VOTERS
April 3, 2013

Master's Thesis Defense

Modeling Half-Cell Potentials and their Relationship to Corrosion of Reinforcing Steel

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Outline

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- Experimental Setup
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- Results – Current Density
- Conclusion
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Introduction

- **Benefits of Non-Destructive Testing (NDT)**
  - Specimen stays intact
  - Reliability
  - Speed of evaluation
- **Common NDT Methods**
  - Ultrasonic – *Vibrations induced in the structure*
  - Ground Penetrating Radar – *Reflection of radar waves off the rebars*
  - Seismic – *Seismic waves induced in the structure and reflections recorded*
  - Visual Inspection – *Observation of the condition of the structure*
  - Acoustic – *Sound waves travel through the concrete and reflect off the rebars*
  - Half-Cell Potential (HCP) – *Based on a transfer of electrons in a reference electrode*

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Introduction

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- **Half-Cell Potential**
- HCP is the difference in potential created when electrons transfer between a metal and its salt across a boundary.
- The HCP measurement system uses a high impedance voltmeter, a reference electrode, and a connection to the rebar.
- The HCP values are read from the voltmeter, then the likelihood of corrosion can be determined based on the HCP reading [ASTM C876].
- Currently, no model exists for the relationship of HCP and time on large scale structures such as bridge decks and parking garages. An objective of this thesis is to model such a relationship and to determine the density of the current in the rebar when the HCP measurements are taken.

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Introduction

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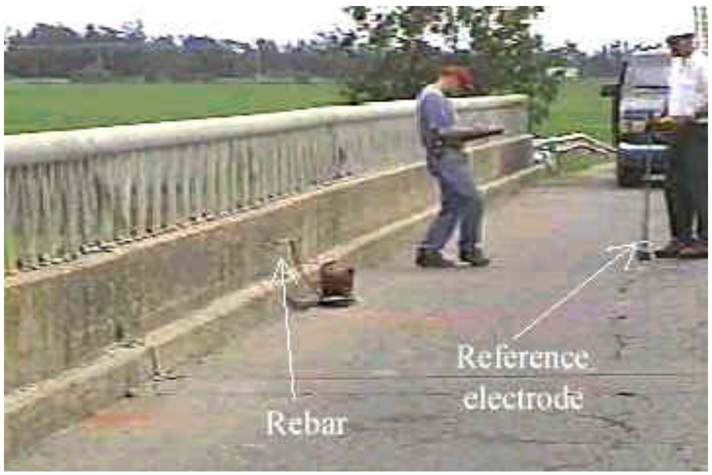
HCP Applications

- Bridge Decks
- Parking Garages
- Retaining Walls



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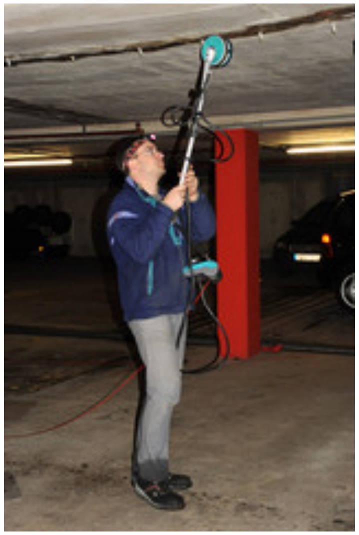

Source: www.canin-concrete-cover.com

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Introduction

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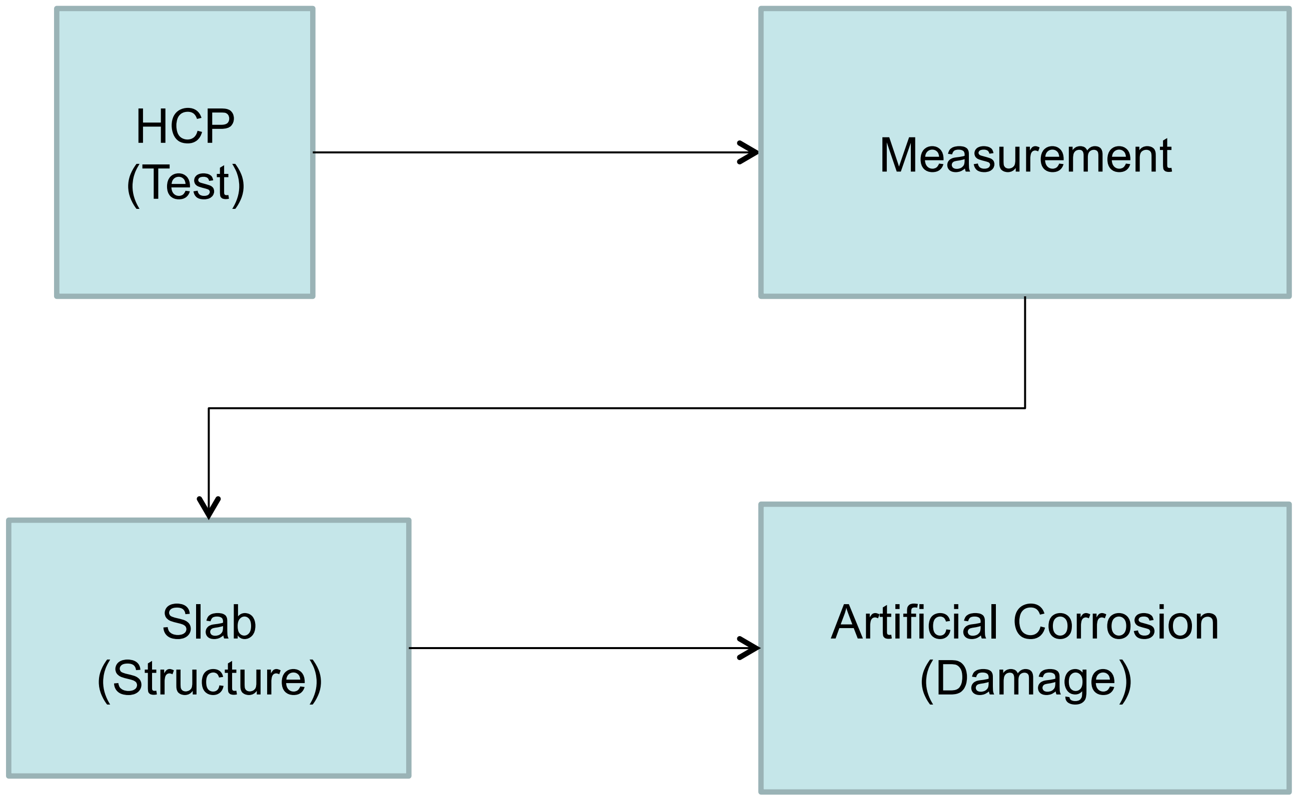
- Currently, there is no model for the spatial distribution of HCP
  - Most prior research has been done on cylinders with only 1 small rebar
  - Large reinforced concrete (RC) structures contain many rebars in a single member
- There is no model of the time history of HCP
  - Prior research has only focused on the HCP at the end of the test
  - HCP values change throughout the life of RC structures as chlorides and chemicals penetrate the concrete cover

Objectives

- Model the time-dependent relationship of HCP on four large RC slabs.
- Determine the importance of concrete cover in influencing the rate of corrosion of steel rebars.
- Calculate the current density in the rebars at the time the measurements are taken.
- Correlate the current density to the amount of corrosion on each rebar.
- Relate current density to HCP to predict the amount of corrosion on each rebar.

