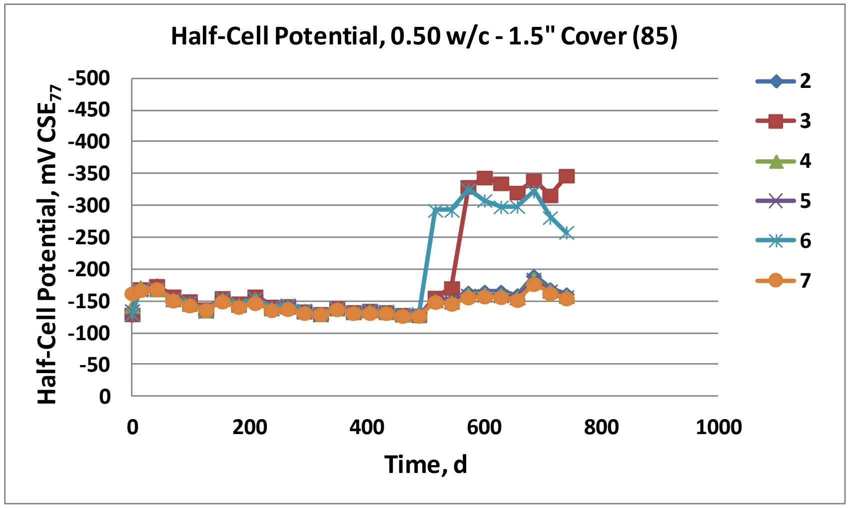

Integrated Current, 0.50 w/c - 1.5" Cover (82)
Integrated Macrocell Current, C
7000
6000
5000
4000
3000
2000
1000
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

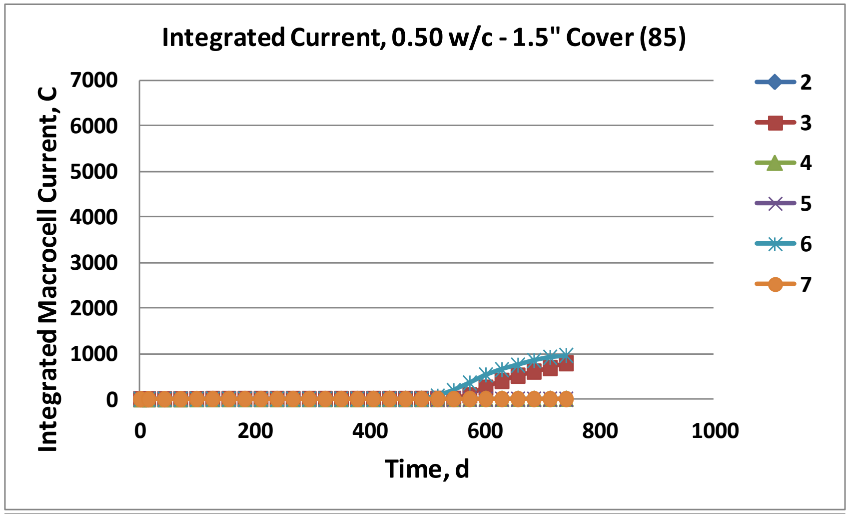

Half-Cell Potential, 0.50 w/c - 1.5" Cover (83)
Half-Cell Potential, mV CSE77
-500
-450
-400
-350
-300
-250
-200
-150
-100
-50
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

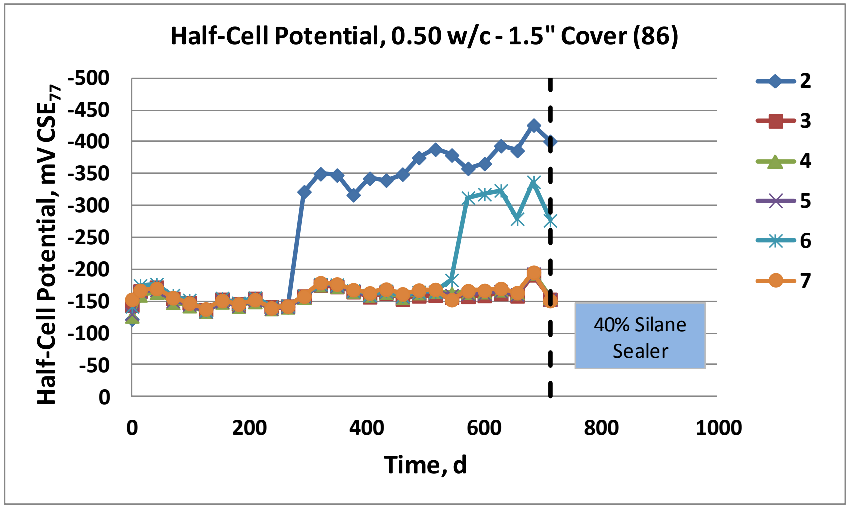

Integrated Current, 0.50 w/c - 1.5" Cover (83)
Integrated Macrocell Current, C
7000
6000
5000
4000
3000
2000
1000
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

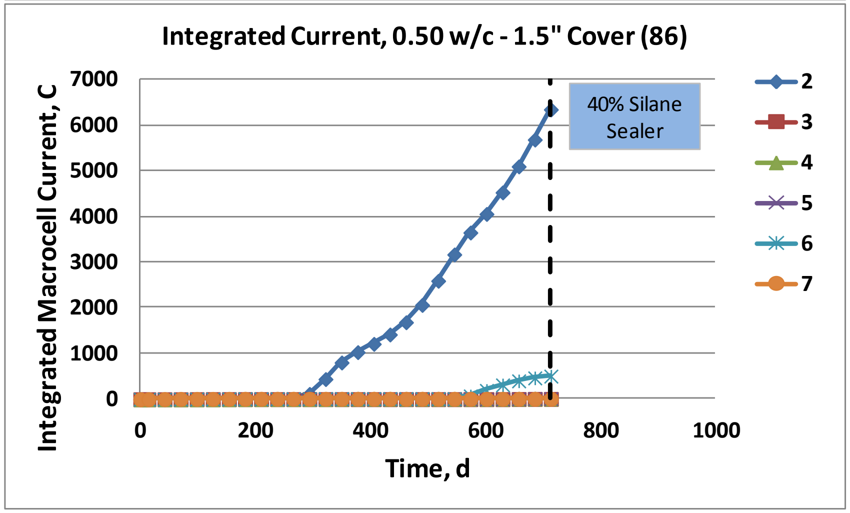

Half-Cell Potential, 0.50 w/c - 1.5" Cover (84)
Half-Cell Potential, mV CSE77
-500
-450
-400
-350
-300
-250
-200
-150
-100
-50
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

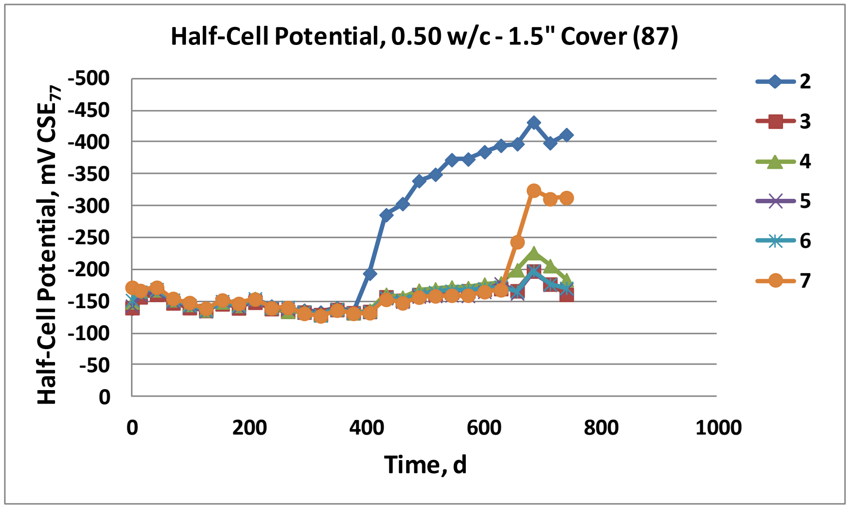

Integrated Current, 0.50 w/c - 1.5" Cover (84)
Integrated Macrocell Current, C
7000
6000
5000
4000
3000
2000
1000
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7

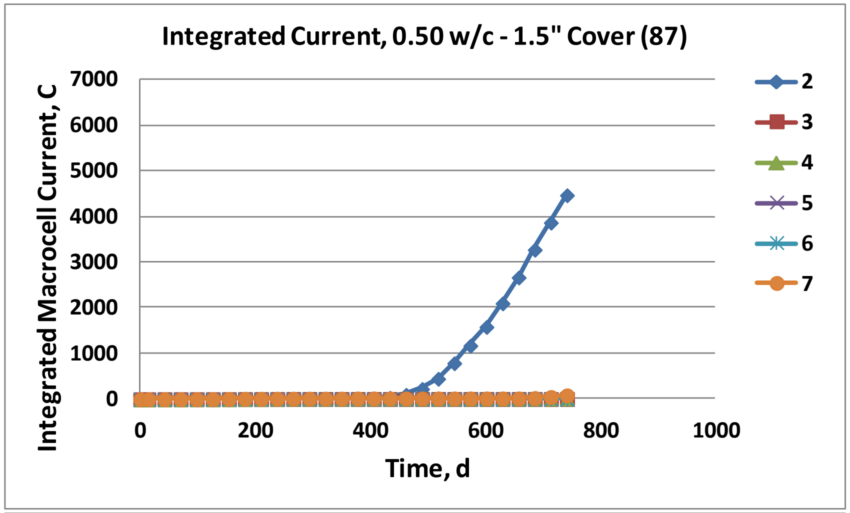

Half-Cell Potential, 0.50 w/c - 1.5" Cover (85)
Half-Cell Potential, mV CSE_{77}
Time, d
2
3
4
5
6
7

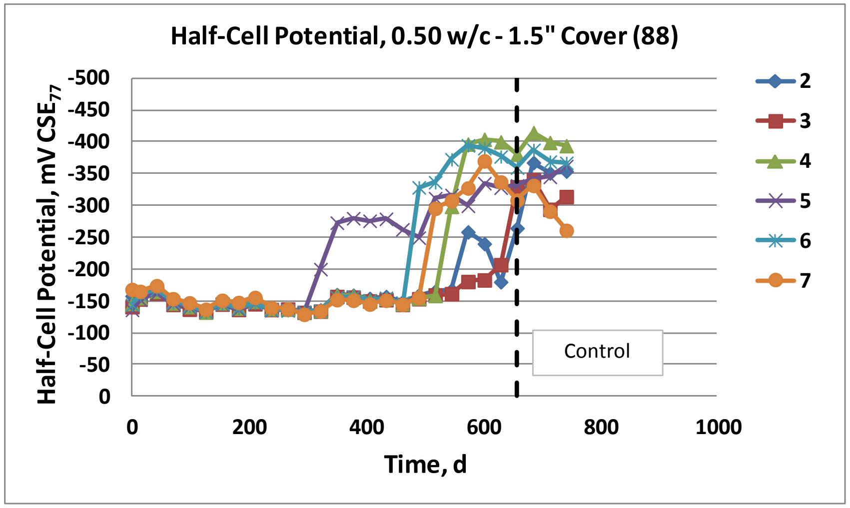

Integrated Current, 0.50 w/c - 1.5" Cover (85)
Integrated Macrocell Current, C
Time, d
2
3
4
5
6
7

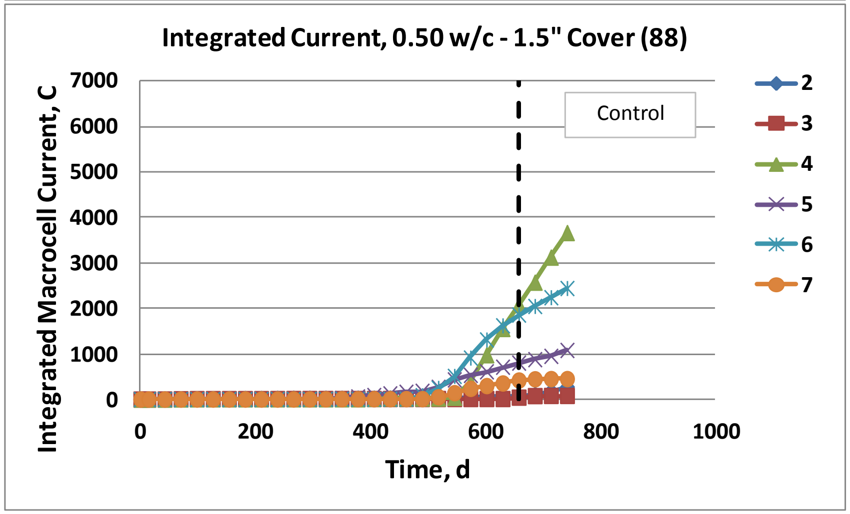

Half-Cell Potential, 0.50 w/c - 1.5" Cover (86)
Half-Cell Potential, mV CSE_{77}
Time, d
40% Silane Sealer
2
3
4
5
6
7

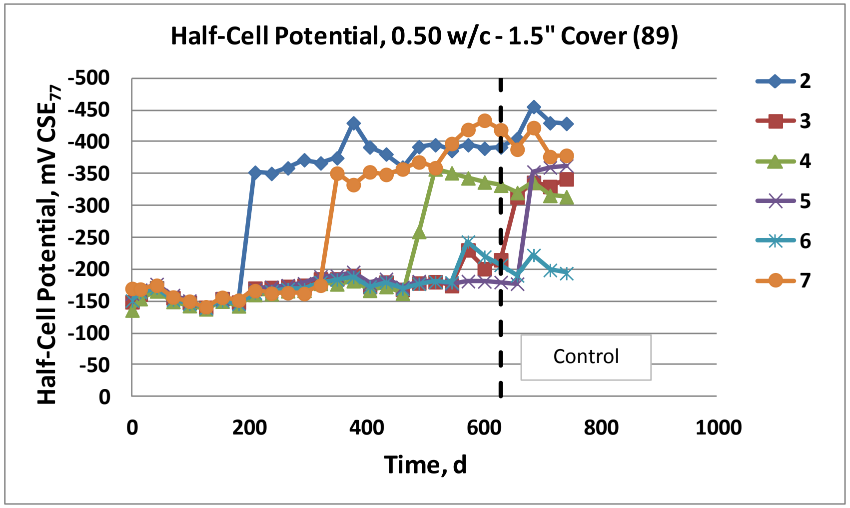

Integrated Current, 0.50 w/c - 1.5" Cover (86)
Integrated Macrocell Current, C
Time, d
40% Silane Sealer
2
3
4
5
6
7

