ABSTRACT

COOK, ANNA KAYE. Evaluation of the Effectiveness of Surface Applied Corrosion Inhibitors for Concrete Bridges. (Under the direction of Dr. Sami Rizkalla and Dr. Amir Mirmiran.)

Deicing salts and salt-water spray can cause serious corrosion problems for reinforced concrete bridge structures. These problems can lead to costly and labor intensive repair and even replacement of the structure. Surface applied corrosion inhibitors are potentially a useful and cost effective way to prolong the life of existing structures. The purpose of this research project was to evaluate the effectiveness of commercially available corrosion inhibitors for surface treatments of existing reinforced concrete bridges.

Reinforced concrete specimens were cast with different levels of initial chloride contents, coated with one of six products tested, and placed in accelerated corrosion environments. Each manufacturer donated their corresponding products for use in the experiment. The manufacturers were also given the test matrix and parameters in advance of the product application and invited to participate in the application process. Environmental conditions, voltmeter, and half cell potential readings were taken on a weekly basis in accordance with ASTM standards. Intermittently, some of these specimens were removed from their environments and evaluated on a visual, mass loss, strength loss, and chloride content basis. This data was then compiled and compared to each other and to control specimens located in a non-corrosive environment.

It was found that surface applied corrosion inhibitors delay the onset of corrosion and the speed of the corrosion process. It was also found that a maximum chloride content of 0.5% by cement weight exists beyond which none of the inhibitor products were useful. Suggestions for further research in this area of study are also included.
EVALUATION OF THE EFFECTIVENESS OF SURFACE APPLIED CORROSION INHIBITORS FOR CONCRETE BRIDGES

by

Anna Kaye Cook

A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Master of Science

Department of Civil, Construction, and Environmental Engineering

Raleigh

2004

APPROVED BY:

____________________ _____________________
Co-chair of Advisory Committee - Co-chair of Advisory Committee
To Logan Teague, who continuously reminded me of Philippians 4:13
- “I can do all things through Christ who strengthens me”.
Biography

Anna Kaye Cook was born on February 15, 1980 in Statesville, North Carolina to Rev. Charles and Katherine Cook. After living in Statesville for 8 years, she moved with her parents to nearby Hiddenite. She graduated from Alexander Central High School in May 1998, and attended North Carolina State University the following fall.

Anna entered the engineering program at NC State University and was involved with many student organizations including Student Ambassadors, WENT (Women Engineers Networking Together), ASCE (American Society of Civil Engineers), SWE (Society of Women Engineers), and Chi Epsilon (civil engineering honor society) among others. She worked throughout college with the North Carolina Department of Transportation and Mulkey Engineers and Consultants (formerly BHME). Anna graduated with honors from NC State University in May 2002, receiving her Bachelor’s degree in Civil Engineering and a minor in Graphic Communications.

Upon graduation, Anna pursued her Master’s of Science in Civil Engineering (Structures Concentration) at NC State University. Her primary research was conducted in the Constructed Facilities Laboratory on Centennial Campus on corrosion inhibitors for concrete bridges.

Anna is currently working for a national civil engineering firm in their Raleigh office designing bridges.
Acknowledgements

I would like to thank the North Carolina Department of Transportation for funding this research and giving me the financial opportunity to attend graduate school. I would especially like to thank those at the NCDOT who were directly involved in this research project. It has been a great experience to work with each and every one of you. For those people at the NCDOT Materials and Test Unit, thank you for always lending a helping hand and for letting us share your facilities for countless hours.

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To my “staff” of assistants – Thank you so much for your help throughout this project. To Stephanie Kruep, I appreciate your dedication in helping me collect data and change out resistors even on those 90+ degree-days. To Jahmaal Tillman, thank you for your tremendous help with countless chloride titrations, mass loss tests, and tension tests. You are now the resident expert on each of these. To Heather Hess, who helped with everything listed above, but most importantly, thank you so much for your help on compiling the immeasurable amount of data from this project. I hope you can sleep at night without seeing never-ending spreadsheets. To all of my assistants, thank you so very much. I would still be working on this project if it weren’t for you all.

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To Logan Teague – You are my best friend and biggest fan. I know that because of your prayers, love, and support, I have persevered. You inspire me to reach for the stars, while still keeping my feet on the ground. This degree is as much yours as it is mine, and from the bottom of my heart and very depths of my soul, I thank you.