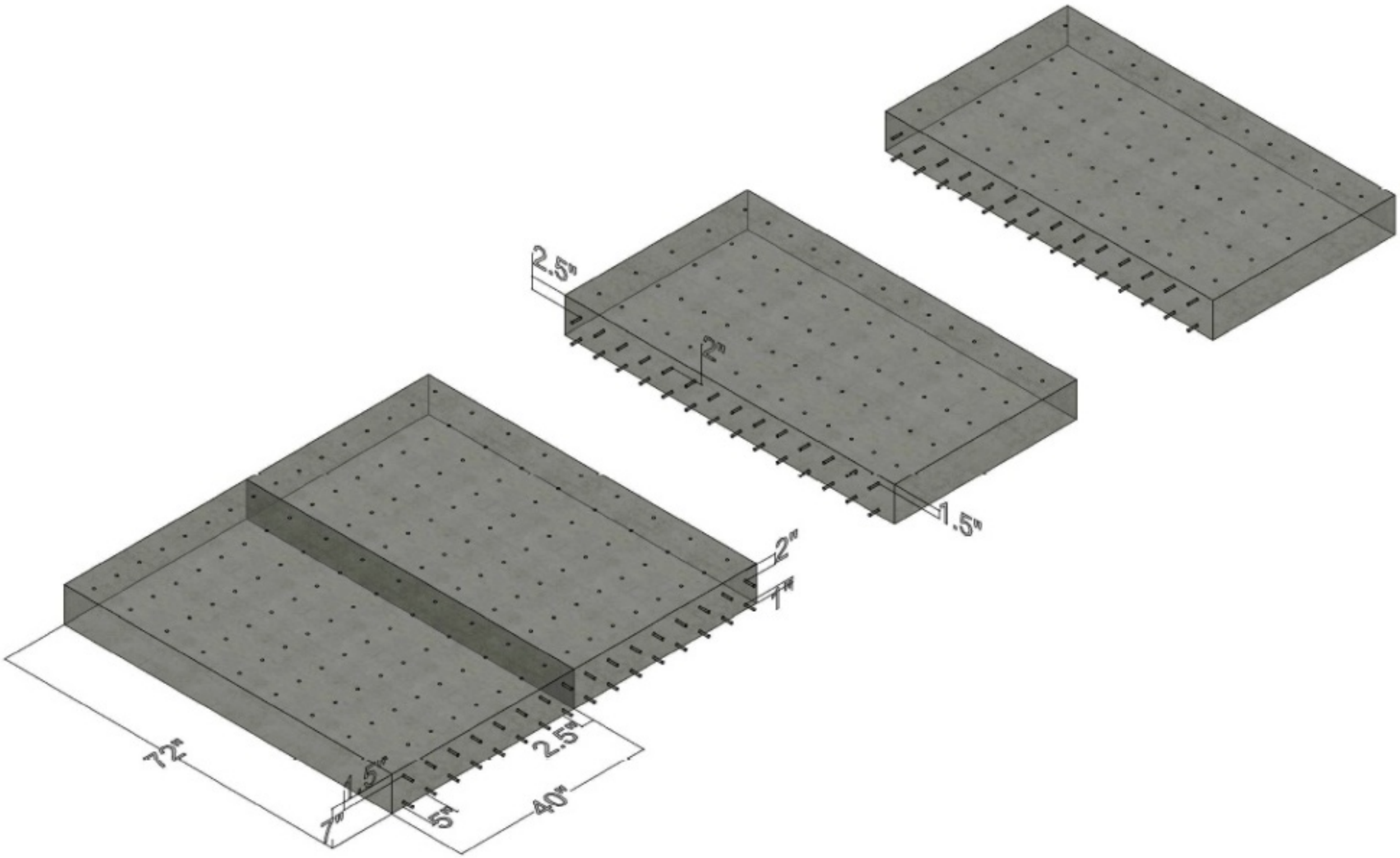
Literature Review



Literature Review

- Corrosion by inducing a current
  - Current induced in the rebars to accelerate the breakdown of the passive layer
  - Current usually measured by current density
- Corrosion by ponding
  - Involves creating an artificial corrosion environment
  - Specimens are either ponded or sprayed with a saline solution
  - Chlorides sometimes included in mix water
- No experiments have been done on large RC slabs

Experimental Setup



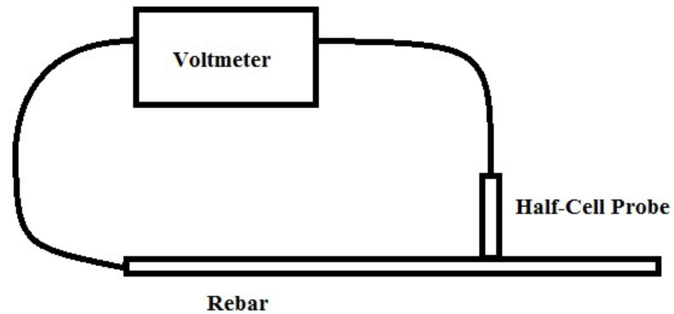
Experimental Setup

- All measurements were taken directly over the rebars to minimize resistance from the concrete.
- Wires were welded to the ends of the rebars to provide a good connection between the rebars and the voltmeter.
- Water / cement = .52
- Compressive strength = 3625 psi

Photo of the experiment
Concrete Lab, CEE, UMass Lowell

Experimental Setup

Measurement Equipment



The voltmeter is connected to the rebars and to a reference electrode. The electrode is placed atop the concrete and a circuit is formed through the concrete and rebar.

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Artificial Corrosion

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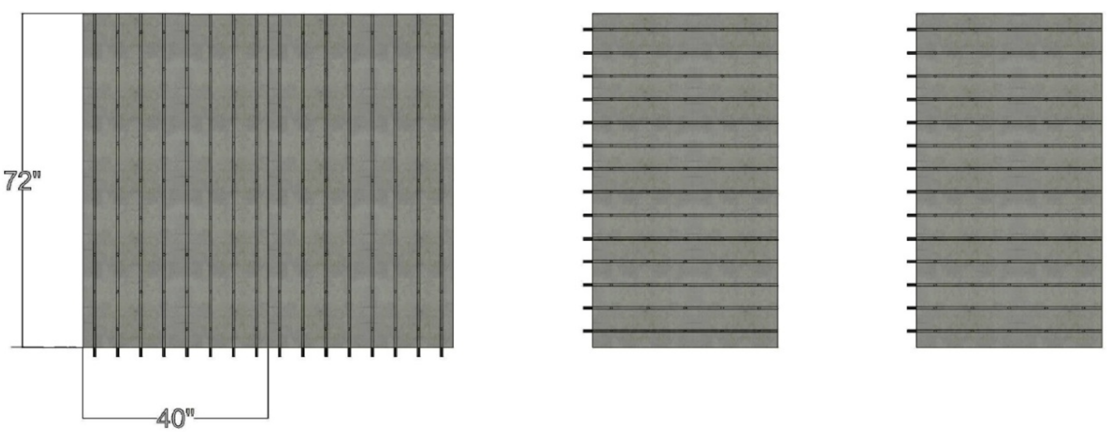
- Adapted version of the Modified Southern Exposure Test [4]
- Ponding cycle
  - Beginning on Friday, the slabs were ponded with a 15% NaCl solution; the temperature was set to 72^{o}F
- Drying Cycle
  - The solution was removed after 4 days and the temperature increased to 100^{o}F
  - HCP measurements were taken at the end of the 3-day drying period
- Slabs were prewetted before measurements were taken to ensure adequate conductivity.