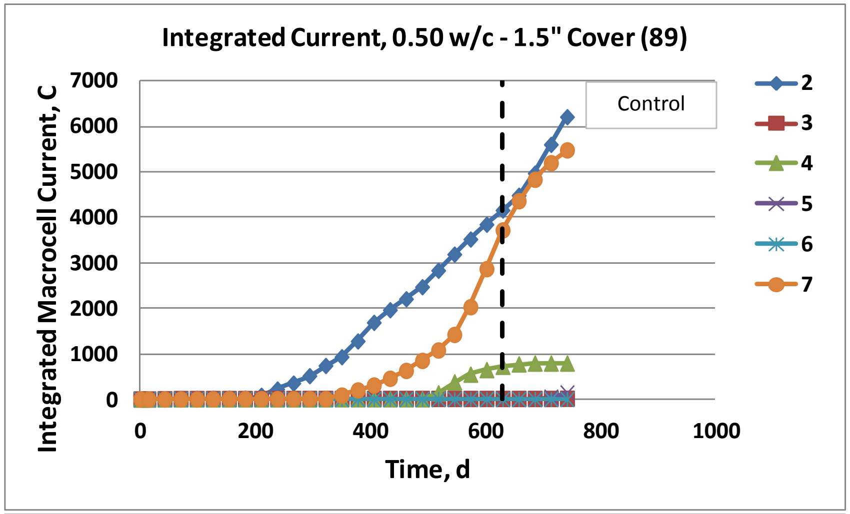

Half-Cell Potential, 0.50 w/c - 1.5" Cover (87)
Half-Cell Potential, mV CSE77
Time, d
-500
-450
-400
-350
-300
-250
-200
-150
-100
-50
0
200
400
600
800
1000
2
3
4
5
6
7

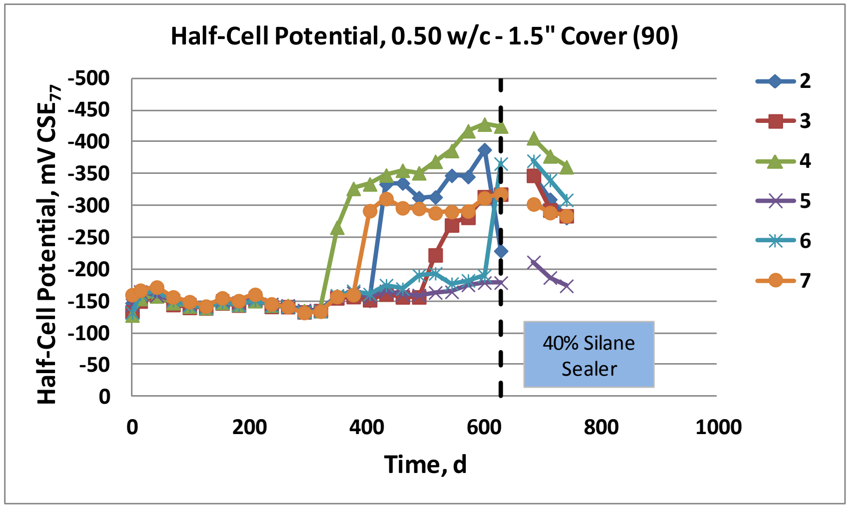

Integrated Current, 0.50 w/c - 1.5" Cover (87)
Integrated Macrocell Current, C
Time, d
7000
6000
5000
4000
3000
2000
1000
0
200
400
600
800
1000
2
3
4
5
6
7

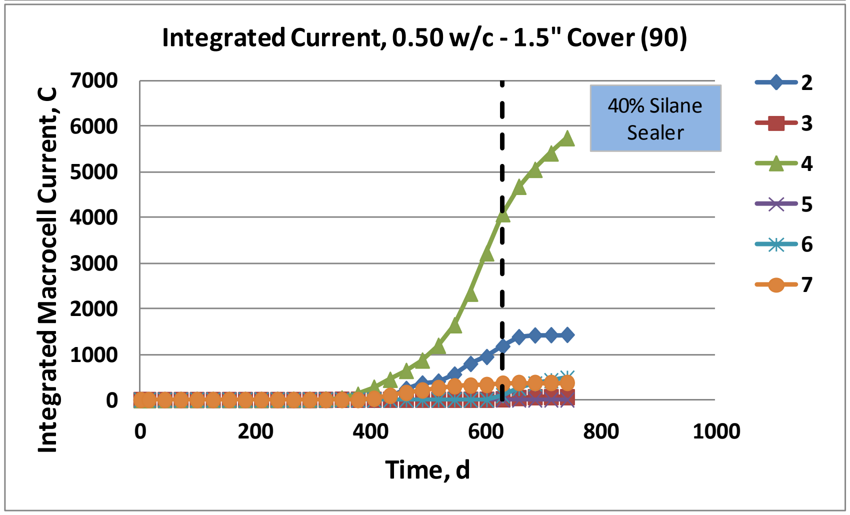

Half-Cell Potential, 0.50 w/c - 1.5" Cover (88)
Half-Cell Potential, mV CSE77
Time, d
Control
-500
-450
-400
-350
-300
-250
-200
-150
-100
-50
0
200
400
600
800
1000
2
3
4
5
6
7


Integrated Current, 0.50 w/c - 1.5" Cover (88)
Integrated Macrocell Current, C
Time, d
Control
7000
6000
5000
4000
3000
2000
1000
0
200
400
600
800
1000
2
3
4
5
6
7


Half-Cell Potential, 0.50 w/c - 1.5" Cover (89)
Half-Cell Potential, mV CSE_{77}
Time, d
Control
2
3
4
5
6
7

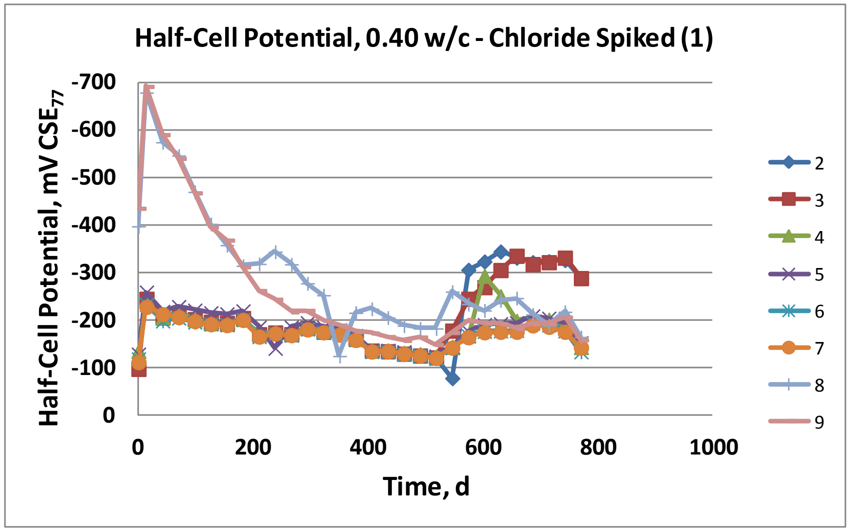

Integrated Current, 0.50 w/c - 1.5" Cover (89)
Integrated Macrocell Current, C
Time, d
Control
2
3
4
5
6
7

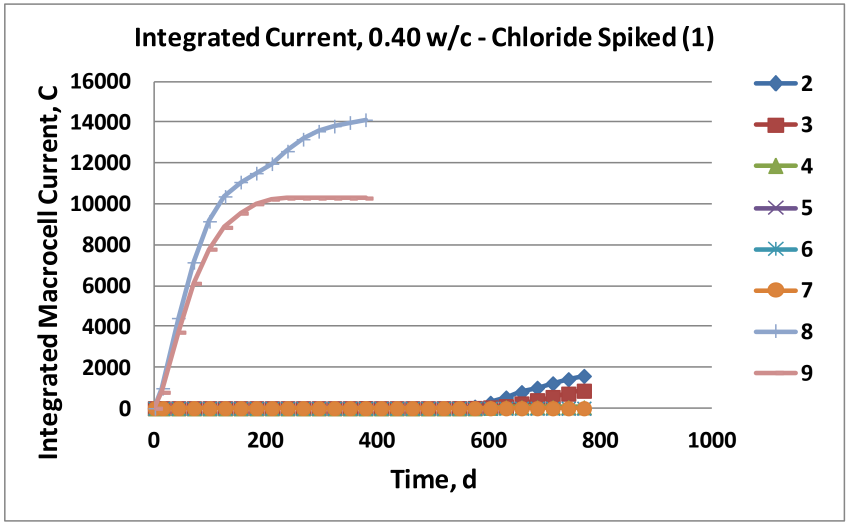

Half-Cell Potential, 0.50 w/c - 1.5" Cover (90)
Half-Cell Potential, mV CSE_{77}
Time, d
40% Silane Sealer
2
3
4
5
6
7

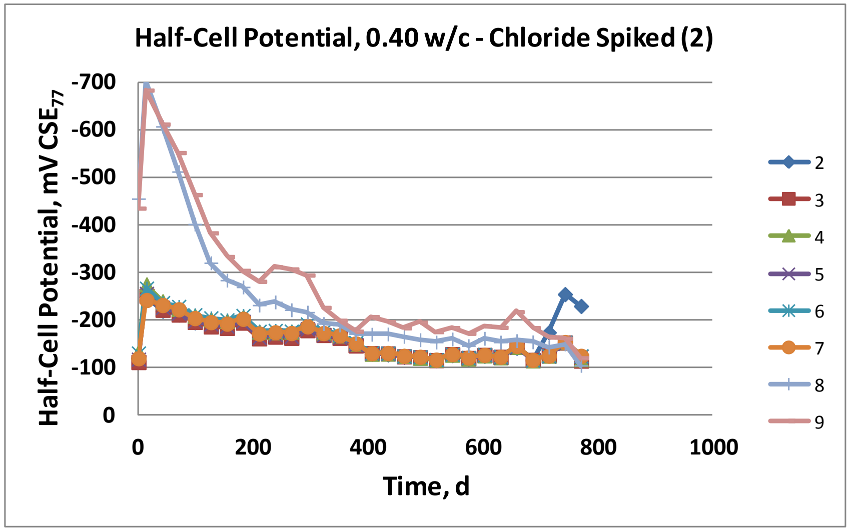

Integrated Current, 0.50 w/c - 1.5" Cover (90)
Integrated Macrocell Current, C
Time, d
40% Silane Sealer
2
3
4
5
6
7