Most importantly I would like to thank God for all His blessings: health, happiness, love of friends and family, and the ability to pursue my hopes and dreams. I owe all that I am to His son for that great and ultimate sacrifice.
# Table of Contents

## List of Tables

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ix</td>
</tr>
</tbody>
</table>

## List of Figures

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
</tr>
</tbody>
</table>

## 1.0 Introduction

1.1 Background and Problem Statement 1
1.2 Need for research 1
1.3 Objectives 2
1.4 Scope and Contents 3

## 2.0 Literature Review

2.1 Introduction 5
2.2 Causes of Corrosion 5
2.3 Mechanism of Corrosion 6
2.4 Corrosion Prevention Methods 9
  2.4.1 New Construction 9
  2.4.2 Existing Structures 10
  2.4.3 Surface Applied Corrosion Inhibitors 11

## 3.0 Experimental Procedure

3.1 Introduction 15
3.2 Test Preparation 15
  3.2.1 Specimen Geometry 15
  3.2.2 Slab Geometry 17
  3.2.3 Formwork and Casting 17
  3.2.4 Test Assembly 21
  3.2.5 Chloride Analysis Cubes 23
3.3 Pilot Tests 24
3.4 Test Setup 28
  3.4.1 Test Parameters 28
  3.4.2 Test Procedure 30
  3.4.3 Application of Corrosion Inhibitors 30
  3.4.4 Epoxy Coating 31
3.5 Exposure Environments 33
  3.5.1 Submersion Baths 33
  3.5.2 Environmental Chamber 35
  3.5.3 Control Environment 38
3.6 Data Collection During Exposure 39
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Manufacturers and Their Corresponding Products Tested</td>
<td>11</td>
</tr>
<tr>
<td>3.1</td>
<td>Chloride Analysis Cube Matrix</td>
<td>24</td>
</tr>
<tr>
<td>3.2</td>
<td>Test Matrix</td>
<td>29</td>
</tr>
<tr>
<td>3.3</td>
<td>Product Application Chart</td>
<td>31</td>
</tr>
</tbody>
</table>
### List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Effects of Corrosion on Reinforced Concrete as Displayed During This Research</td>
<td>7</td>
</tr>
<tr>
<td>2.2</td>
<td>Mechanism of Corrosion in Macrocell and Microcell</td>
<td>8</td>
</tr>
<tr>
<td>2.3</td>
<td>Chloride Attack on Steel Bars</td>
<td>9</td>
</tr>
<tr>
<td>3.1</td>
<td>Specimen Geometry</td>
<td>16</td>
</tr>
<tr>
<td>3.2</td>
<td>Formwork for the Specimens</td>
<td>18</td>
</tr>
<tr>
<td>3.3</td>
<td>Formwork for the Cubes</td>
<td>18</td>
</tr>
<tr>
<td>3.4</td>
<td>Chloride Addition During Specimen and Cube Casting</td>
<td>19</td>
</tr>
<tr>
<td>3.5</td>
<td>Casting of the Specimens and the Cubes</td>
<td>20</td>
</tr>
<tr>
<td>3.6</td>
<td>Casting of the Slabs</td>
<td>21</td>
</tr>
<tr>
<td>3.7</td>
<td>Test Setup</td>
<td>22</td>
</tr>
<tr>
<td>3.8</td>
<td>Resistor and Clip Connection</td>
<td>23</td>
</tr>
<tr>
<td>3.9</td>
<td>Pilot Test Setup</td>
<td>25</td>
</tr>
<tr>
<td>3.10</td>
<td>Failed Specimen</td>
<td>26</td>
</tr>
<tr>
<td>3.11</td>
<td>Pilot Test 2: Setup with Strain Indicator Box</td>
<td>27</td>
</tr>
<tr>
<td>3.12</td>
<td>Pilot Test 2: Using DEMEC Points and Dial Gauge</td>
<td>27</td>
</tr>
<tr>
<td>3.13</td>
<td>Pilot Test 2: Spotting Cracks</td>
<td>28</td>