	Sun	Mon	Tue	Wed	Thru	Fri	Sat
AM	Wet	Wet	Wet	Dry	Dry	Dry	Wet
PM	Wet	Wet	Dry	Dry	Dry	Wet	Wet

Data Collection

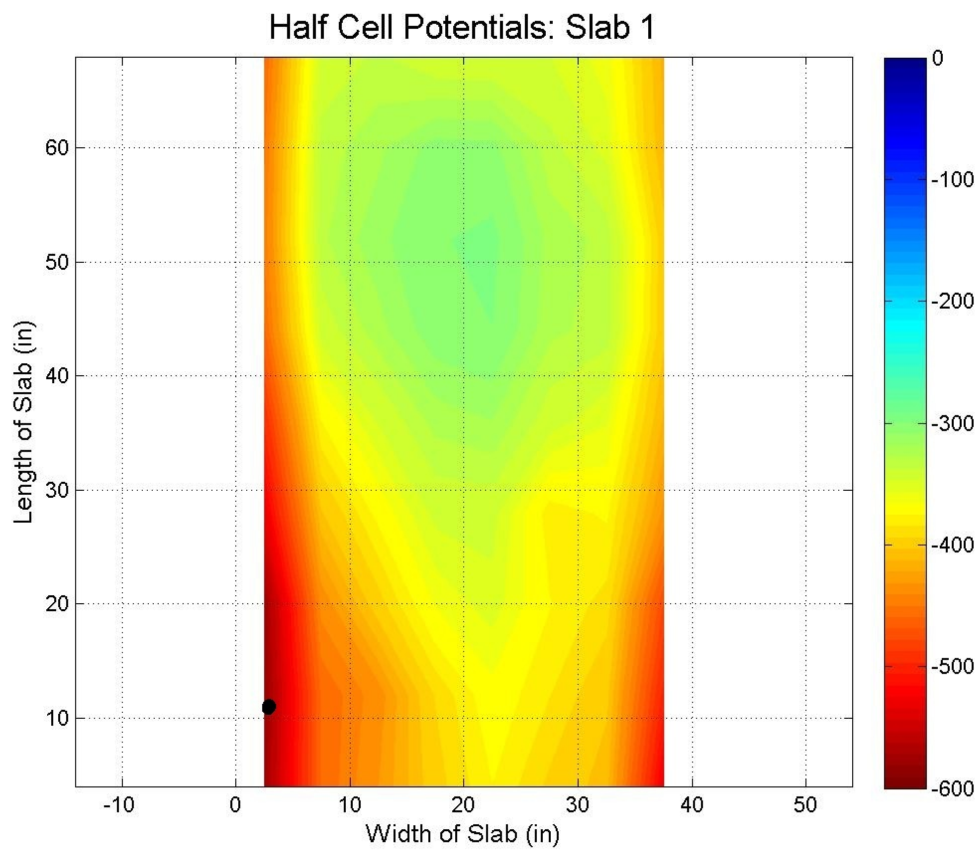
- A total of 72 measurements were taken on Slabs 1 (1.5” cover) and 2 (2” cover)
  - Each slab contained eight rebars
  - Nine measurements were taken per rebar
- A total of 70 measurements were taken on Slabs 3 and 4 (control)
  - Each slab contained fourteen transverse rebars
  - Five measurements were taken on each rebar



Data Collection

- Test lasted 52 weeks
- Interpretation of Data
  - ASTM C876 - 09
  - HCP > -200 mV indicates the rebar is 10% likely to be corroded
  - -200mV > HCP > -350 mV indicates the likelihood of corrosion is uncertain
  - -350mV > HCP indicates the rebar is 90% likely to be corroded

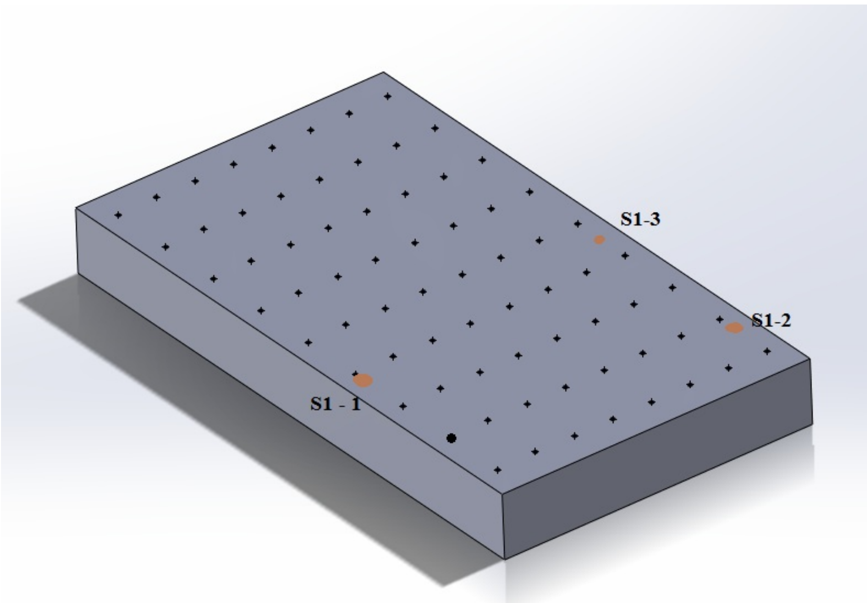
HCP Contour Maps

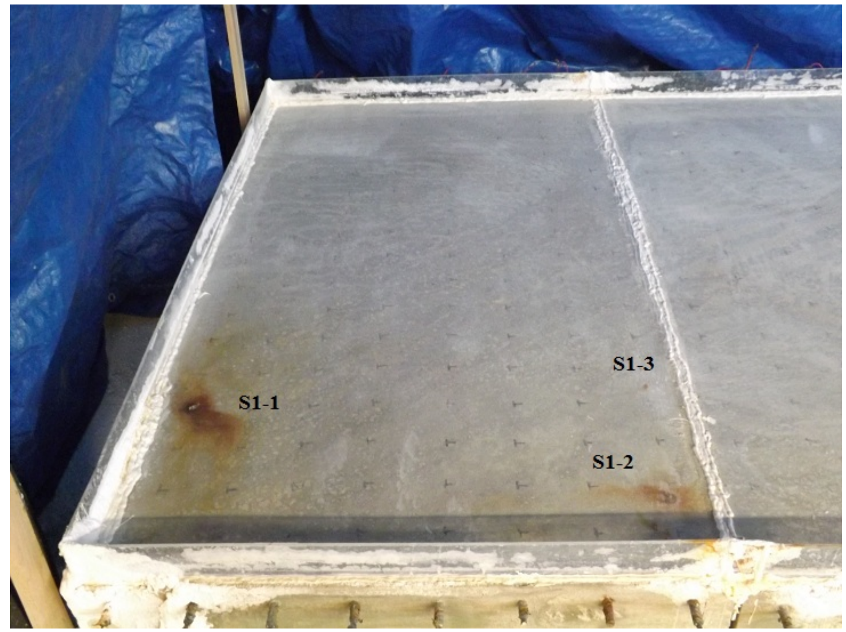


(Week 52)

Contour maps were as expected for Slab 1

HCP Results - Slab 1

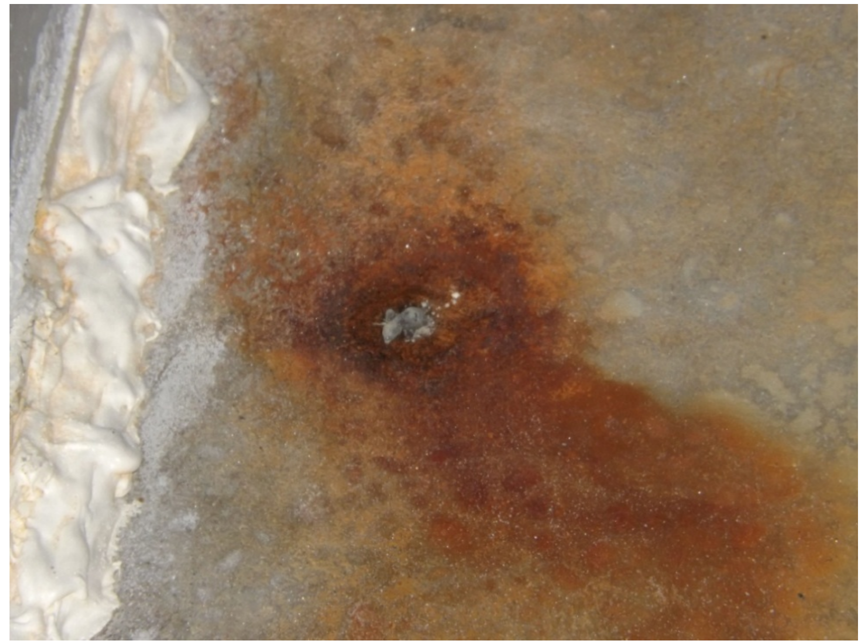




Concrete Laboratory, CEE, UMass Lowell
(Week 52)