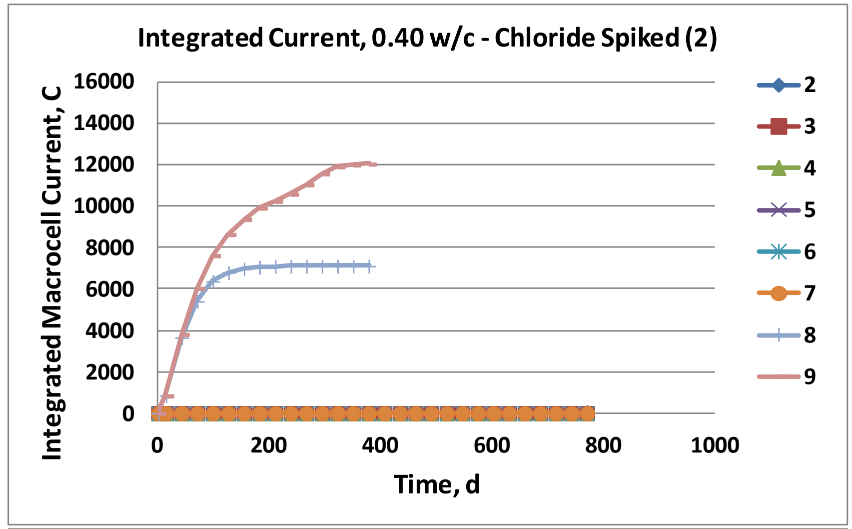
1.5-inch Cover Repair Treatment Slabs

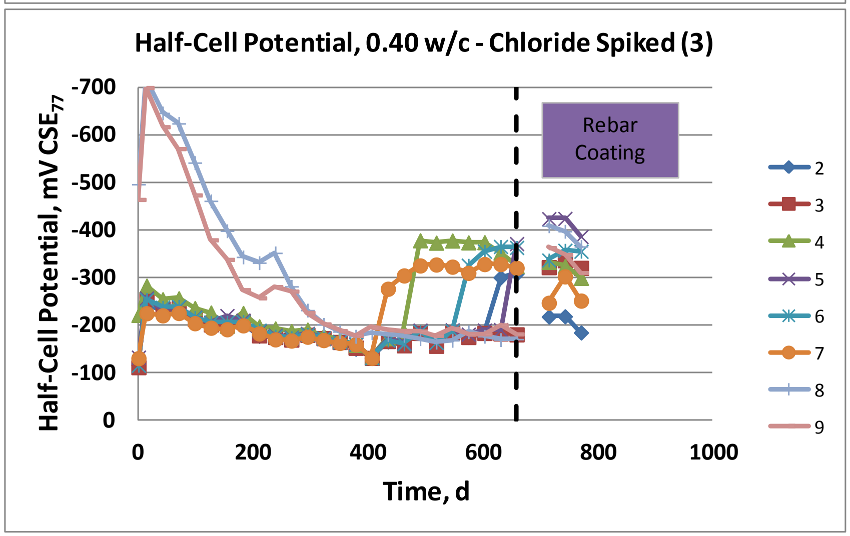
Batch #1

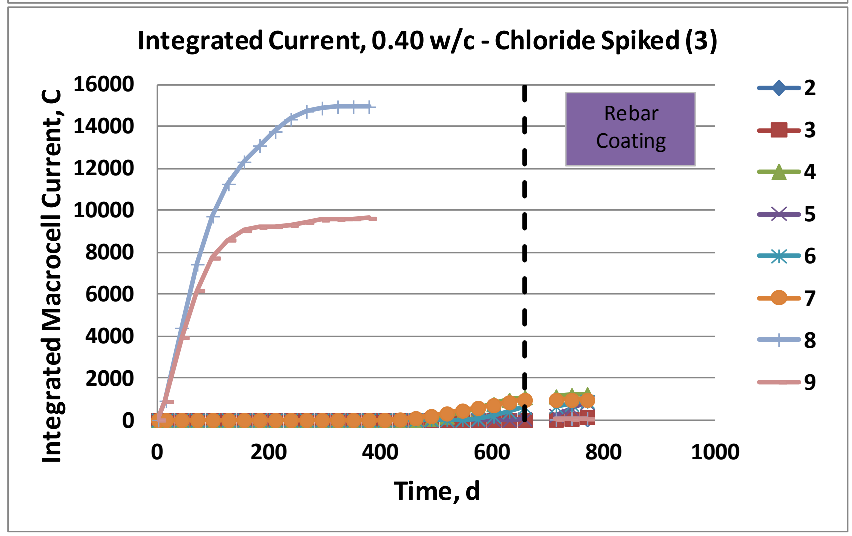


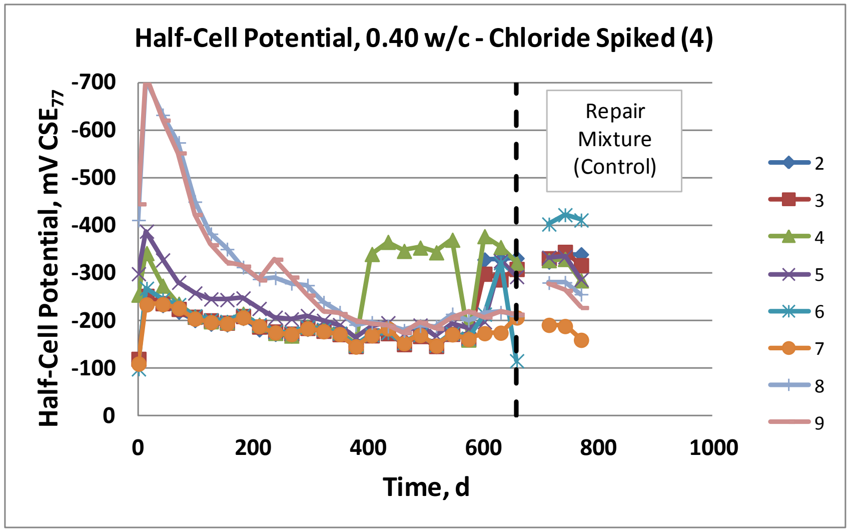


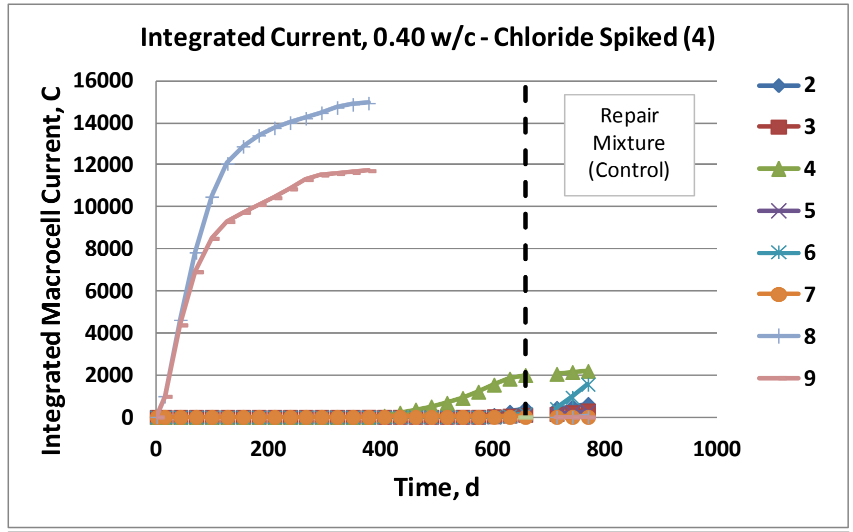

Half-Cell Potential, 0.40 w/c - Chloride Spiked (2)
Half-Cell Potential, mV CSE77
-700
-600
-500
-400
-300
-200
-100
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

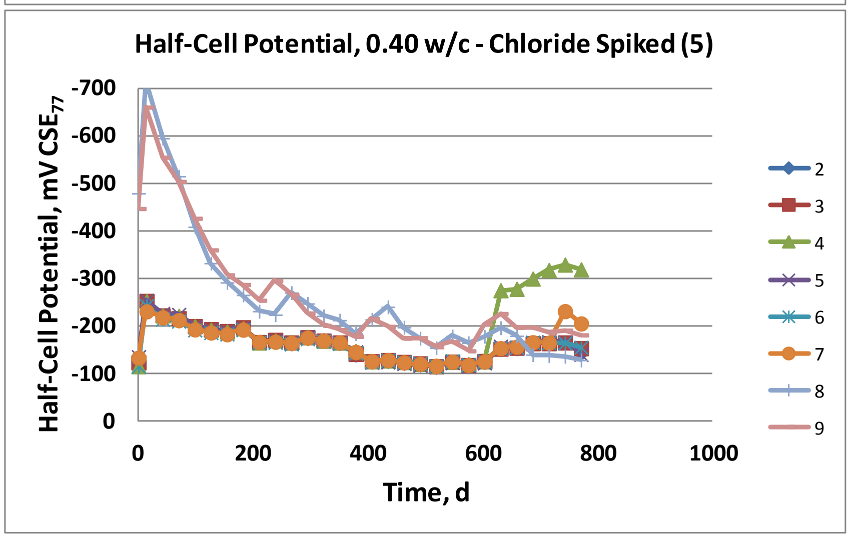

Integrated Current, 0.40 w/c - Chloride Spiked (2)
Integrated Macrocell Current, C
16000
14000
12000
10000
8000
6000
4000
2000
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

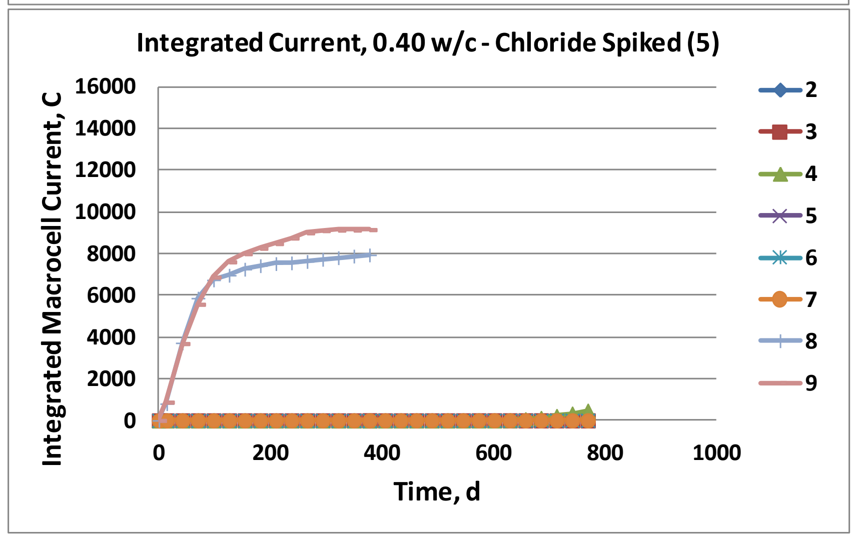

Half-Cell Potential, 0.40 w/c - Chloride Spiked (3)
Half-Cell Potential, mV CSE77
Rebar Coating
-700
-600
-500
-400
-300
-200
-100
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

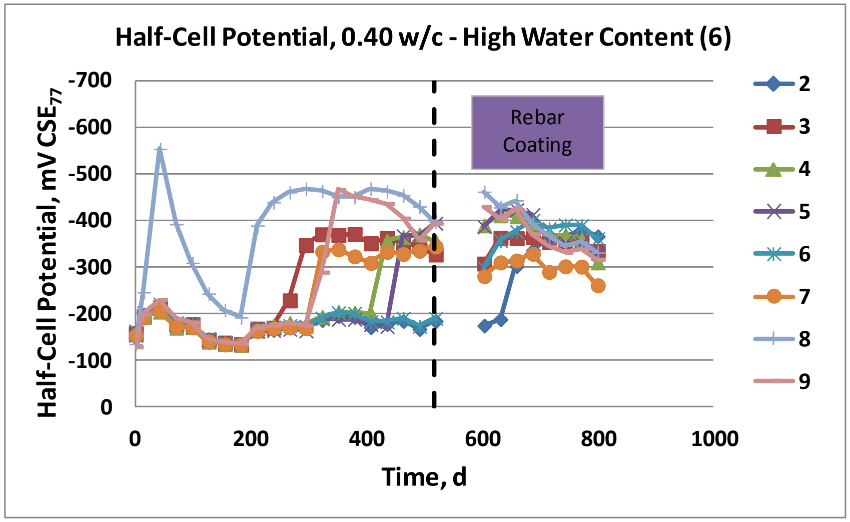

Integrated Current, 0.40 w/c - Chloride Spiked (3)
Integrated Macrocell Current, C
Rebar Coating
16000
14000
12000
10000
8000
6000
4000
2000
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

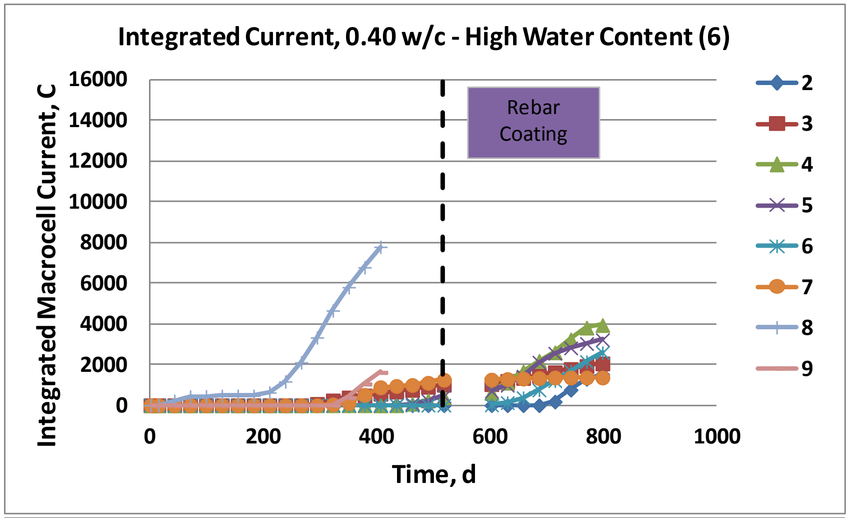

Half-Cell Potential, 0.40 w/c - Chloride Spiked (4)
Half-Cell Potential, mV CSE$_{77}$
Time, d
Repair Mixture (Control)
-700
-600
-500
-400
-300
-200
-100
0
0
200
400
600
800
1000
2
3
4
5
6
7
8
9

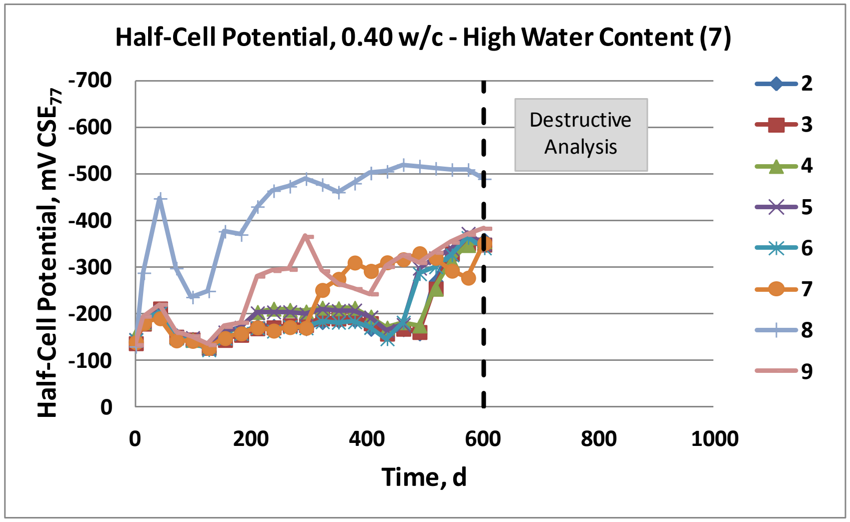

Integrated Current, 0.40 w/c - Chloride Spiked (4)
Integrated Macrocell Current, C
Time, d
Repair Mixture (Control)
16000
14000
12000
10000
8000
6000
4000
2000
0
0
200
400
600
800
1000
2
3
4
5
6
7
8
9

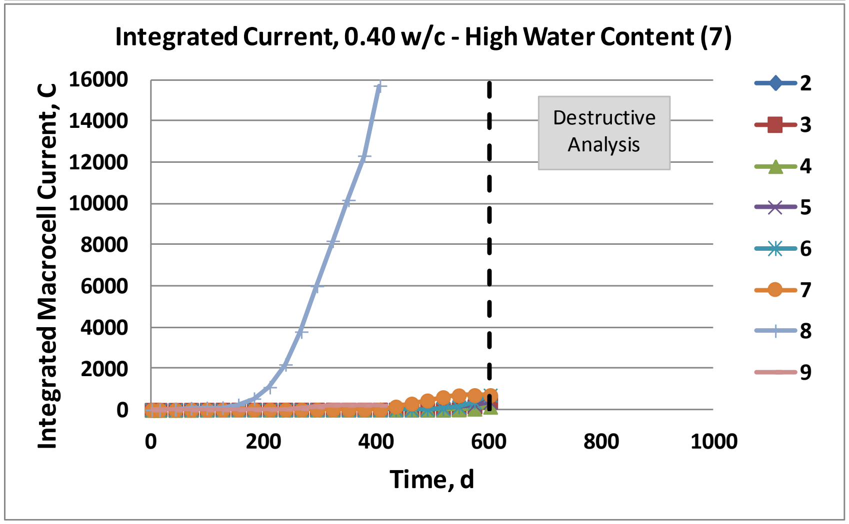

Half-Cell Potential, 0.40 w/c - Chloride Spiked (5)
Half-Cell Potential, mV CSE$_{77}$
Time, d
-700
-600
-500
-400
-300
-200
-100
0
0
200
400
600
800
1000
2
3
4
5
6
7
8
9

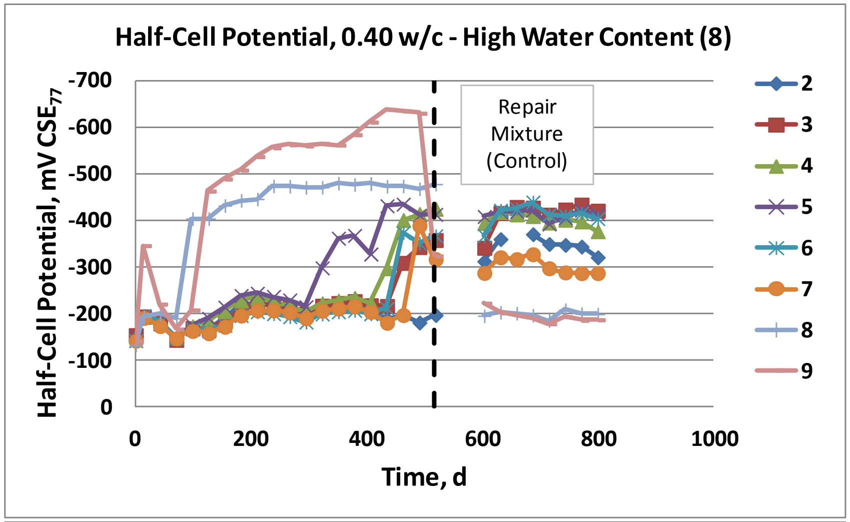

Integrated Current, 0.40 w/c - Chloride Spiked (5)
Integrated Macrocell Current, C
Time, d
16000
14000
12000
10000
8000
6000
4000
2000
0
0
200
400
600
800
1000
2
3
4
5
6
7
8
9