</tr>
<tr>
<td>3.14</td>
<td>Epoxy Coating of the Slabs and Specimens</td>
<td>32</td>
</tr>
<tr>
<td>3.15</td>
<td>Epoxy Coating of the Cubes</td>
<td>32</td>
</tr>
<tr>
<td>3.16</td>
<td>Loaded Bath in Wet Cycle</td>
<td>34</td>
</tr>
<tr>
<td>3.17</td>
<td>Loaded Bath in Dry Cycle</td>
<td>35</td>
</tr>
</tbody>
</table>
3.18 Original Environmental Chamber
3.19 Assembled Environmental Chamber
3.20 Control Environment Specimens
3.21 Typical Volmeter Reading Procedure
3.22 Typical Half Cell Potential Reading Procedure
3.23 Typical Salinity Measurement Procedure
3.24 pH Measurement Reading
3.25 Temperature Monitoring
3.26 Cubes and Powder Ready for Chloride Analysis Testing
3.27 Weighing the Dried Powder Samples
3.28 Filtering Chloride Samples
3.29 Titrating a Prepared Chloride Sample
3.30 Visual Evaluation Procedure
3.31 Bars Submerged in Chemical Cleaning Solution
3.32 Brushing Bars After Chemical Bath
3.33 Drying the Bars After Chemical Bath
3.34 Weighing a Bar After the Cleaning Process
3.35 Tension Test Setup
3.36 Extensometer Setup
3.37 Bar After Failure in Tension
4.1 Corrosion Rate for Control Specimens (Set #2)
4.2 Corrosion Rate for Bath 2, 0.0% Chloride, Pre-Cracked
4.3 Corrosion Rate for Chamber Shelf 3, 2.0% Chloride, Post-Cracked
4.4 Cumulative Corrosion over Time for Control Specimens (Set #2) 57
4.5 Cumulative Corrosion over Time for Bath 2, 0.0% Chloride, Pre-Cracked 59
4.6 Cumulative Corrosion over Time for Chamber Shelf 3, 2.0% Chloride, Post-Cracked 60
4.7 Half Cell Readings for Control Specimens (Set #2) 62
4.8 Half Cell Readings for Bath 2, 0.0% Chloride, Pre-Cracked 63
4.9 Half Cell Readings for Chamber Shelf 3, 2.0% Chloride, Post-Cracked 64
4.10 Salinity Over Time for Bath and Chamber Environments 67
4.11 pH over Time for Bath and Chamber Environments 68
4.12 Temperature over Time for Bath and Chamber Environments 69
4.13 Humidity and Temperature Over Time for Control Environment 70
4.14 Chloride Content for Control Specimens 72
4.15 Chloride Content for Bath Specimens – 1.5% Chloride 73
4.16 Chloride Content for Chamber Specimens – 0.0% Chloride 74
4.17 % Chloride Surface Corrosion at End Sections for 1.0% Chloride (Set #1) 76
4.18 % Chloride Surface Corrosion at End Sections for 1.0% Chloride (Set #2) 77
4.19 % Chloride Rib Loss at End Sections for 1.0% Chloride (Set #1) 78
4.20 % Chloride Rib Loss at End Sections for 1.0% Chloride (Set #2) 79
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.21</td>
<td>% Chloride Surface Corrosion at Midsection for 0.0% Chloride (Set #1)</td>
</tr>
<tr>
<td>4.22</td>
<td>% Chloride Surface Corrosion at Midsection for 1.5% Chloride (Set #1)</td>
</tr>
<tr>
<td>4.23</td>
<td>% Chloride Surface Corrosion at Midsection for 3.0% Chloride (Set #1)</td>
</tr>
<tr>
<td>4.24</td>
<td>% Chloride Surface Corrosion at Midsection for 0.0% Chloride (Set #2)</td>
</tr>
<tr>
<td>4.25</td>
<td>% Chloride Surface Corrosion at Midsection for 1.5% Chloride (Set #2)</td>
</tr>
<tr>
<td>4.26</td>