HCP Results - Slab 1

S1-1



HCP = -530 mV

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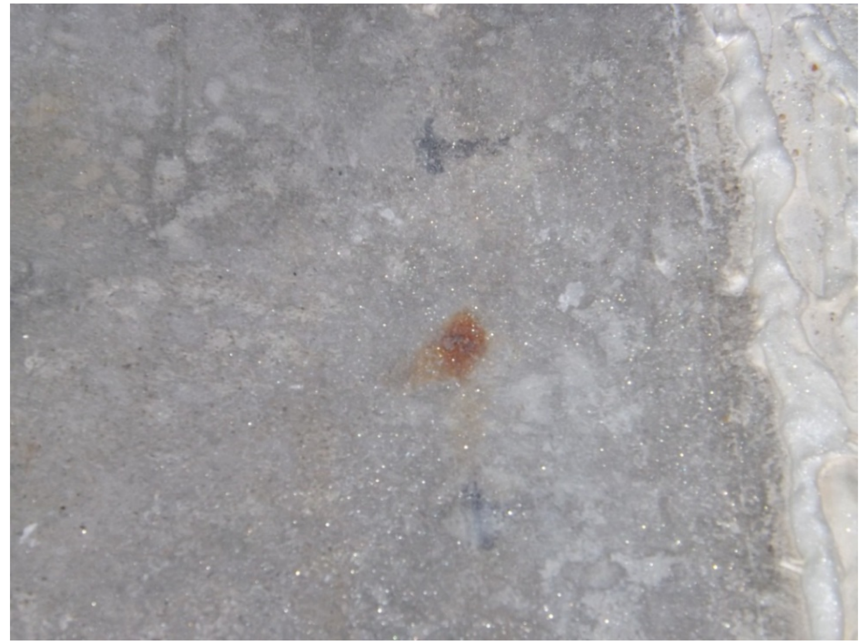
(Week 52)

HCP Results – Slab 1

S1-2

HCP = -501 mV

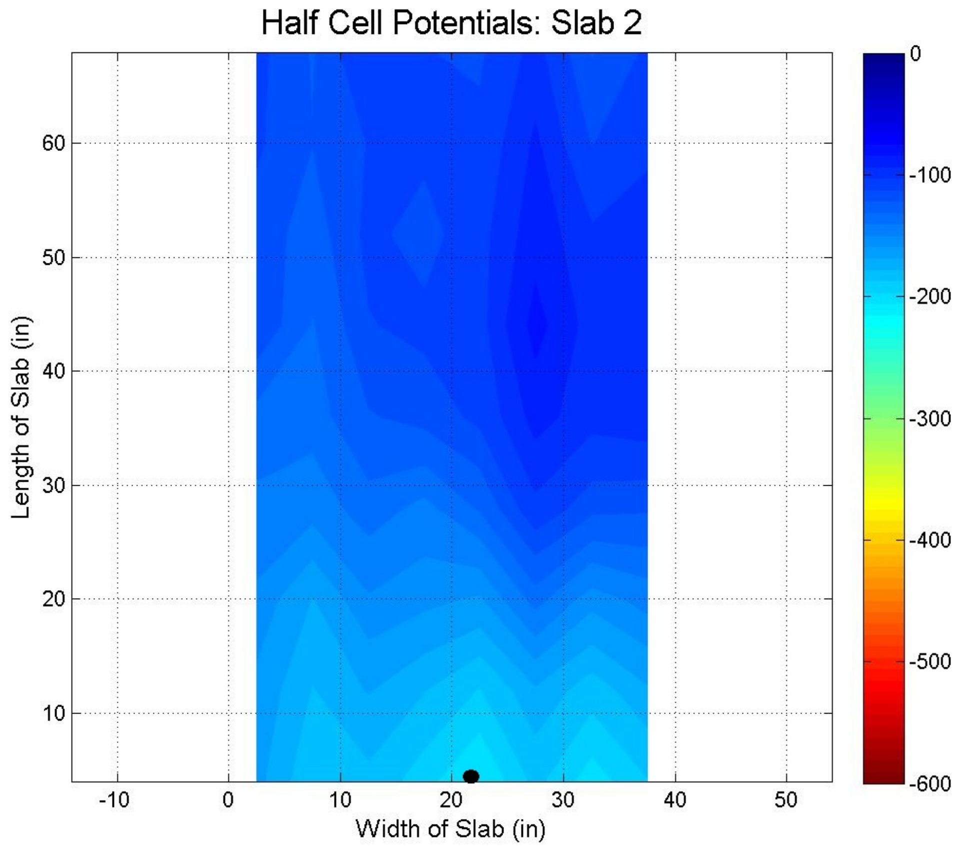
S1-3



HCP = -422 mV

Concrete Laboratory, CEE, UMass Lowell
(Week 52)

HCP Contour Maps

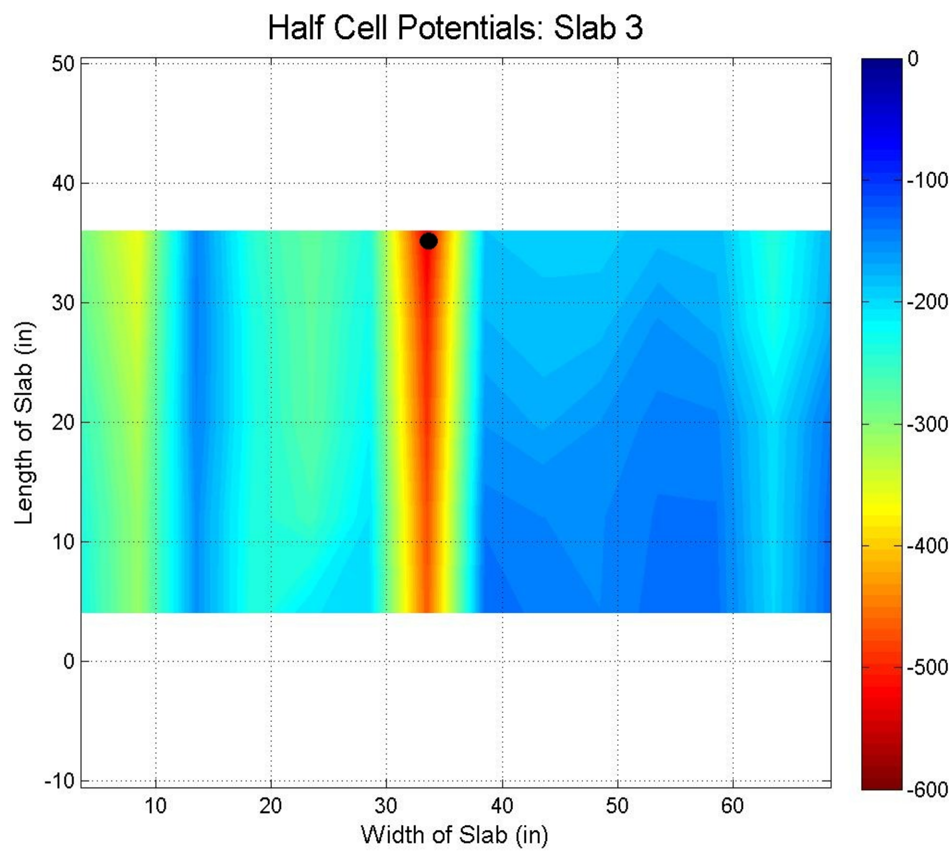


(Week 52)