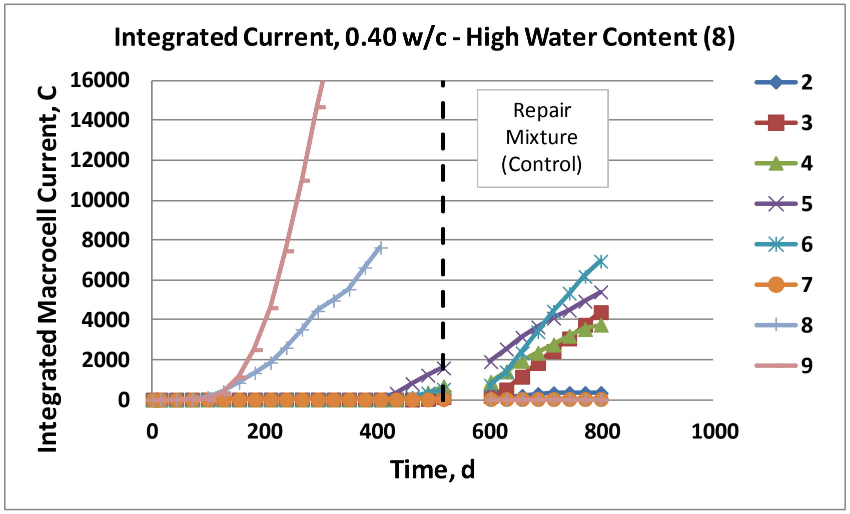

Half-Cell Potential, 0.40 w/c - High Water Content (6)
Half-Cell Potential, mV CSE_{77}
Time, d
Rebar Coating
-700
-600
-500
-400
-300
-200
-100
0
200
400
600
800
1000
2
3
4
5
6
7
8
9

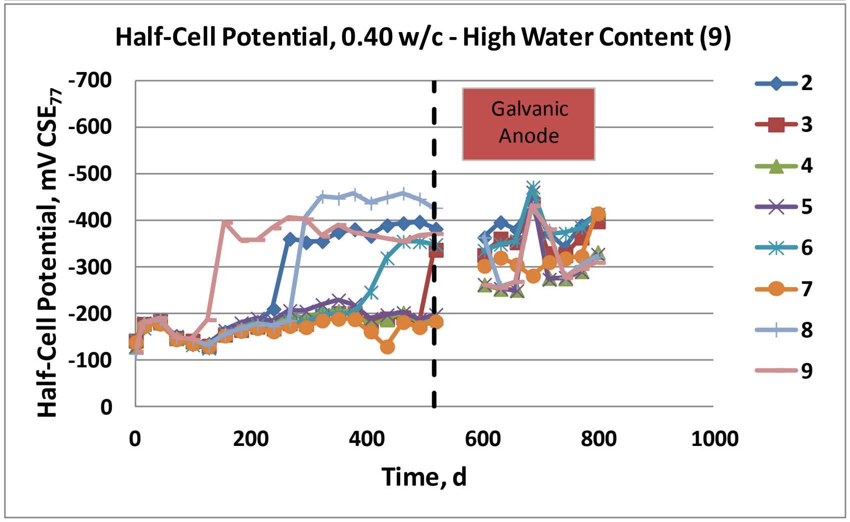

Integrated Current, 0.40 w/c - High Water Content (6)
Integrated Macrocell Current, C
Time, d
Rebar Coating
16000
14000
12000
10000
8000
6000
4000
2000
0
200
400
600
800
1000
2
3
4
5
6
7
8
9

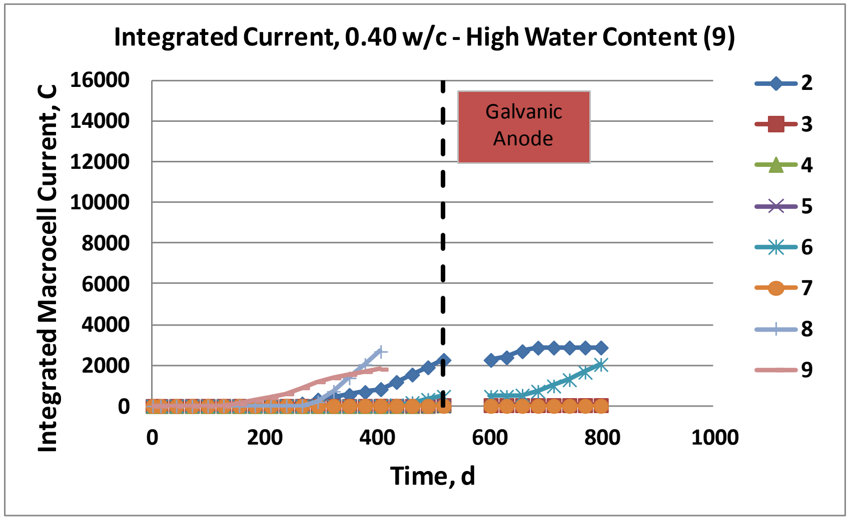

Half-Cell Potential, 0.40 w/c - High Water Content (7)
Half-Cell Potential, mV CSE_{77}
Time, d
Destructive Analysis
-700
-600
-500
-400
-300
-200
-100
0
200
400
600
800
1000
2
3
4
5
6
7
8
9

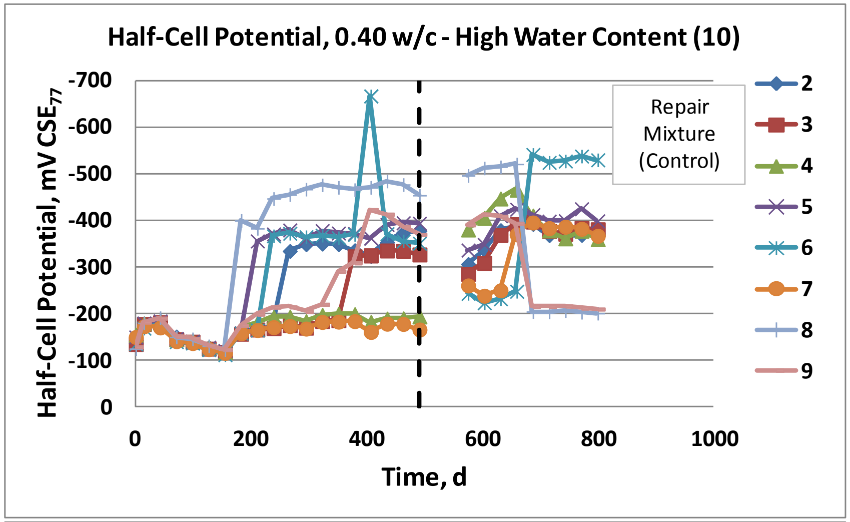

Integrated Current, 0.40 w/c - High Water Content (7)
Integrated Macrocell Current, C
Time, d
Destructive Analysis
16000
14000
12000
10000
8000
6000
4000
2000
0
200
400
600
800
1000
2
3
4
5
6
7
8
9

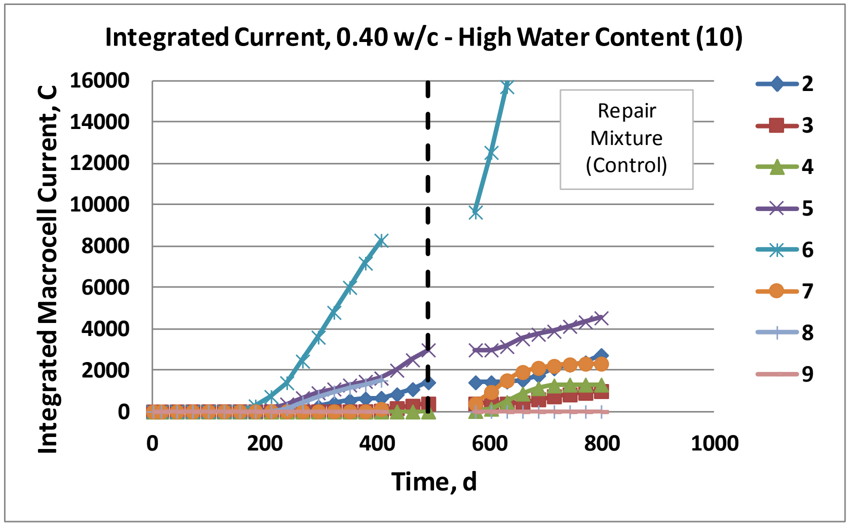

Half-Cell Potential, 0.40 w/c - High Water Content (8)
Half-Cell Potential, mV CSE77
Time, d
Repair Mixture (Control)
2
3
4
5
6
7
8
9

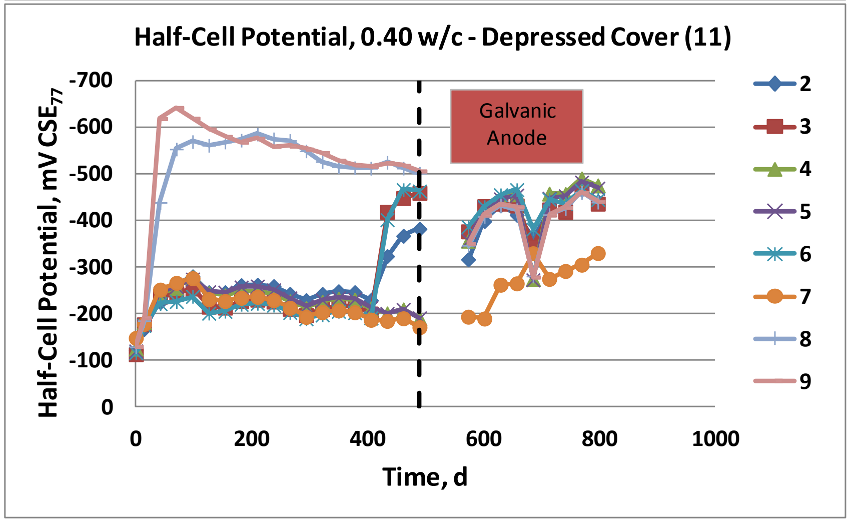

Integrated Current, 0.40 w/c - High Water Content (8)
Integrated Macrocell Current, C
Time, d
Repair Mixture (Control)
2
3
4
5
6
7
8
9

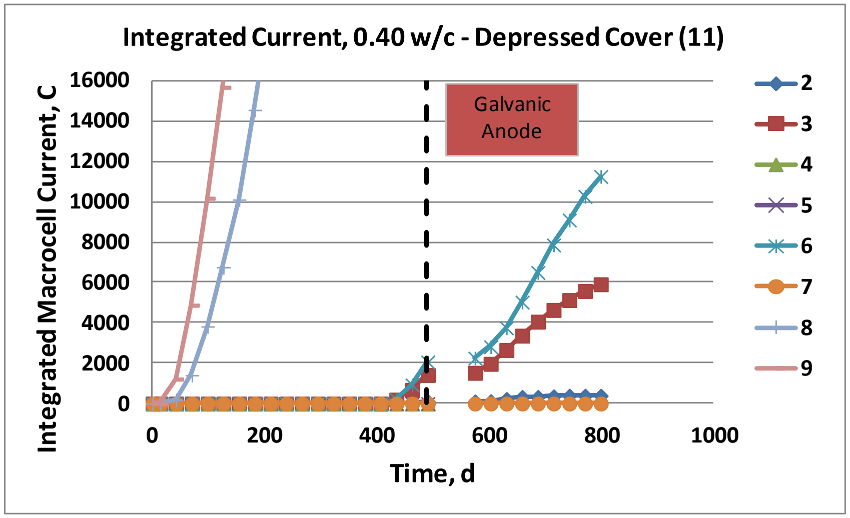

Half-Cell Potential, 0.40 w/c - High Water Content (9)
Half-Cell Potential, mV CSE77
Time, d
Galvanic Anode
2
3
4
5
6
7
8
9

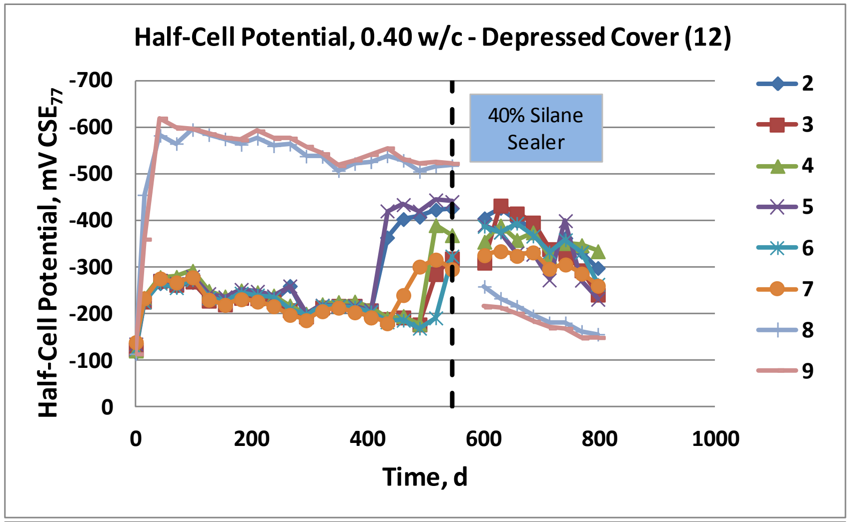

Integrated Current, 0.40 w/c - High Water Content (9)
Integrated Macrocell Current, C
Time, d
Galvanic Anode
2
3
4
5
6
7
8
9

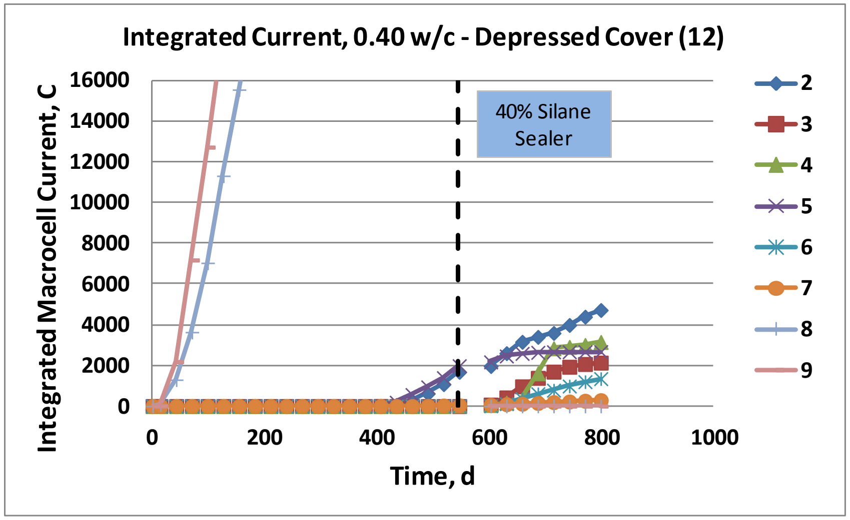

Half-Cell Potential, 0.40 w/c - High Water Content (10)
Half-Cell Potential, mV CSE_{77}
Time, d
Repair Mixture (Control)
2
3
4
5
6
7
8
9