<td>% Chloride Surface Corrosion at Midsection for 3.0% Chloride (Set #2)</td>
</tr>
<tr>
<td>4.27</td>
<td>Time Step of Surface Corrosion for 0.0% Chloride, Pre-Cracked Specimens</td>
</tr>
<tr>
<td>4.28</td>
<td>% Chloride Rib Loss in Midsections for 0.0% Chloride (Set #1)</td>
</tr>
<tr>
<td>4.29</td>
<td>% Chloride Rib Loss in Midsections for 1.5% Chloride (Set #1)</td>
</tr>
<tr>
<td>4.30</td>
<td>% Chloride Rib Loss in Midsections for 3.0% Chloride (Set #1)</td>
</tr>
<tr>
<td>4.31</td>
<td>% Chloride Rib Loss in Midsections for 0.0% Chloride (Set #2)</td>
</tr>
<tr>
<td>4.32</td>
<td>% Chloride Rib Loss in Midsections for 1.5% Chloride (Set #2)</td>
</tr>
<tr>
<td>4.33</td>
<td>% Chloride Rib Loss in Midsections for 3.0% Chloride (Set #2)</td>
</tr>
<tr>
<td>4.34</td>
<td>Time Step of Rib Loss for 0.0% Chloride, Pre-Cracked Specimens</td>
</tr>
<tr>
<td>4.35</td>
<td>Cumulative Mass Loss/Length for Control Specimens</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>4.36</td>
<td>Cumulative Mass Loss/Length for Bath 4, 0.0% Chloride, Post-Cracked Specimens</td>
</tr>
<tr>
<td>4.37</td>
<td>Cumulative Mass Loss/Length for Chamber 0.0% Chloride, Shelf 3, Post-Cracked Specimens</td>
</tr>
<tr>
<td>4.38</td>
<td>Typical Load Deflection Curve for Bath 4, 0.0% Chloride, NO CI Specimen, Post-Cracked</td>
</tr>
<tr>
<td>4.39</td>
<td>Percent Strength Loss Based on Tension Tests for Bath 3, 0.0% Chloride, Post-Cracked</td>
</tr>
<tr>
<td>4.40</td>
<td>Percent Strength Loss Based on Tension Tests for Chamber 0.5% Chloride, Shelf 4, Pre-Cracked</td>
</tr>
<tr>
<td>4.41</td>
<td>Visual Ratings for Bath 2, 0.0% Chloride, Pre-Cracked Specimens</td>
</tr>
<tr>
<td>4.42</td>
<td>Mass Loss and Strength Loss for Bath 2, 0.0% Chloride, Pre-Cracked Specimens</td>
</tr>
<tr>
<td>4.43</td>
<td>Visual Ratings for Chamber 0.5% Chloride, Shelf 2, Pre-Cracked Specimens</td>
</tr>
<tr>
<td>4.44</td>
<td>Mass Loss and Strength Loss for Chamber 0.5% Chloride, Shelf 2, Pre-Cracked Specimens</td>
</tr>
<tr>
<td>A.1</td>
<td>Corrosion Rate for Control Set #1</td>
</tr>
<tr>
<td>A.2</td>
<td>Corrosion Rate for Control Set #2</td>
</tr>
<tr>
<td>A.3</td>
<td>Corrosion Rate for Bath 1, 0.0% Chloride, Pre-Cracked</td>
</tr>
<tr>
<td>A.4</td>
<td>Corrosion Rate for Bath 1, 0.5% Chloride, Pre-Cracked</td>
</tr>
<tr>
<td>A.5</td>
<td>Corrosion Rate for Bath 1, 1.0% Chloride, Pre-Cracked</td>
</tr>
<tr>
<td>A.6</td>
<td>Corrosion Rate for Bath 1, 1.5% Chloride, Pre-Cracked</td>
</tr>
<tr>
<td>A.7</td>
<td>Corrosion Rate for Bath 1, 2.0% Chloride, Pre-Cracked</td>
</tr>
<tr>
<td>A.8</td>
<td>Corrosion Rate for Bath 1, 3.0% Chloride, Pre-Cracked</td>
</tr>
<tr>
<td>A.9</td>
<td>Corrosion Rate for Bath 2, 0.0% Chloride, Pre-Cracked</td>
</tr>
<tr>
<td>A.10</td>
<td>Corrosion Rate for Bath 2, 0.5% Chloride, Pre-Cracked</td>
</tr>
<tr>
<td></td>
<td>Description</td>
</tr>
<tr>
<td>---</td>
<td>-------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>A.11</td>