Slab 2 shows lower HCP at the front of the slab

- Spatial location of the point of measurement is important

HCP Contour Maps

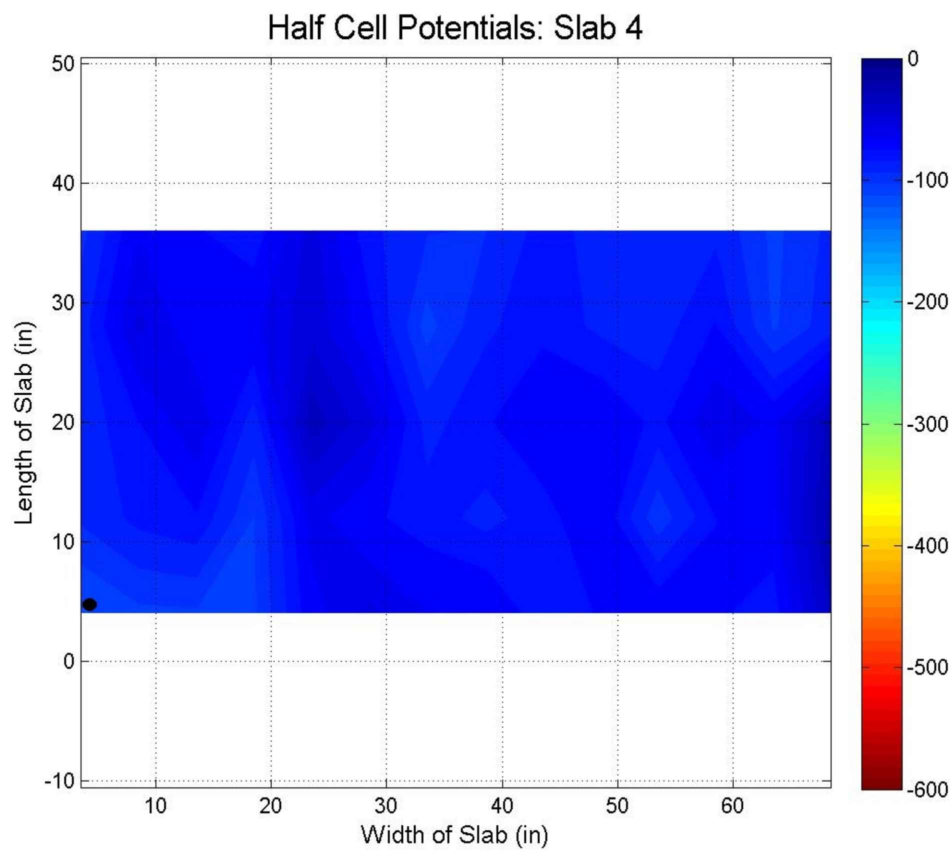


(Week 52)

Slab 3 shows more corrosion with areas of less concrete cover

- Variations in concrete cover affect HCP

HCP Contour Maps

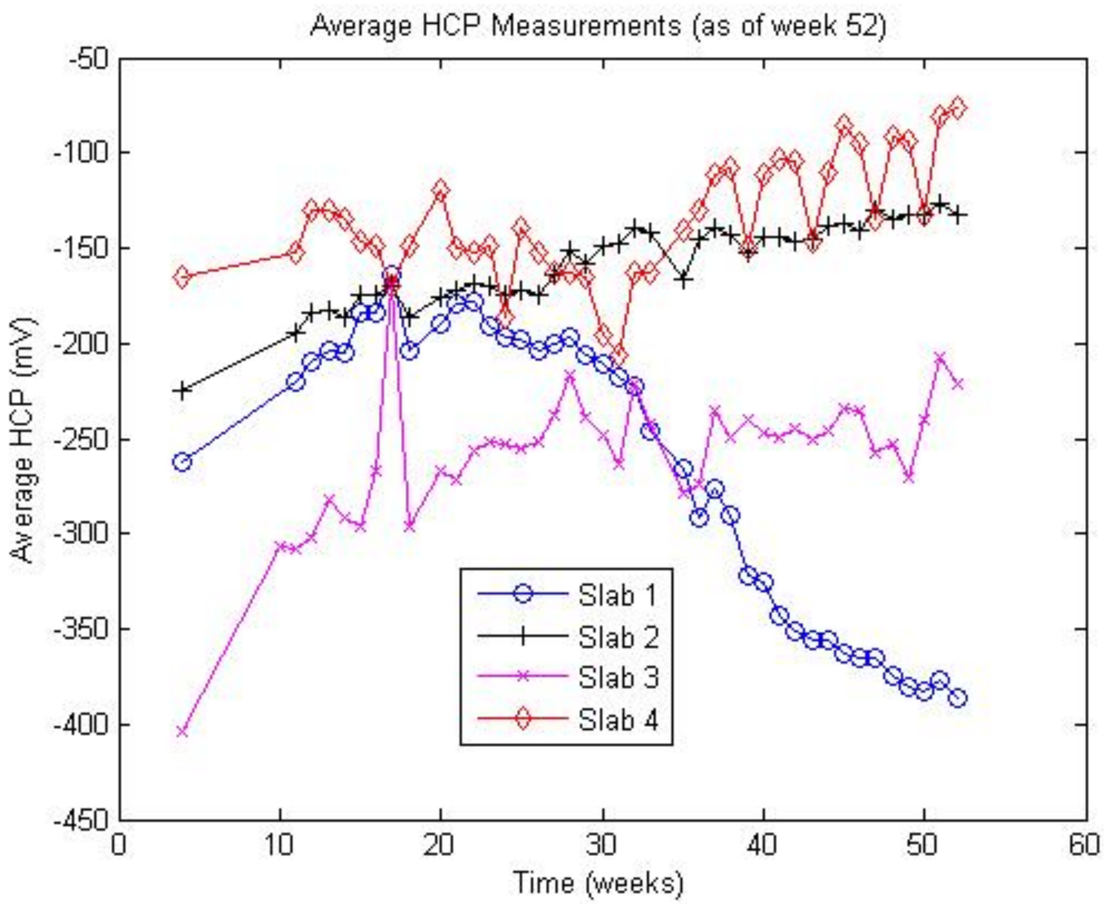


(Week 52)

The contour map for Slab 4 was as expected

- It shows minor variations across the entire slab (80mV)

Average HCP vs. Time



Average HCP vs. Time

- All Slabs show an increase until Week 14
  - Residual pore water
- Slab 2 stays fairly constant after Week 28
  - About (-140 mV)
- Slab 3 shows more variability than Slab 2, but stays relatively constant after Week 24
  - About (-240 mV)
- Slab 4 is more noisy than the minimum values

Average HCP vs. Time

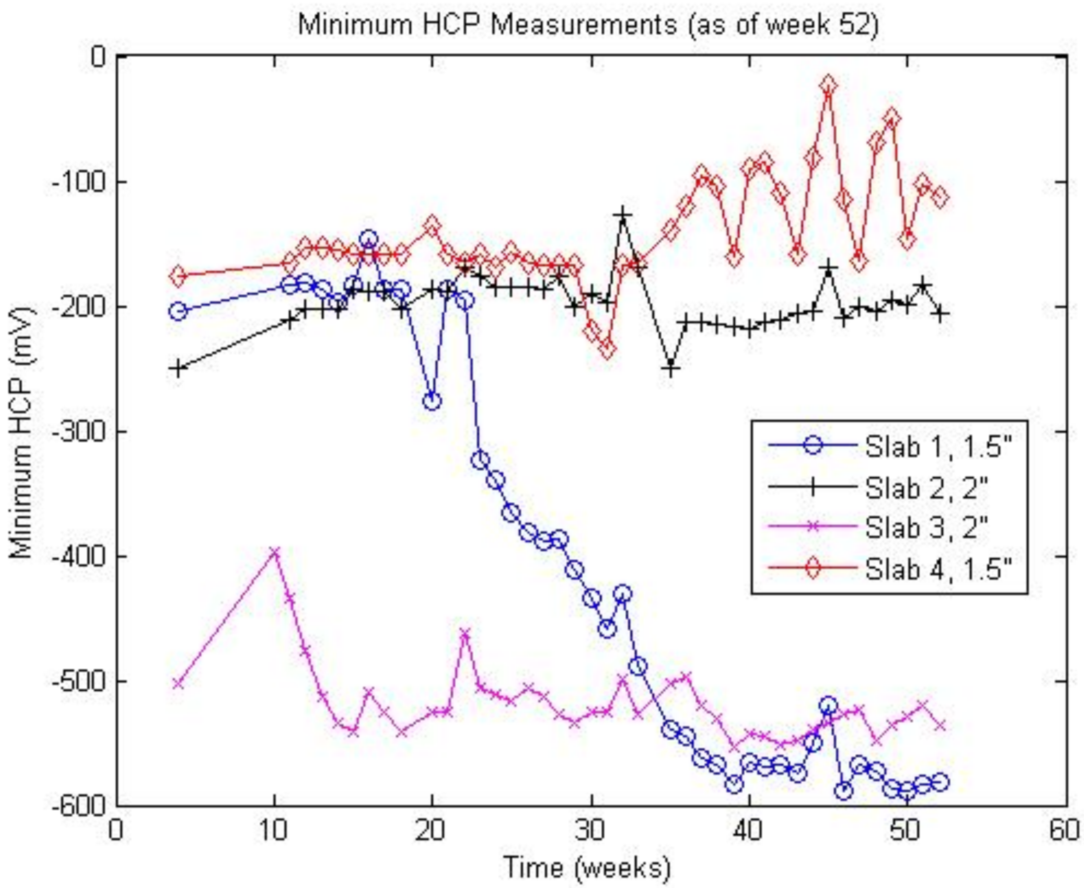
$$HCP(t) = P_1 t^3 + P_2 t^2 + P_3 t + P_4$$