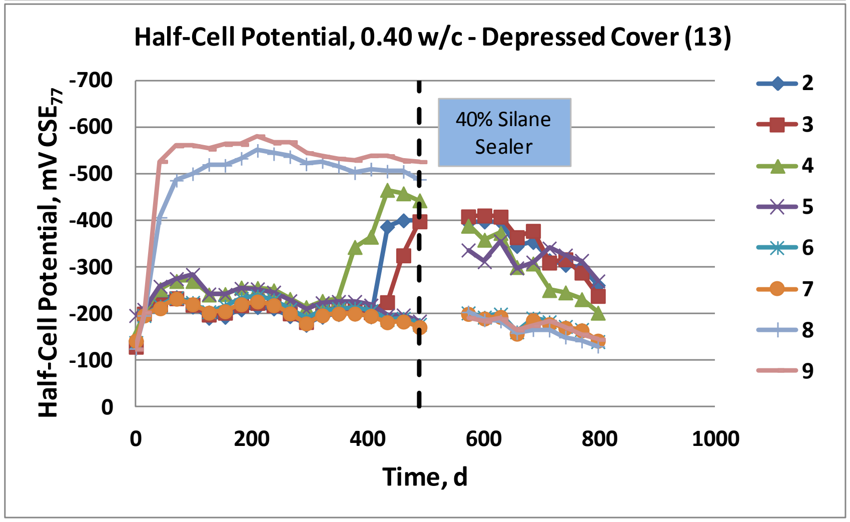

Integrated Current, 0.40 w/c - High Water Content (10)
Integrated Macrocell Current, C
Time, d
Repair Mixture (Control)
2
3
4
5
6
7
8
9

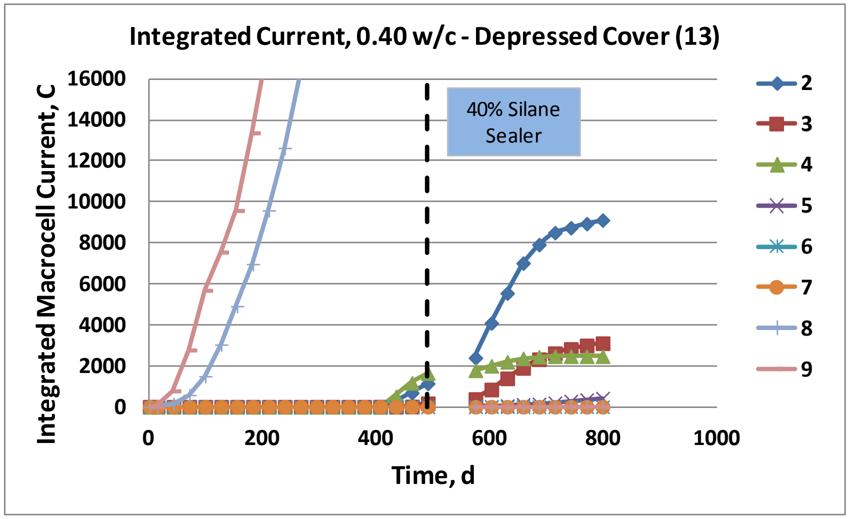

Half-Cell Potential, 0.40 w/c - Depressed Cover (11)
Half-Cell Potential, mV CSE_{77}
Time, d
Galvanic Anode
2
3
4
5
6
7
8
9

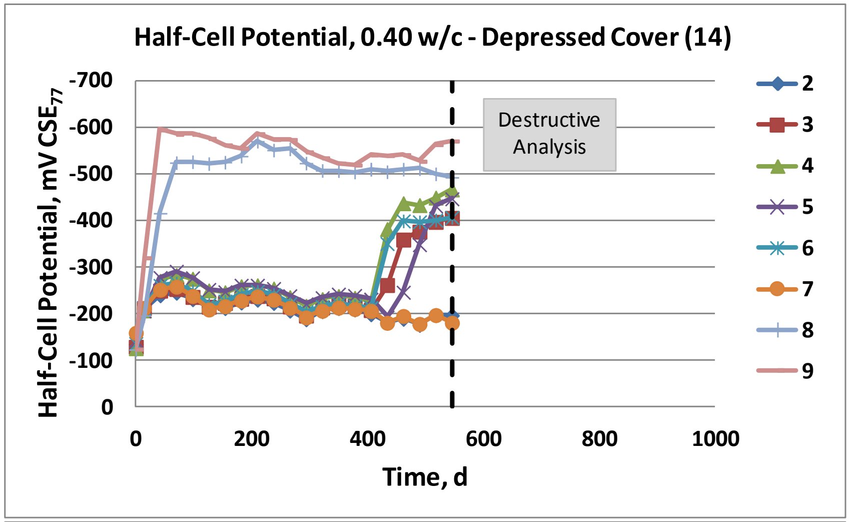

Integrated Current, 0.40 w/c - Depressed Cover (11)
Integrated Macrocell Current, C
Time, d
Galvanic Anode
2
3
4
5
6
7
8
9

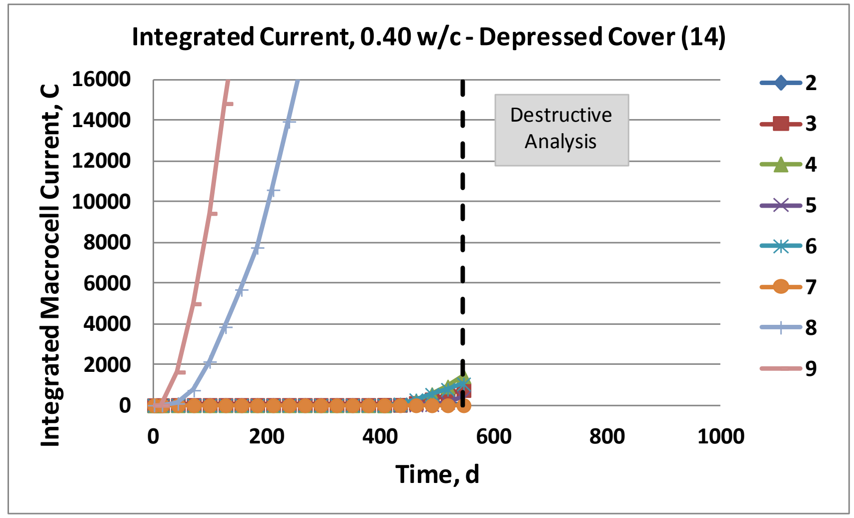

Half-Cell Potential, 0.40 w/c - Depressed Cover (12)
Half-Cell Potential, mV CSE77
Time, d
40% Silane Sealer
-700
-600
-500
-400
-300
-200
-100
0
0
200
400
600
800
1000
2
3
4
5
6
7
8
9

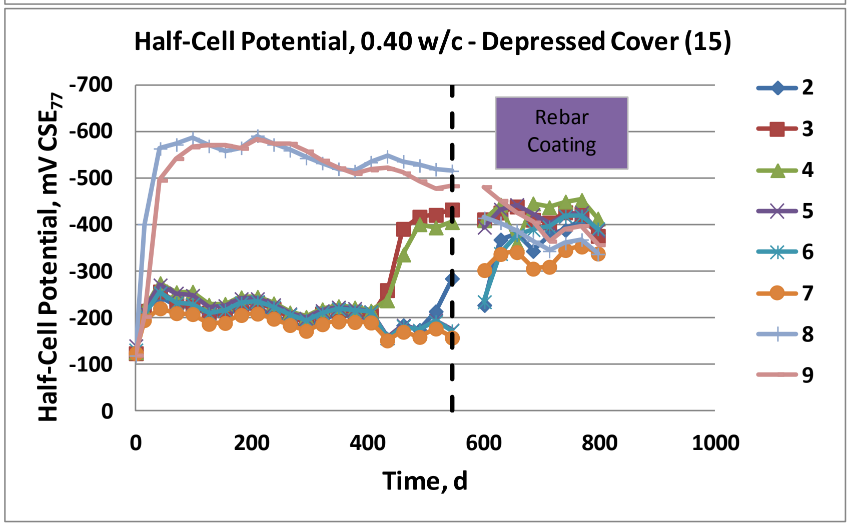

Integrated Current, 0.40 w/c - Depressed Cover (12)
Integrated Macrocell Current, C
Time, d
40% Silane Sealer
16000
14000
12000
10000
8000
6000
4000
2000
0
0
200
400
600
800
1000
2
3
4
5
6
7
8
9

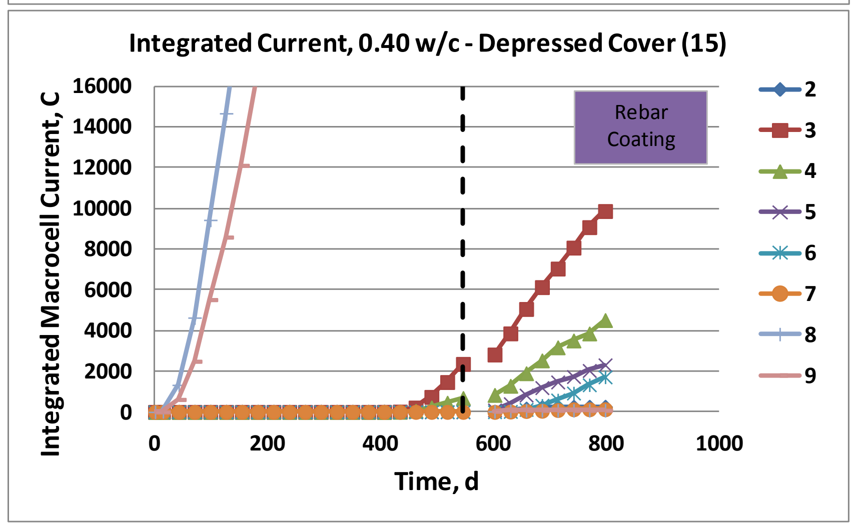

Half-Cell Potential, 0.40 w/c - Depressed Cover (13)
Half-Cell Potential, mV CSE77
Time, d
40% Silane Sealer
-700
-600
-500
-400
-300
-200
-100
0
0
200
400
600
800
1000
2
3
4
5
6
7
8
9


Integrated Current, 0.40 w/c - Depressed Cover (13)
Integrated Macrocell Current, C
Time, d
40% Silane Sealer
16000
14000
12000
10000
8000
6000
4000
2000
0
0
200
400
600
800
1000
2
3
4
5
6
7
8
9

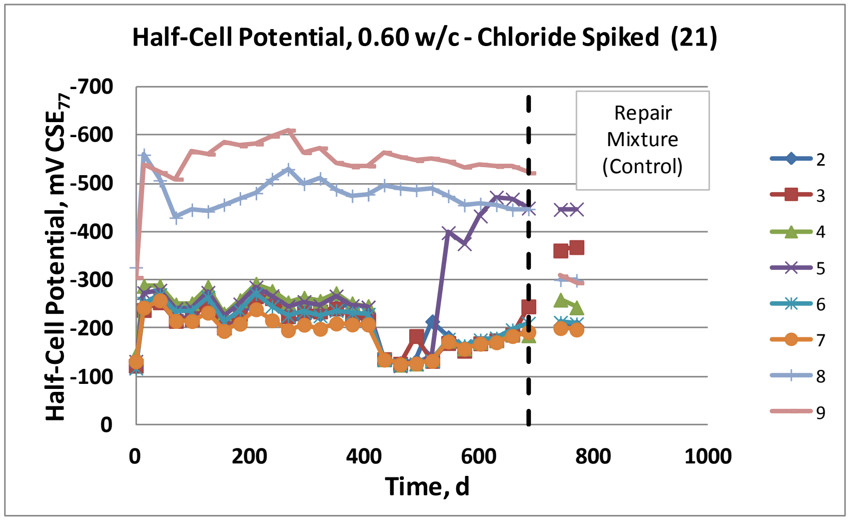

Half-Cell Potential, 0.40 w/c - Depressed Cover (14)
Half-Cell Potential, mV CSE77
Time, d
Destructive Analysis
2
3
4
5
6
7
8
9

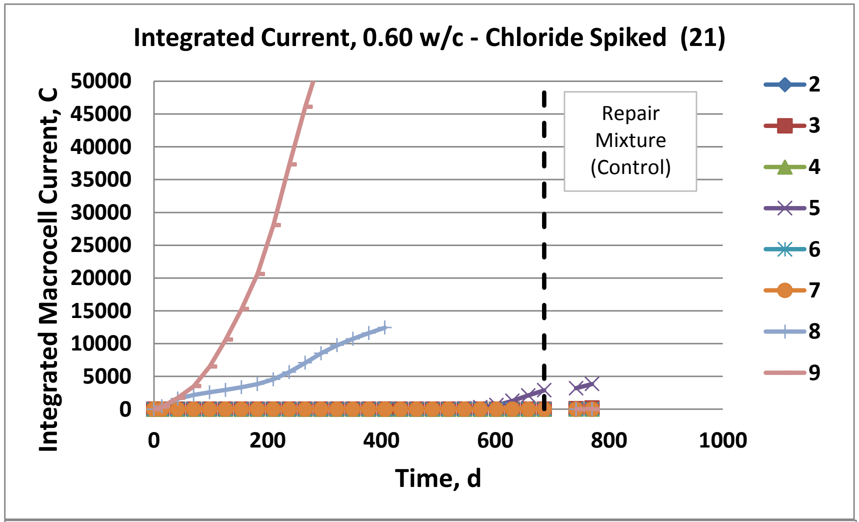

Integrated Current, 0.40 w/c - Depressed Cover (14)
Integrated Macrocell Current, C
Time, d
Destructive Analysis
2
3
4
5
6
7
8
9

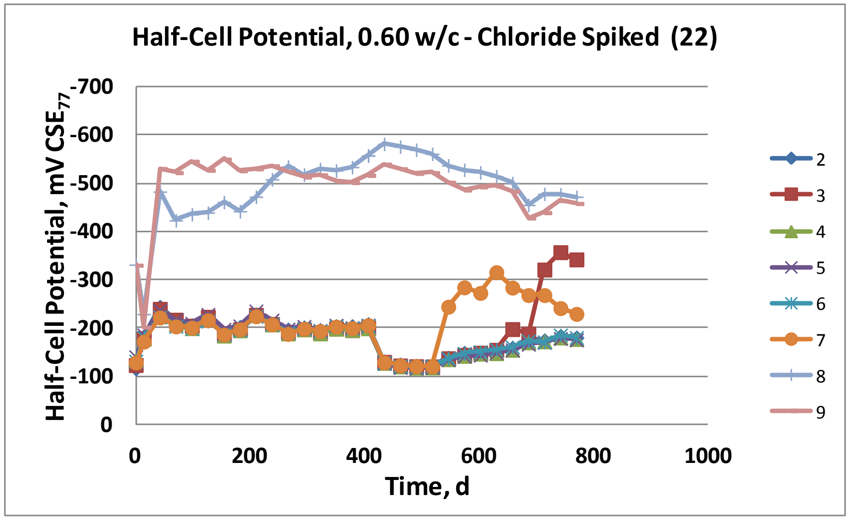

Half-Cell Potential, 0.40 w/c - Depressed Cover (15)
Half-Cell Potential, mV CSE77
Time, d
Rebar Coating
2
3
4
5
6
7
8
9