<td>Corrosion Rate for Bath 2, 1.0% Chloride, Pre-Cracked</td>
</tr>
<tr>
<td>A.12</td>
<td>Corrosion Rate for Bath 2, 1.5% Chloride, Pre-Cracked</td>
</tr>
<tr>
<td>A.13</td>
<td>Corrosion Rate for Bath 2, 2.0% Chloride, Pre-Cracked</td>
</tr>
<tr>
<td>A.14</td>
<td>Corrosion Rate for Bath 2, 3.0% Chloride, Pre-Cracked</td>
</tr>
<tr>
<td>A.15</td>
<td>Corrosion Rate for Bath 3, 0.0% Chloride, Post-Cracked</td>
</tr>
<tr>
<td>A.16</td>
<td>Corrosion Rate for Bath 3, 0.5% Chloride, Post-Cracked</td>
</tr>
<tr>
<td>A.17</td>
<td>Corrosion Rate for Bath 3, 1.0% Chloride, Post-Cracked</td>
</tr>
<tr>
<td>A.18</td>
<td>Corrosion Rate for Bath 3, 1.5% Chloride, Post-Cracked</td>
</tr>
<tr>
<td>A.19</td>
<td>Corrosion Rate for Bath 3, 2.0% Chloride, Post-Cracked</td>
</tr>
<tr>
<td>A.20</td>
<td>Corrosion Rate for Bath 3, 3.0% Chloride, Post-Cracked</td>
</tr>
<tr>
<td>A.21</td>
<td>Corrosion Rate for Bath 4, 0.0% Chloride, Post-Cracked</td>
</tr>
<tr>
<td>A.22</td>
<td>Corrosion Rate for Bath 4, 0.5% Chloride, Post-Cracked</td>
</tr>
<tr>
<td>A.23</td>
<td>Corrosion Rate for Bath 4, 1.0% Chloride, Post-Cracked</td>
</tr>
<tr>
<td>A.24</td>
<td>Corrosion Rate for Bath 4, 1.5% Chloride, Post-Cracked</td>
</tr>
<tr>
<td>A.25</td>
<td>Corrosion Rate for Bath 4, 2.0% Chloride, Post-Cracked</td>
</tr>
<tr>
<td>A.26</td>
<td>Corrosion Rate for Bath 4, 3.0% Chloride, Post-Cracked</td>
</tr>
<tr>
<td>A.27</td>
<td>Corrosion Rate for Chamber Shelf 1, 0.0% Chloride, Post-Cracked</td>
</tr>
<tr>
<td>A.28</td>
<td>Corrosion Rate for Chamber Shelf 1, 0.5% Chloride, Post-Cracked</td>
</tr>
<tr>
<td>A.29</td>
<td>Corrosion Rate for Chamber Shelf 1, 1.0% Chloride, Post-Cracked</td>
</tr>
<tr>
<td>A.30</td>
<td>Corrosion Rate for Chamber Shelf 1, 1.5% Chloride, Post-Cracked</td>
</tr>
</tbody>
</table>
A.31 Corrosion Rate for Chamber Shelf 1, 2.0% Chloride, Post-Cracked 133
A.32 Corrosion Rate for Chamber Shelf 1, 3.0% Chloride, Post-Cracked 133
A.33 Corrosion Rate for Chamber Shelf 2, 0.0% Chloride, Pre-Cracked 134
A.34 Corrosion Rate for Chamber Shelf 2, 0.5% Chloride, Pre-Cracked 134
A.35 Corrosion Rate for Chamber Shelf 2, 1.0% Chloride, Pre-Cracked 135
A.36 Corrosion Rate for Chamber Shelf 2, 1.5% Chloride, Pre-Cracked 135
A.37 Corrosion Rate for Chamber Shelf 2, 2.0% Chloride, Pre-Cracked 136
A.38 Corrosion Rate for Chamber Shelf 2, 3.0% Chloride, Pre-Cracked 136
A.39 Corrosion Rate for Chamber Shelf 3, 0.0% Chloride, Post-Cracked 137
A.40 Corrosion Rate for Chamber Shelf 3, 0.5% Chloride, Post-Cracked 137
A.41 Corrosion Rate for Chamber Shelf 3, 1.0% Chloride, Post-Cracked 138
A.42 Corrosion Rate for Chamber Shelf 3, 1.5% Chloride, Post-Cracked 138
A.43 Corrosion Rate for Chamber Shelf 3, 2.0% Chloride, Post-Cracked 139
A.44 Corrosion Rate for Chamber Shelf 3, 3.0% Chloride, Post-Cracked 139
A.45 Corrosion Rate for Chamber Shelf 4, 0.0% Chloride, Pre-Cracked 140
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.46</td>
<td>Corrosion Rate for Chamber Shelf 4, 0.5% Chloride, Pre-Cracked</td>