Parameter	Slab 1	Slab 2	Slab 3	Slab 4
P_1	0.007496	0.000089	0.00658	0.000542
P_2	-0.8519	-0.1015	-0.6689	0.03798
P_3	23.51	4.971	21.77	-2.601
P_4	-370.2	-237.7	-473.8	-123.2
R^2	0.9697	0.9064	0.6618	0.5263

Assumptions:

- Equation is only valid for 52 weeks
- R^2 is representative of experimental data

Minimum HCP vs. Time



Minimum HCP vs. Time

- Slab 1 shows an expected, decreasing trend
- Slab 2 stays fairly constant throughout the entire experiment (-180 mV)
- Slab 3 dips sharply at the start, but remains constant afterward (-550 mV)
  - Possible excess mix water trapped in slab
- Slab 4 stays constant throughout the first 30 weeks, but rises afterwards (-120 mV)
  - Possible indicator of background noise

Minimum HCP vs. Time

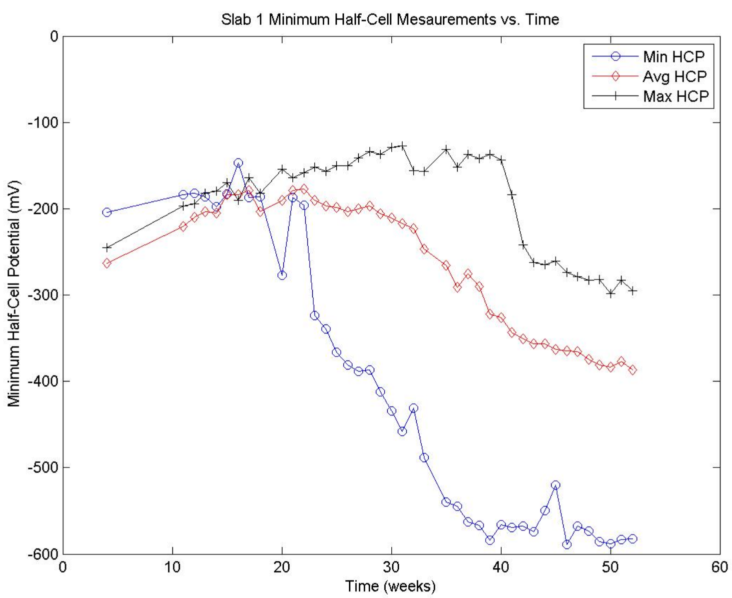
$$HCP(t) = P_1 t^3 + P_2 t^2 + P_3 t + P_4$$

Parameter	Slab 1	Slab 2	Slab 3	Slab 4
P_1	0.01942	0.002688	-5.64×10^{-6}	-0.00231
P_2	-1.606	-0.2607	0.03406	0.2762
P_3	25.91	7.750	-3.235	-7.857
P_4	-279.2	-238.6	-457.0	-104.6
R^2	0.9627	0.4537	0.3132	0.4030

Effect of Concrete Cover

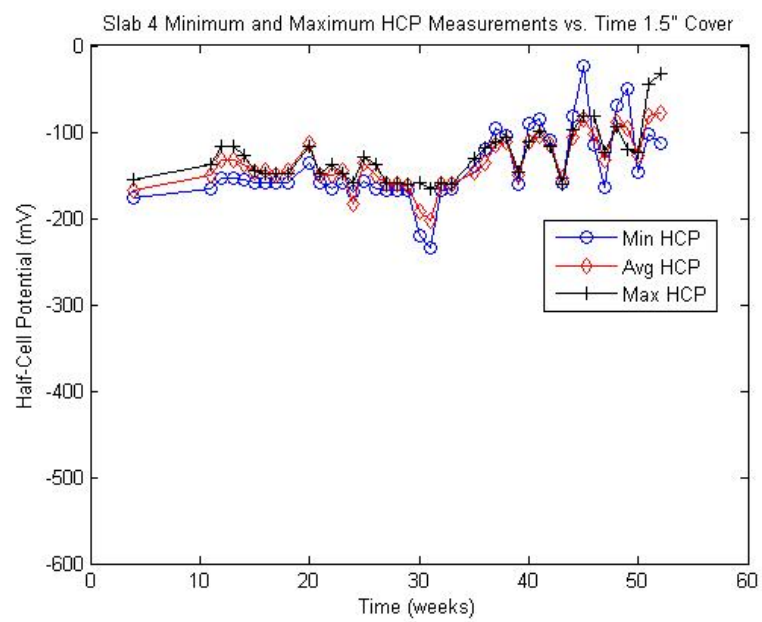
1.5" Concrete Cover

Slab 1 (Week 52)



47.1% Decrease in Average HCP

Slab 4 (Week 52)