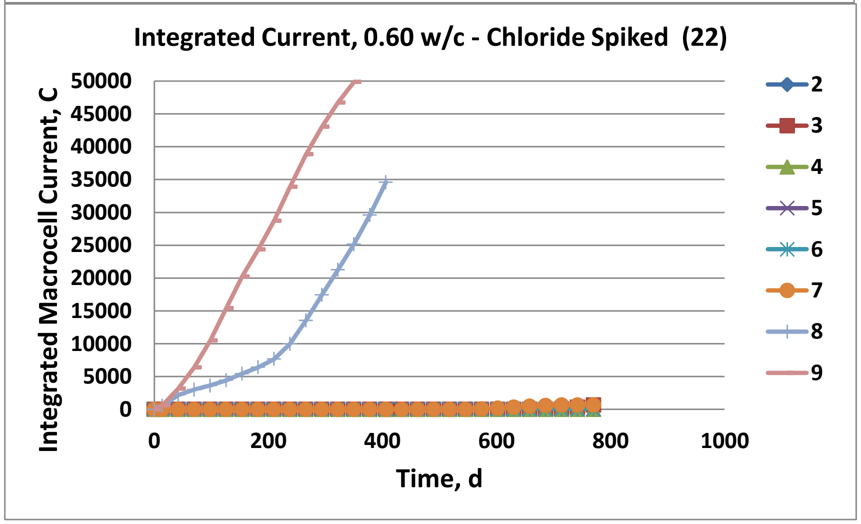

Integrated Current, 0.40 w/c - Depressed Cover (15)
Integrated Macrocell Current, C
Time, d
Rebar Coating
2
3
4
5
6
7
8
9

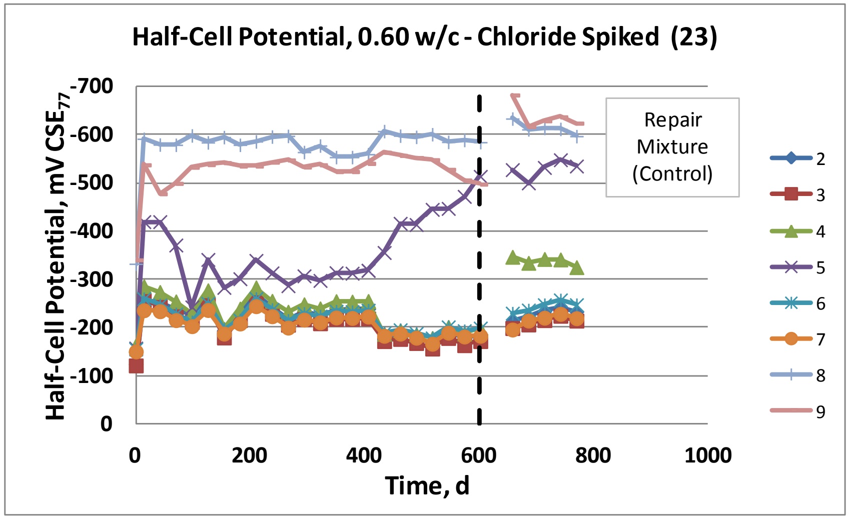
Batch #2

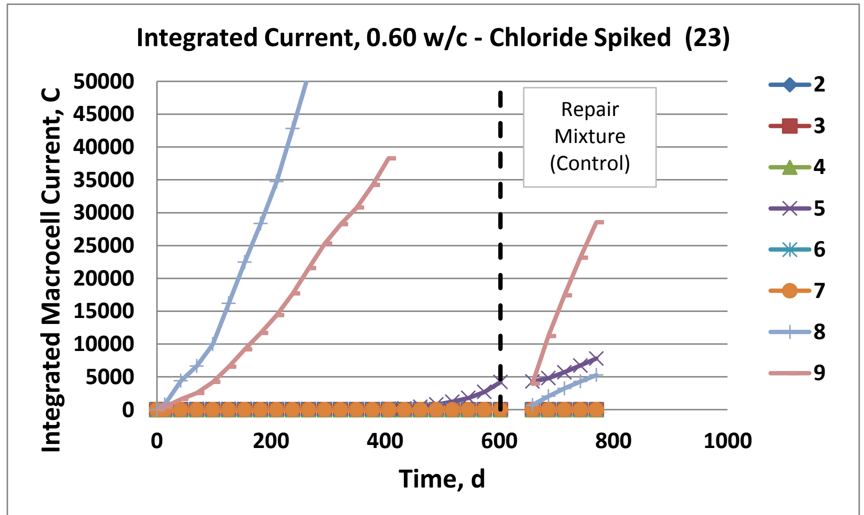

Half-Cell Potential, 0.60 w/c - Chloride Spiked (21)
Half-Cell Potential, mV CSE_{77}
Time, d
Repair Mixture (Control)
2
3
4
5
6
7
8
9

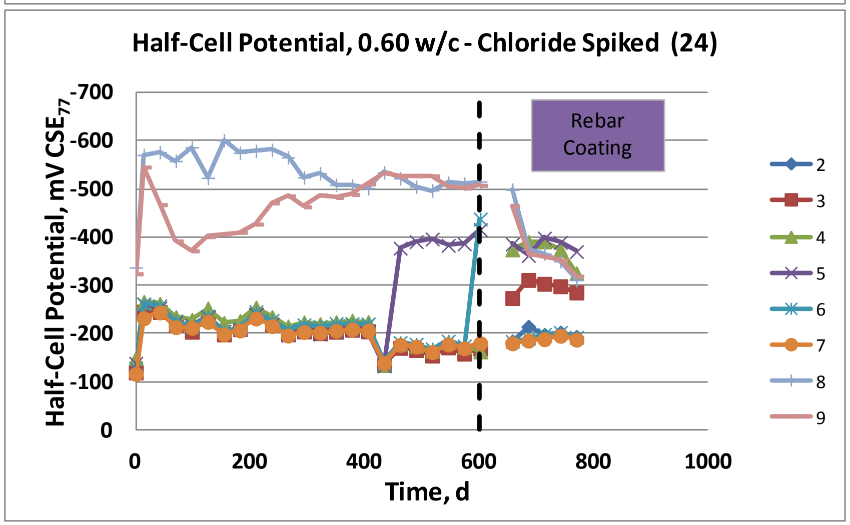

Integrated Current, 0.60 w/c - Chloride Spiked (21)
Integrated Macrocell Current, C
Time, d
Repair Mixture (Control)
2
3
4
5
6
7
8
9

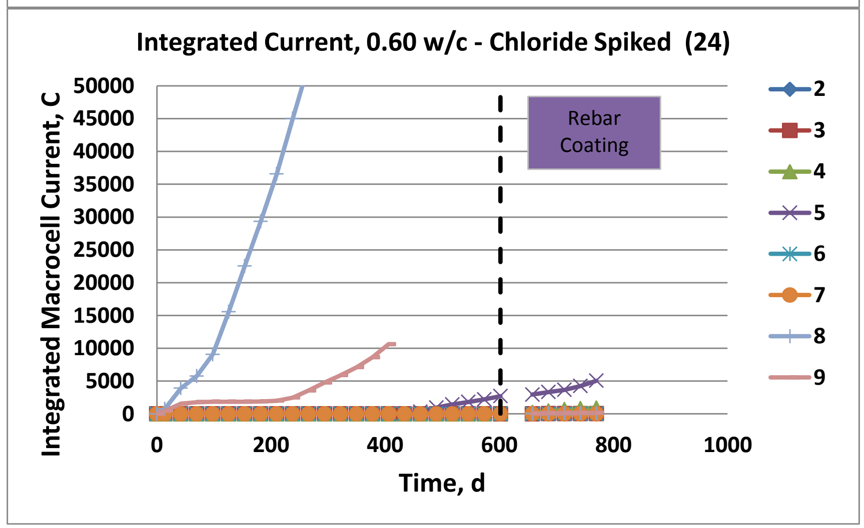

Half-Cell Potential, 0.60 w/c - Chloride Spiked (22)
Half-Cell Potential, mV CSE_{77}
Time, d
2
3
4
5
6
7
8
9

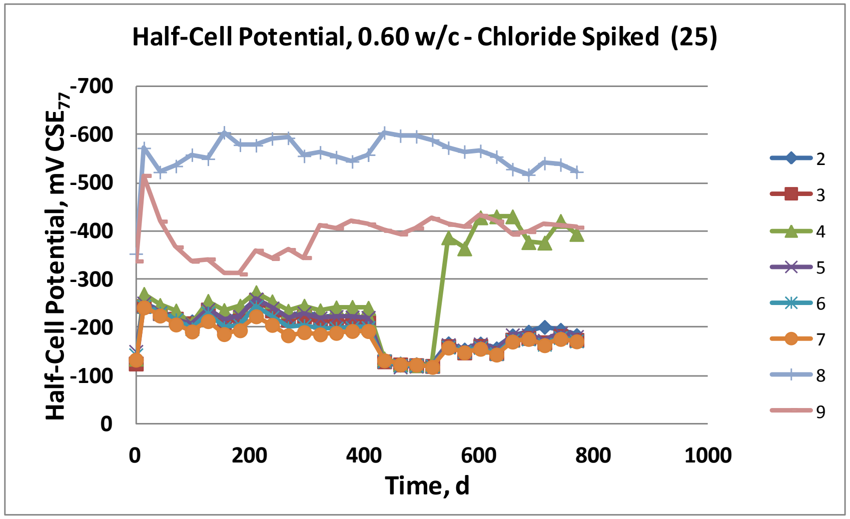

Integrated Current, 0.60 w/c - Chloride Spiked (22)
Integrated Macrocell Current, C
Time, d
2
3
4
5
6
7
8
9

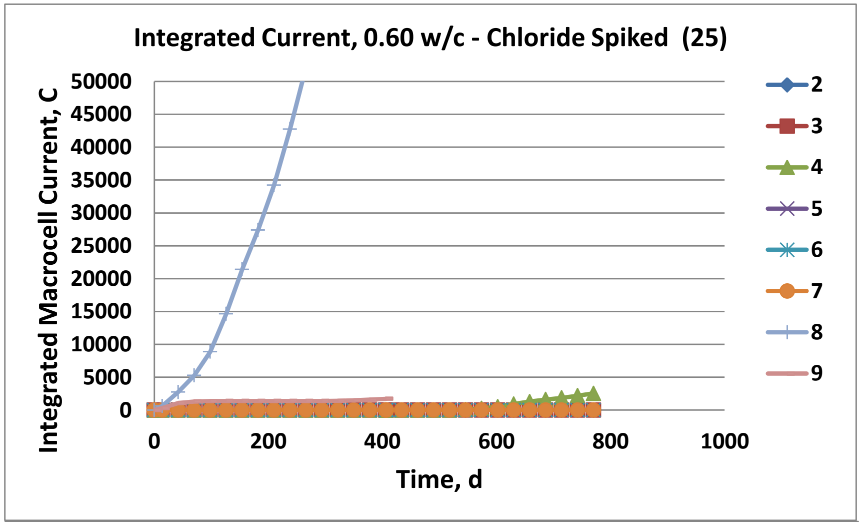

Half-Cell Potential, 0.60 w/c - Chloride Spiked (23)
Repair Mixture (Control)
Half-Cell Potential, mV CSE_{77}
-700
-600
-500
-400
-300
-200
-100
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

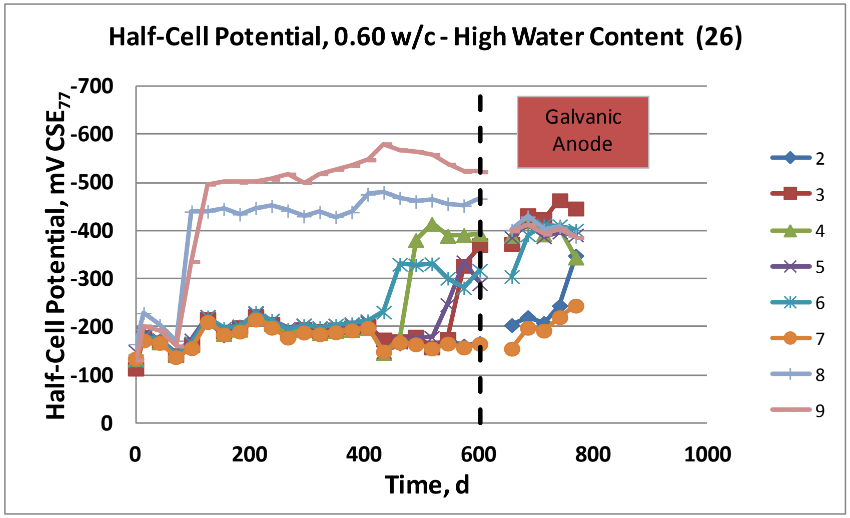

Integrated Current, 0.60 w/c - Chloride Spiked (23)
Repair Mixture (Control)
Integrated Macrocell Current, C
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

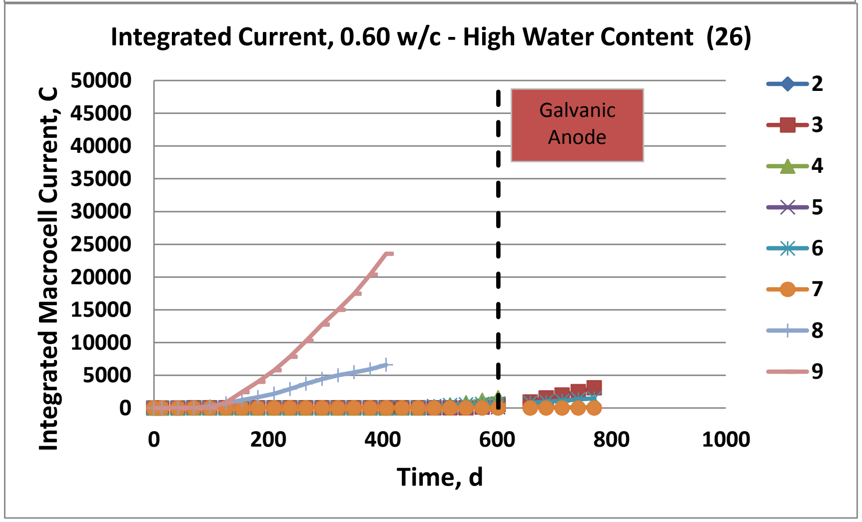

Half-Cell Potential, 0.60 w/c - Chloride Spiked (24)
Rebar Coating
Half-Cell Potential, mV CSE_{77}
-700
-600
-500
-400
-300
-200
-100
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

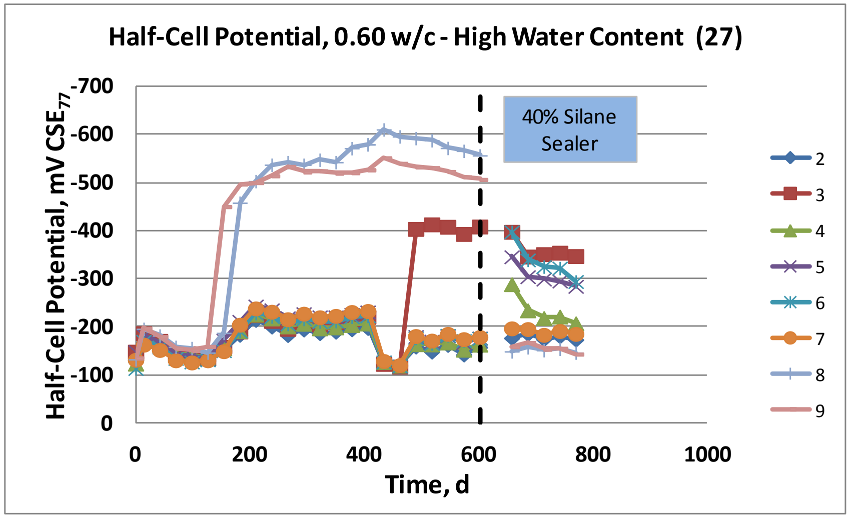

Integrated Current, 0.60 w/c - Chloride Spiked (24)
Rebar Coating
Integrated Macrocell Current, C
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

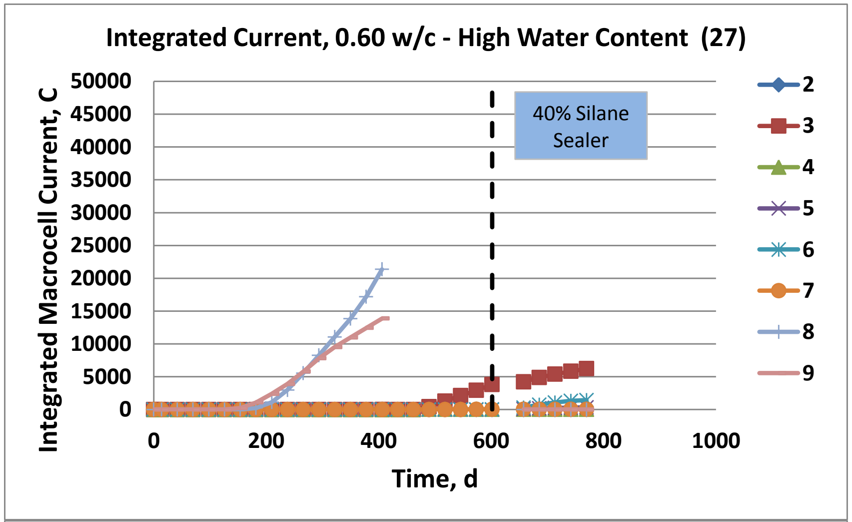

Half-Cell Potential, 0.60 w/c - Chloride Spiked (25)
Half-Cell Potential, mV CSE77
-700
-600
-500
-400
-300
-200
-100
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

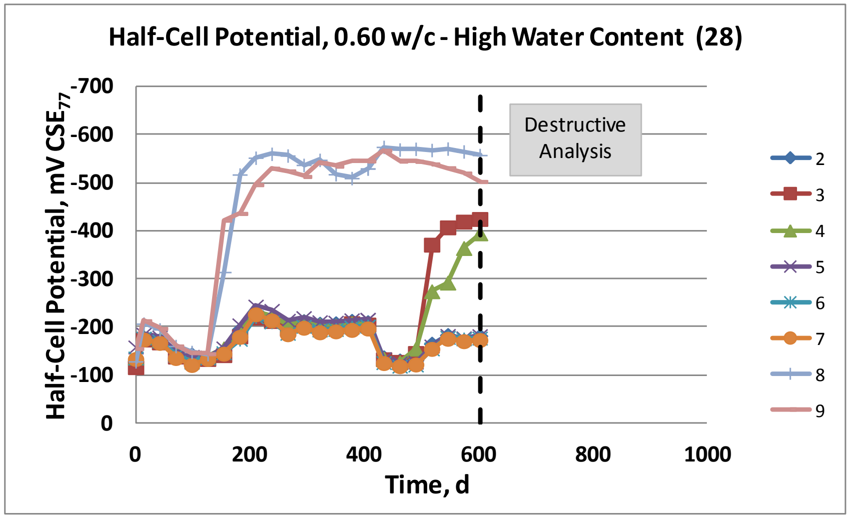

Integrated Current, 0.60 w/c - Chloride Spiked (25)
Integrated Macrocell Current, C
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

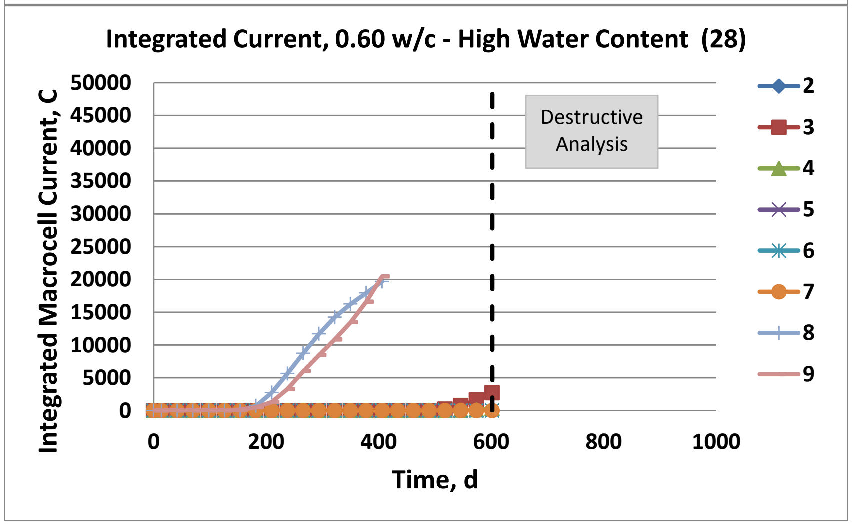

Half-Cell Potential, 0.60 w/c - High Water Content (26)
Galvanic Anode
Half-Cell Potential, mV CSE77
-700
-600
-500
-400
-300
-200
-100
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

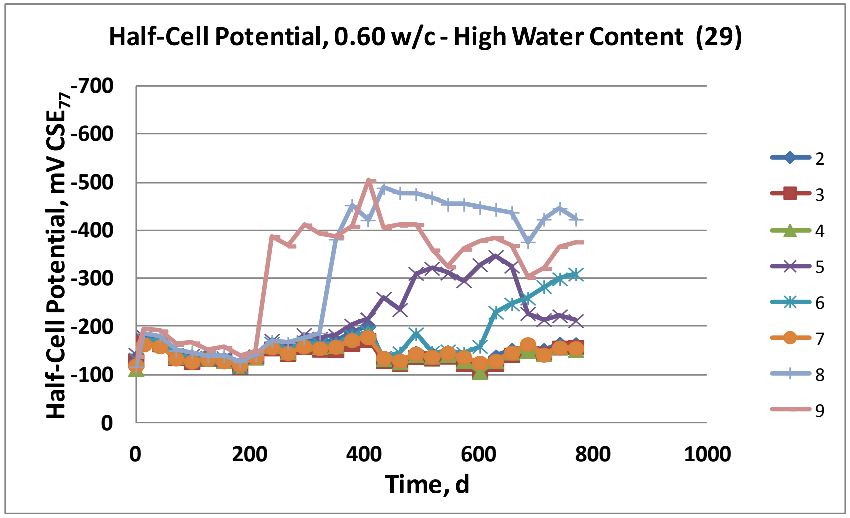

Integrated Current, 0.60 w/c - High Water Content (26)
Galvanic Anode
Integrated Macrocell Current, C
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

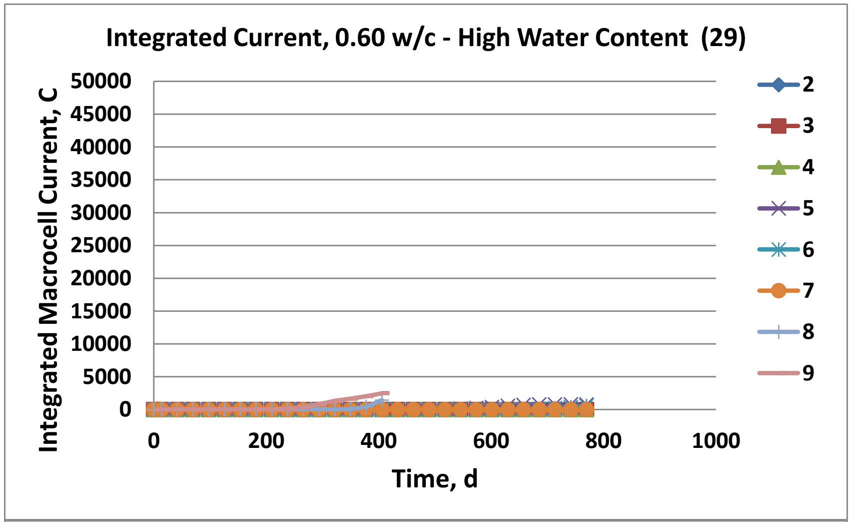

Half-Cell Potential, 0.60 w/c - High Water Content (27)
Half-Cell Potential, mV CSE77
Time, d
40% Silane Sealer
-700
-600
-500
-400
-300
-200
-100
0
0
200
400
600
800
1000
2
3
4
5
6
7
8
9

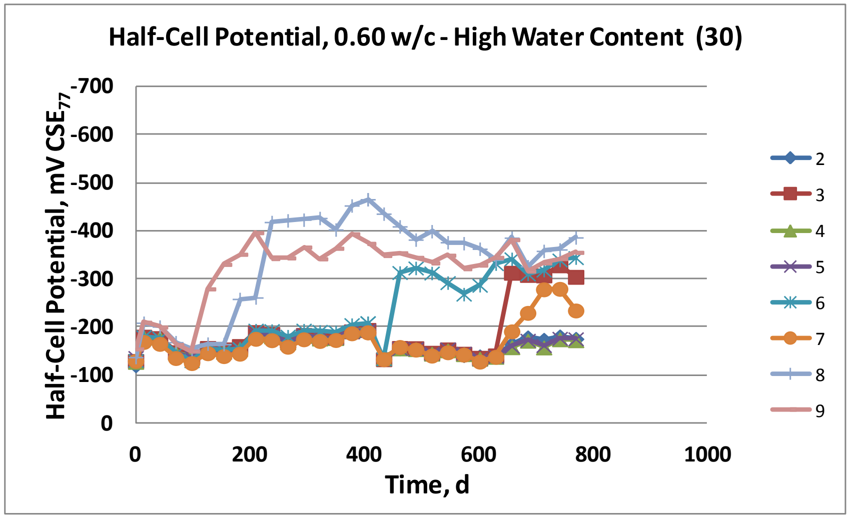

Integrated Current, 0.60 w/c - High Water Content (27)
Integrated Macrocell Current, C
Time, d
40% Silane Sealer
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
200
400
600
800
1000
2
3
4
5
6
7
8
9

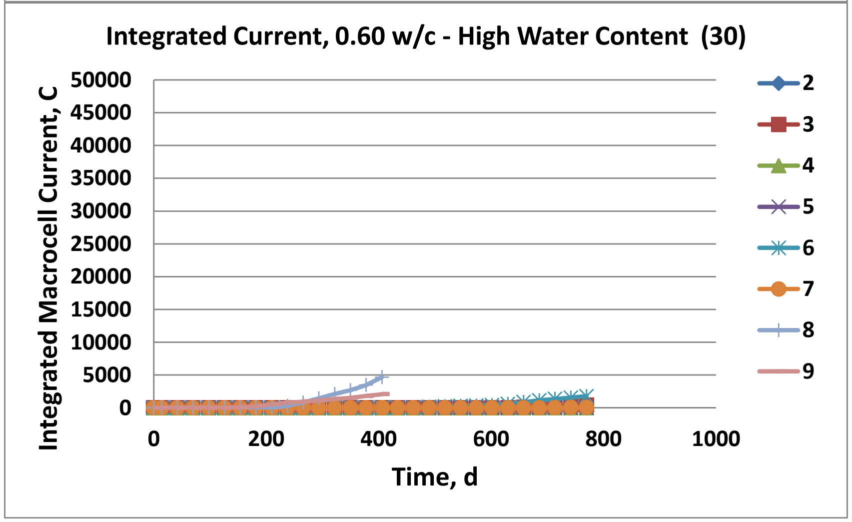

Half-Cell Potential, 0.60 w/c - High Water Content (28)
Half-Cell Potential, mV CSE77
Time, d
Destructive Analysis
-700
-600
-500
-400
-300
-200
-100
0
0
200
400
600
800
1000
2
3
4
5
6
7
8
9

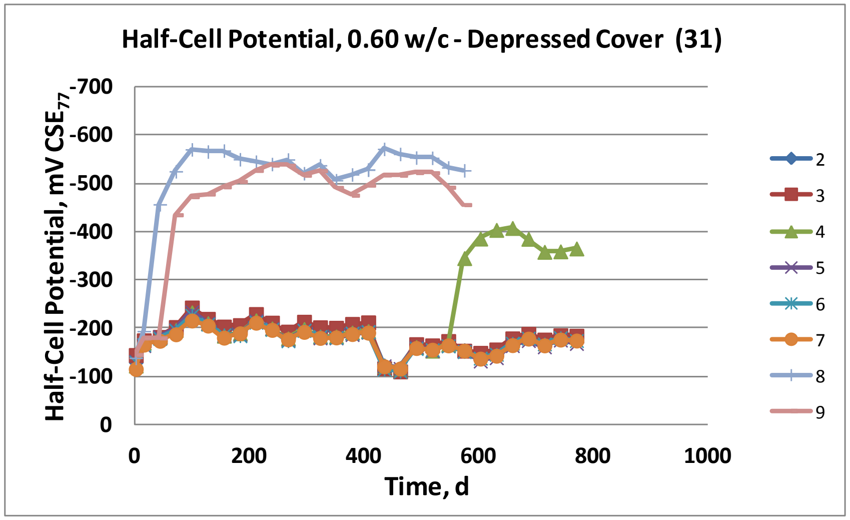

Integrated Current, 0.60 w/c - High Water Content (28)
Integrated Macrocell Current, C
Time, d
Destructive Analysis
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
200
400
600
800
1000
2
3
4
5
6
7
8
9