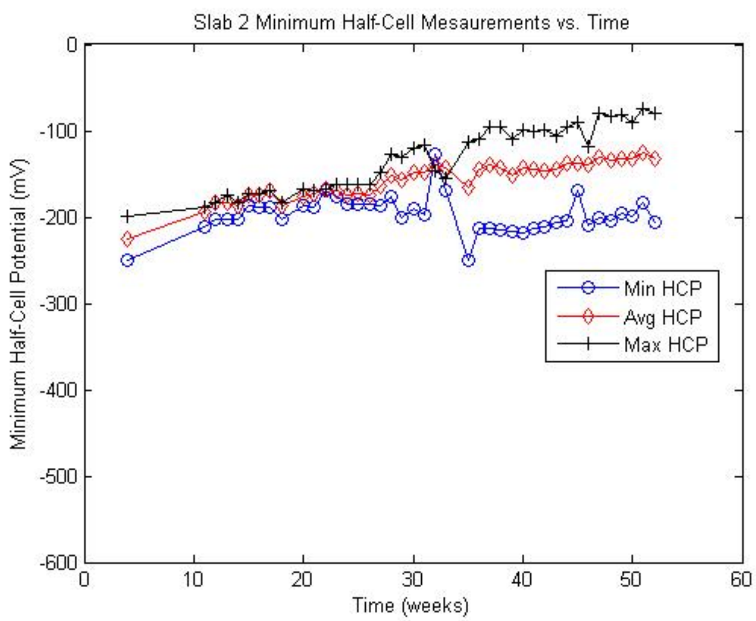


50.2% Increase in Average HCP

Effect of Concrete Cover

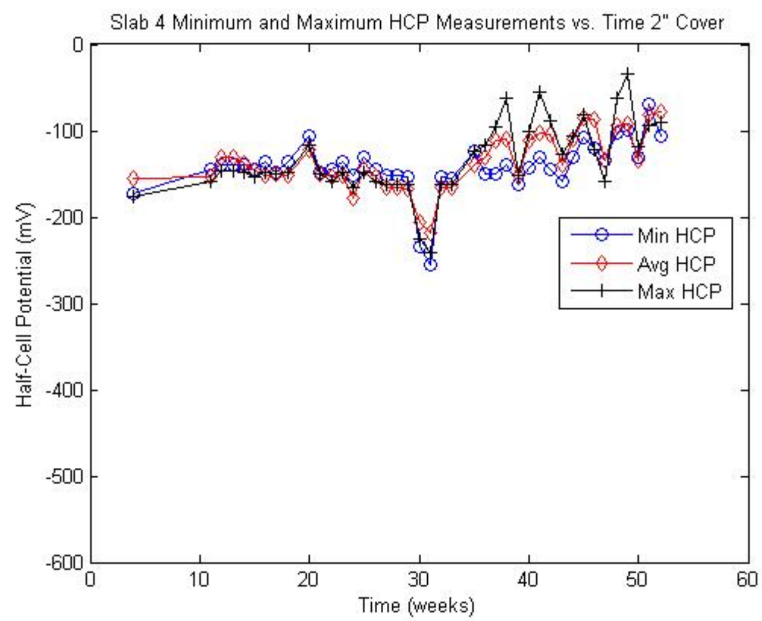
2" Concrete Cover

Slab 2 (Week 52)



41.1% Increase in Average HCP

Slab 4 (Week 52)

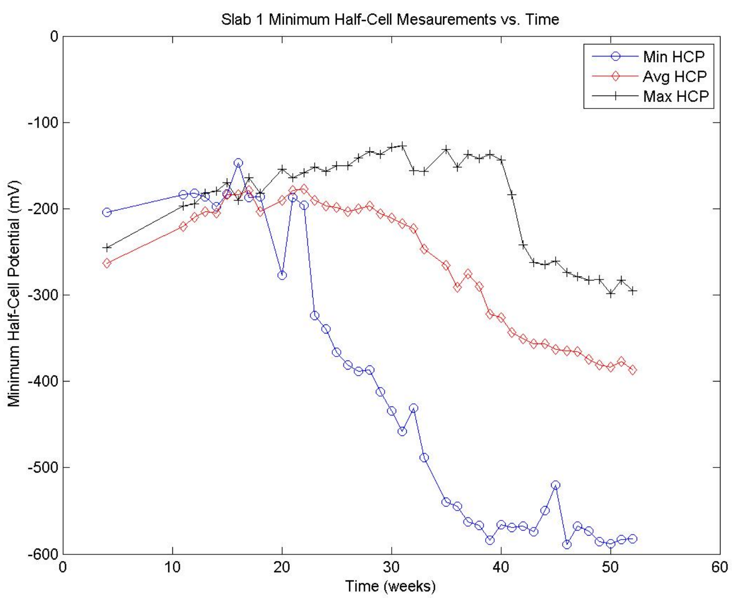


50.2% Increase in Average HCP

Effect of Concrete Cover

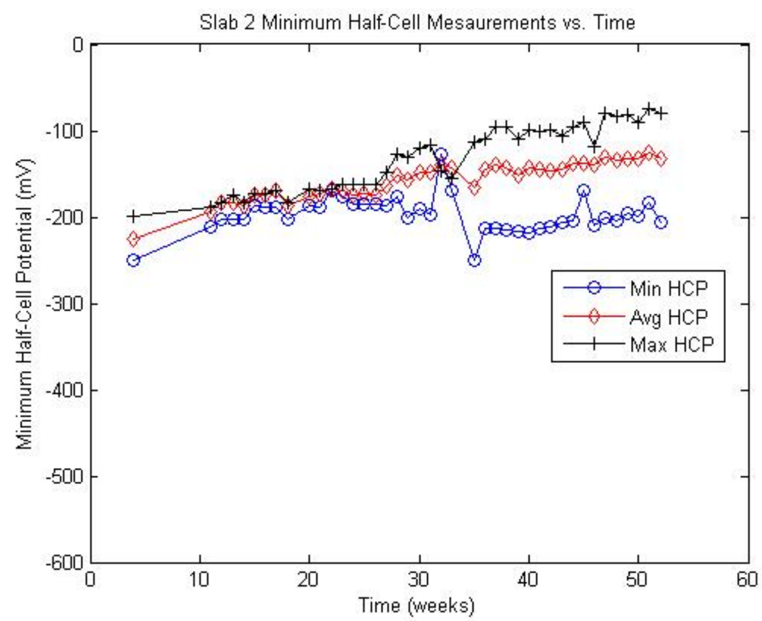
1.5" vs. 2" Concrete Cover

Slab 1 (Week 52)



47.1% Decrease in Average HCP

Slab 2 (Week 52)



41.1% Increase in Average HCP

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Current Density

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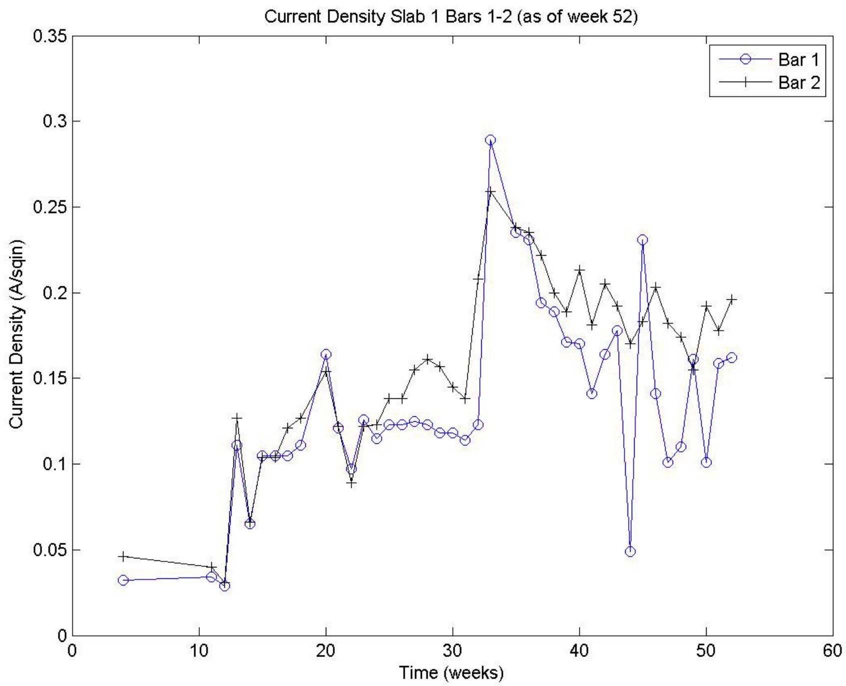
- Inversely related to rebar diameter
  - Decreased bar diameter forces the same amount of current through a smaller cross-section, thus current density increases.
- Calculated using the following equation [19] :

$$I_i = \frac{1}{B\Delta L_i} \Sigma_{j=1}^{n} \frac{\delta E_{i,j} B \Delta L_j}{w \delta L_{i,j}}$$

  - I_i = current density at one point on the rebar
  - B = width of the rebar
  - E = potential difference
  - L = length of the element
  - w = specific resistivity of the concrete

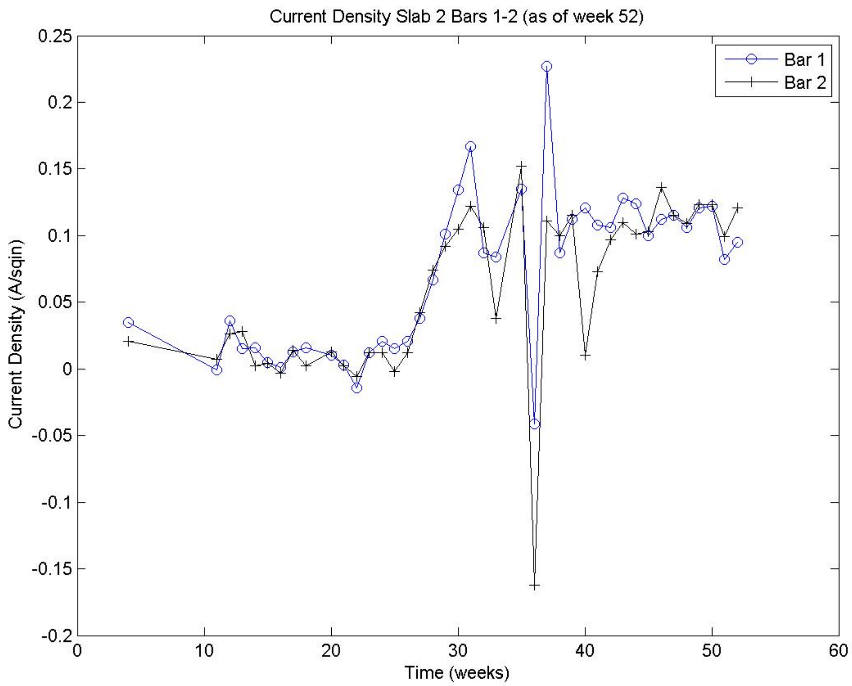
Current Density – Slab 1



Bar Number	1	2
Week 4	0.032	0.046
Week 52	0.162	0.196
Absolute Change	0.130	0.151
Percent Change	408	332

- Overall, the current density in the rebars in Slab 1 increases significantly, as expected.
- The increases cannot be linked to decreases in HCP because the changes in the weekly measurements do not coincide.

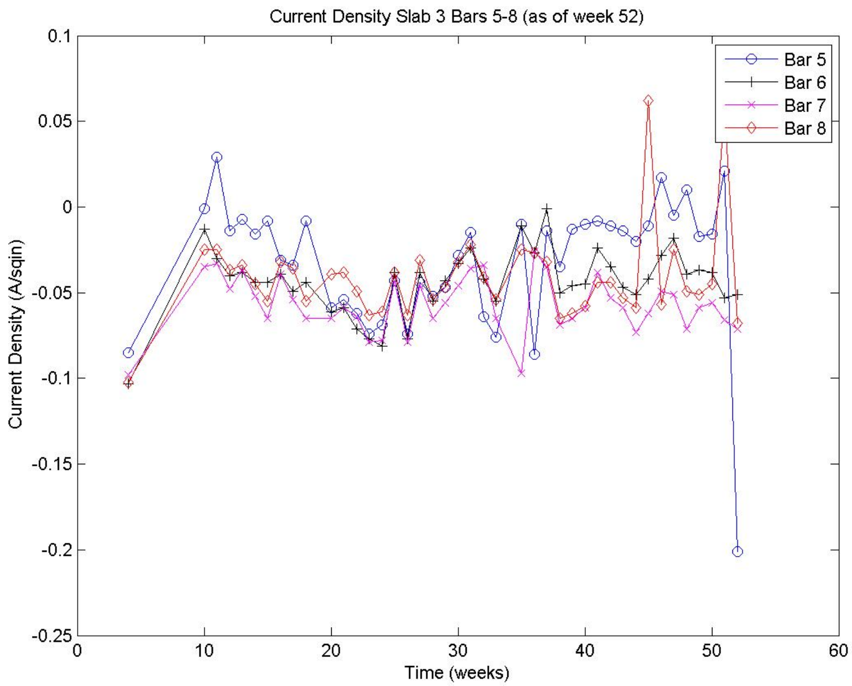
Current Density – Slab 2



Bar Number	1	2
Week 4	0.035	0.021
Week 52	0.095	0.121
Absolute Change	0.060	0.101
Percent Change	173	476

- The current density increases in the rebars in Slab 2 were proportionally greater than in Slab 1 (Slab 1 = 165% Slab 2 = 1136%) although no evidence of corrosion exists.
- A possible explanation is that the ends of the connecting wires became highly resistive during the experiment.

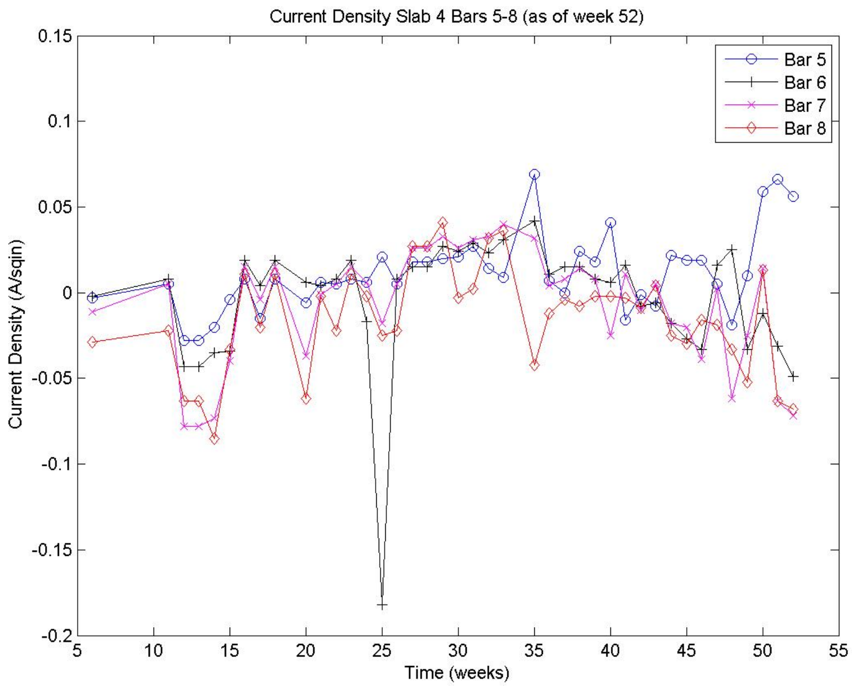
Current Density – Slab 3



Bar Number	5	6
Week 4	0.085	0.103
Week 52	0.201	0.051
Absolute Change	0.117	-0.052
Percent Change	137	-50

- The concrete cover has a major influence on the current density in the rebars.
- The rebars with more than 1.5” of concrete cover do not show as much change in the current density as the bars with 1.5” of cover.

Current Density – Slab 4



Bar Number	5	6
Week 4	0.0003	-0.002
Week 52	0.056	-0.049
Absolute Change	0.059	-0.047
Percent Change	1754	-2579

- Slab 4 was the control slab and was not ponded throughout the experiment.
- These results reinforce the results from Slab 3; there is a significant difference between the bars with 1.5” cover and those with greater than 1.5” cover.

Conclusions

- HCP varies with distance from the voltmeter and location on the slab
  - HCP will be lower at points closer to the edge of the slab and farther from the connection to the voltmeter
  - HCP can be accurately modeled using cubic polynomials
- Concrete cover is the most important factor in the time for corrosion to start on an RC slab
  - Rebars with 1.5” of cover showed significant corrosion during the experiment
  - Rebars with more than 1.5” of cover did not corrode at all
- Concrete cover significantly affects the current density in the rebars at the time of measurement
  - Rebars with 1.5” of cover showed significant increases in the current density as the experiment progressed
  - All other rebars exhibited much less variation throughout the experiment

Contributions

- Voltmeter readings closer to the voltmeter are more reliable
- Developed a time and spatial data set for artificially corroded RC slabs for 52 weeks
- Validated previous research work showing increasing current density with increasing corrosion

Future Work

- The HCP data from Slab 4 can be used to determine the amount of noise in measurements from the other three slabs. This will allow the data to be denoised and the models to be revised and simplified.
- The current density could be examined to find a relationship between the concrete cover and the current density.
- The relationship between the current density and the HCP may also be examined. This will ensure the most accurate relationship between the two parameters and would provide an easier way to approximate the condition of RC structures.

Acknowledgements

- The National Institute for Standards and Technology for funding this research
- Professor Ming Wang and Northeastern University for providing funds through the VOTERS project
- Carlos Jaquez, Hao Liu, and Ross Gladstone for their help in collecting HCP data
- Thank you to Professors Leitch and Faraji for being on my thesis committee
- Thank you to Professor Yu for being my advisor

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Thank You

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