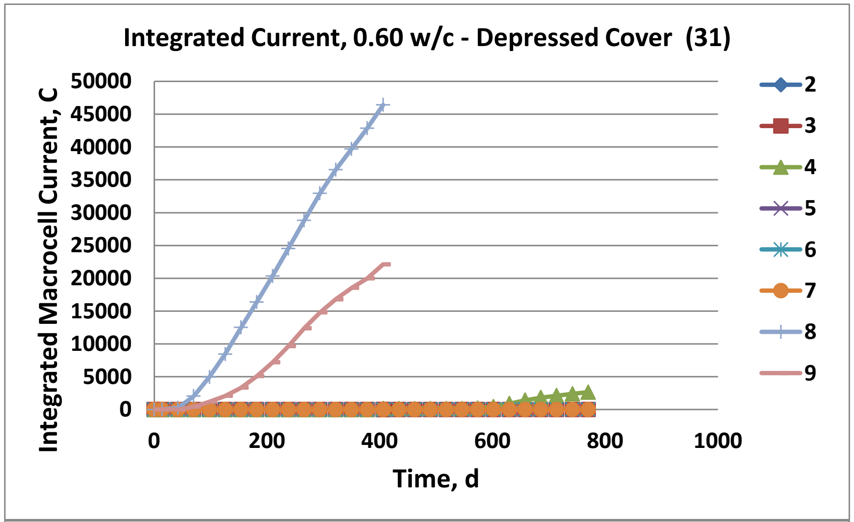

Half-Cell Potential, 0.60 w/c - High Water Content (29)
Half-Cell Potential, mV CSE77
-700
-600
-500
-400
-300
-200
-100
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

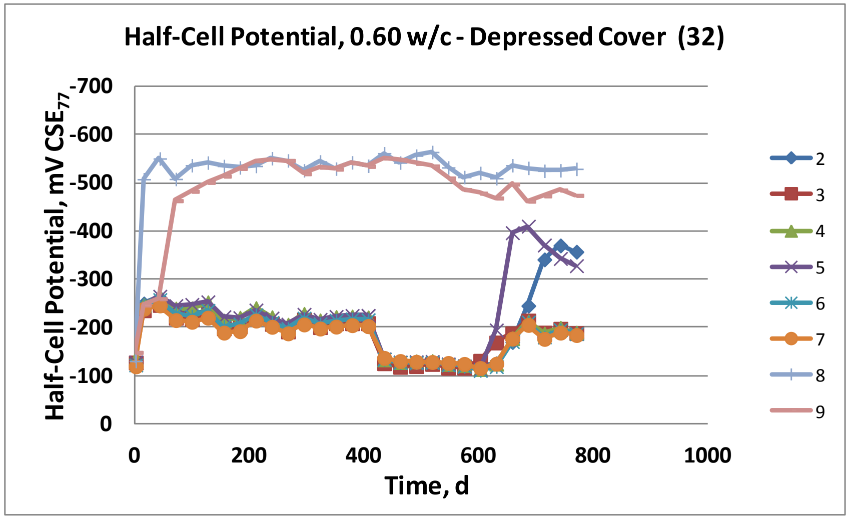

Integrated Current, 0.60 w/c - High Water Content (29)
Integrated Macrocell Current, C
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

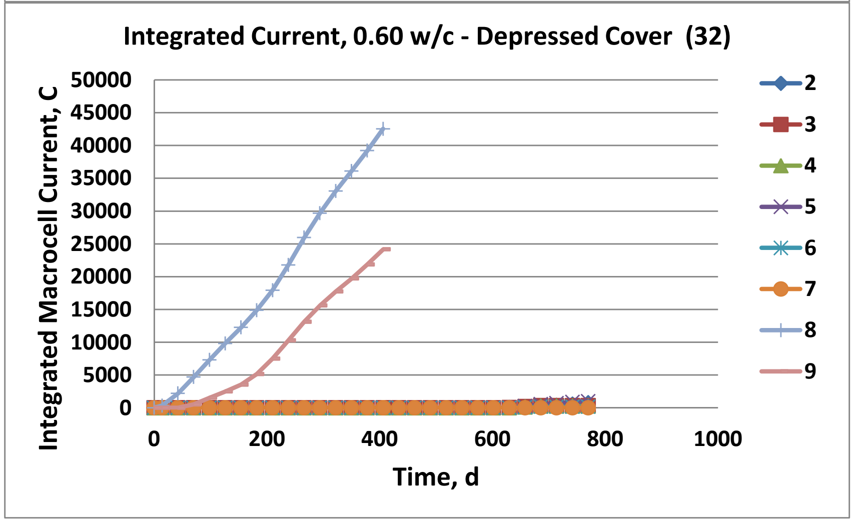

Half-Cell Potential, 0.60 w/c - High Water Content (30)
Half-Cell Potential, mV CSE77
-700
-600
-500
-400
-300
-200
-100
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

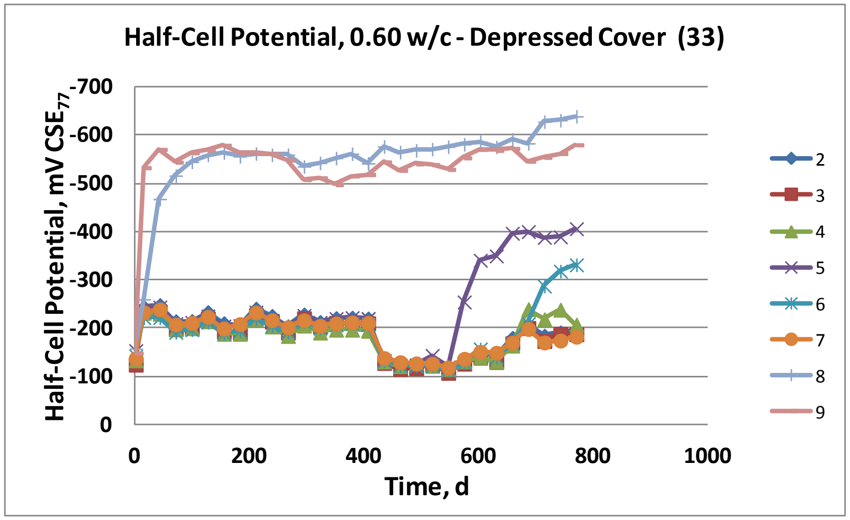

Integrated Current, 0.60 w/c - High Water Content (30)
Integrated Macrocell Current, C
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

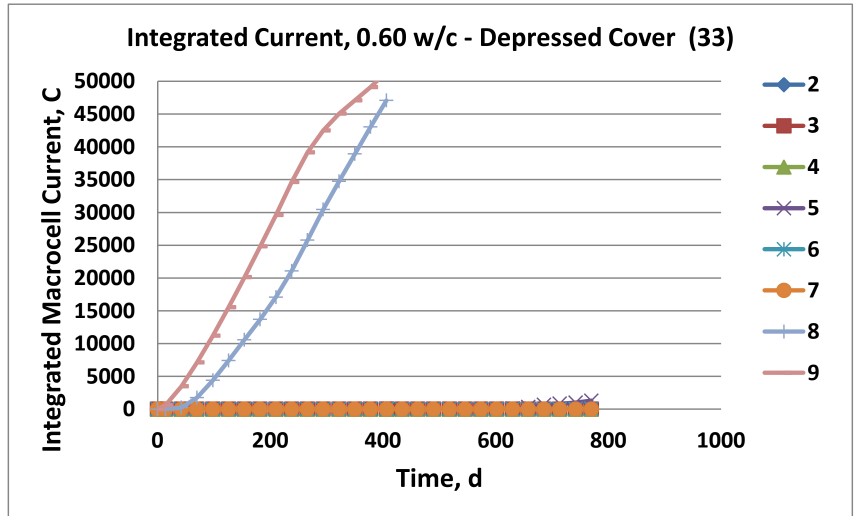

Half-Cell Potential, 0.60 w/c - Depressed Cover (31)
Half-Cell Potential, mV CSE_{77}
-700
-600
-500
-400
-300
-200
-100
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

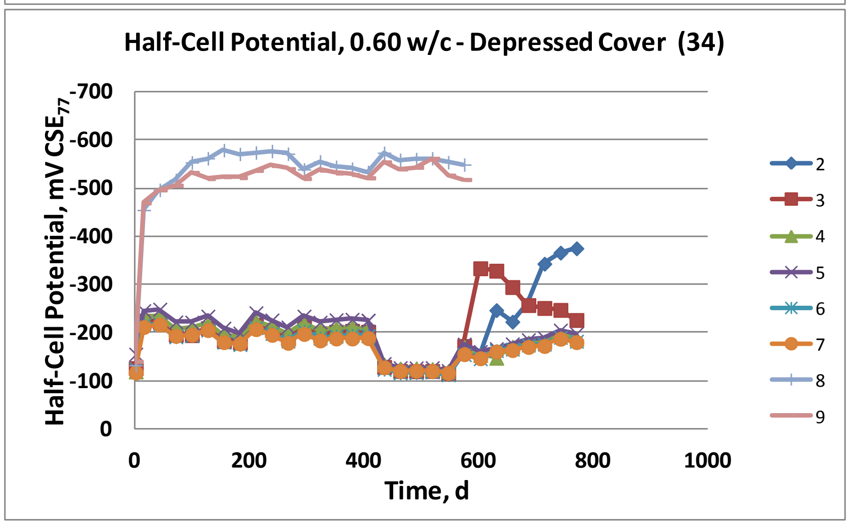

Integrated Current, 0.60 w/c - Depressed Cover (31)
Integrated Macrocell Current, C
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

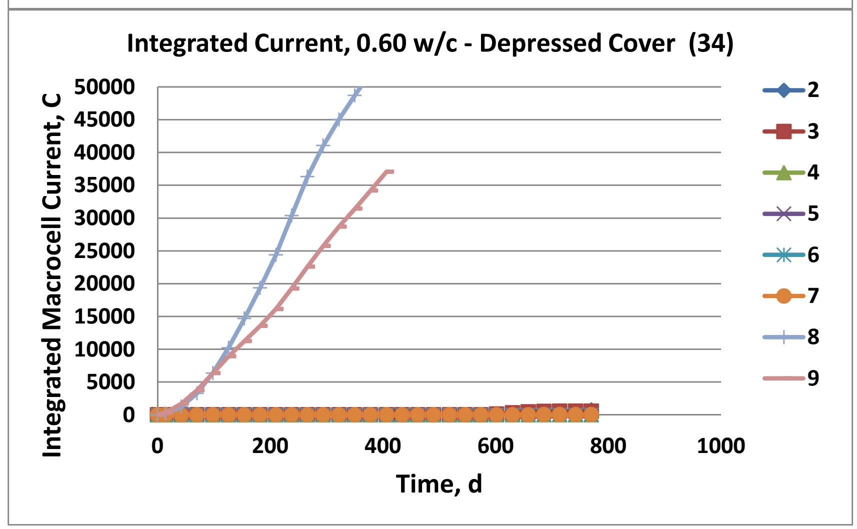

Half-Cell Potential, 0.60 w/c - Depressed Cover (32)
Half-Cell Potential, mV CSE_{77}
-700
-600
-500
-400
-300
-200
-100
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

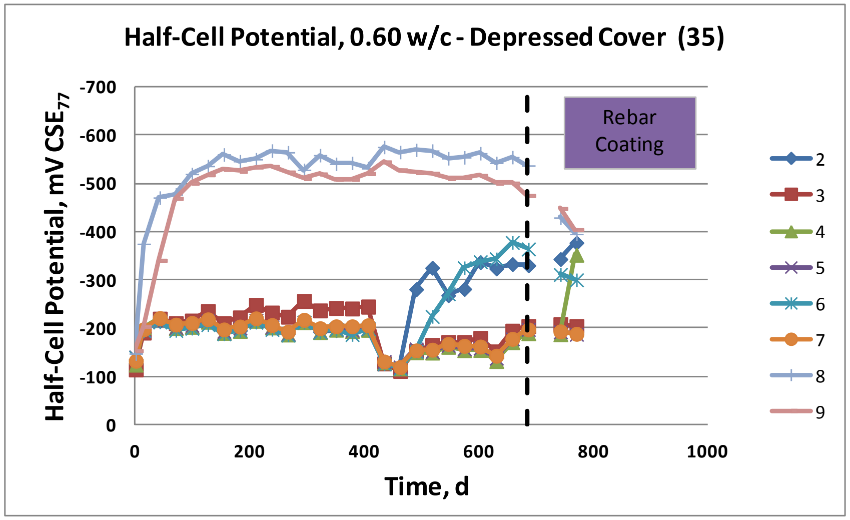

Integrated Current, 0.60 w/c - Depressed Cover (32)
Integrated Macrocell Current, C
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
200
400
600
800
1000
Time, d
2
3
4
5
6
7
8
9

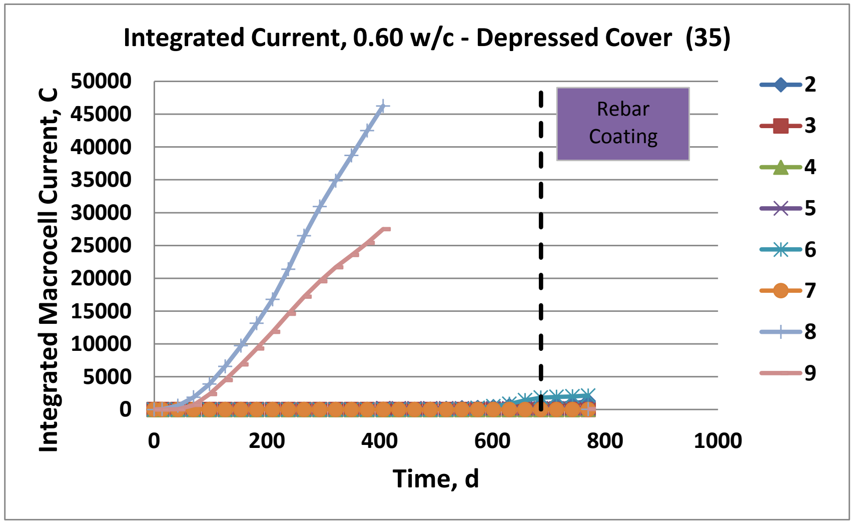

Half-Cell Potential, 0.60 w/c - Depressed Cover (33)
Half-Cell Potential, mV CSE_{77}
Time, d
2
3
4
5
6
7
8
9


Integrated Current, 0.60 w/c - Depressed Cover (33)
Integrated Macrocell Current, C
Time, d
2
3
4
5
6
7
8
9


Half-Cell Potential, 0.60 w/c - Depressed Cover (34)
Half-Cell Potential, mV CSE_{77}
Time, d
2
3
4
5
6
7
8
9


Integrated Current, 0.60 w/c - Depressed Cover (34)
Integrated Macrocell Current, C
Time, d
2
3
4
5
6
7
8
9


Half-Cell Potential, 0.60 w/c - Depressed Cover (35)
Half-Cell Potential, mV CSE77
-700
-600
-500
-400
-300
-200
-100
0
0
200
400
600
800
1000
Time, d
Rebar Coating
2
3
4
5
6
7
8
9


Integrated Current, 0.60 w/c - Depressed Cover (35)
Integrated Macrocell Current, C
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
200
400
600
800
1000
Time, d
Rebar Coating
2
3
4
5
6
7
8
9