<td>140</td>
</tr>
<tr>
<td>A.47</td>
<td>Corrosion Rate for Chamber Shelf 4, 1.0% Chloride, Pre-Cracked</td>
<td>141</td>
</tr>
<tr>
<td>A.48</td>
<td>Corrosion Rate for Chamber Shelf 4, 1.5% Chloride, Pre-Cracked</td>
<td>141</td>
</tr>
<tr>
<td>A.49</td>
<td>Corrosion Rate for Chamber Shelf 4, 2.0% Chloride, Pre-Cracked</td>
<td>142</td>
</tr>
<tr>
<td>A.50</td>
<td>Corrosion Rate for Chamber Shelf 4, 3.0% Chloride, Pre-Cracked</td>
<td>142</td>
</tr>
<tr>
<td>B.1</td>
<td>Cumulative Corrosion over Time for Control Set #1</td>
<td>143</td>
</tr>
<tr>
<td>B.2</td>
<td>Cumulative Corrosion over Time for Control Set #2</td>
<td>143</td>
</tr>
<tr>
<td>B.3</td>
<td>Cumulative Corrosion over Time for Bath 1, 0.0% Chloride, Pre-Cracked</td>
<td>144</td>
</tr>
<tr>
<td>B.4</td>
<td>Cumulative Corrosion over Time for Bath 1, 0.5% Chloride, Pre-Cracked</td>
<td>144</td>
</tr>
<tr>
<td>B.5</td>
<td>Cumulative Corrosion over Time for Bath 1, 1.0% Chloride, Pre-Cracked</td>
<td>145</td>
</tr>
<tr>
<td>B.6</td>
<td>Cumulative Corrosion over Time for Bath 1, 1.5% Chloride, Pre-Cracked</td>
<td>145</td>
</tr>
<tr>
<td>B.7</td>
<td>Cumulative Corrosion over Time for Bath 1, 2.0% Chloride, Pre-Cracked</td>
<td>146</td>
</tr>
<tr>
<td>B.8</td>
<td>Cumulative Corrosion over Time for Bath 1, 3.0% Chloride, Pre-Cracked</td>
<td>146</td>
</tr>
<tr>
<td>B.9</td>
<td>Cumulative Corrosion over Time for Bath 2, 0.0% Chloride, Pre-Cracked</td>
<td>147</td>
</tr>
<tr>
<td>B.10</td>
<td>Cumulative Corrosion over Time for Bath 2, 0.5% Chloride, Pre-Cracked</td>
<td>147</td>
</tr>
<tr>
<td>B.11</td>
<td>Cumulative Corrosion over Time for Bath 2, 1.0% Chloride, Pre-Cracked</td>
<td>148</td>
</tr>
</tbody>
</table>
B.12  Cumulative Corrosion over Time for Bath 2, 1.5% Chloride, Pre-Cracked
B.13  Cumulative Corrosion over Time for Bath 2, 2.0% Chloride, Pre-Cracked
B.14  Cumulative Corrosion over Time for Bath 2, 3.0% Chloride, Pre-Cracked
B.15  Cumulative Corrosion over Time for Bath 3, 0.0% Chloride, Post-Cracked
B.16  Cumulative Corrosion over Time for Bath 3, 0.5% Chloride, Post-Cracked
B.17  Cumulative Corrosion over Time for Bath 3, 1.0% Chloride, Post-Cracked
B.18  Cumulative Corrosion over Time for Bath 3, 1.5% Chloride, Post-Cracked
B.19  Cumulative Corrosion over Time for Bath 3, 2.0% Chloride, Post-Cracked
B.20  Cumulative Corrosion over Time for Bath 3, 3.0% Chloride, Post-Cracked
B.21  Cumulative Corrosion over Time for Bath 4, 0.0% Chloride, Post-Cracked
B.22  Cumulative Corrosion over Time for Bath 4, 0.5% Chloride, Post-Cracked
B.23  Cumulative Corrosion over Time for Bath 4, 1.0% Chloride, Post-Cracked
B.24  Cumulative Corrosion over Time for Bath 4, 1.5% Chloride, Post-Cracked
B.25  Cumulative Corrosion over Time for Bath 4, 2.0% Chloride, Post-Cracked
B.26  Cumulative Corrosion over Time for Bath 4, 3.0% Chloride, Post-Cracked
| B.27 | Cumulative Corrosion over Time for Chamber Shelf 1, 0.0% Chloride, Post-Cracked | 156 |
| B.28 | Cumulative Corrosion over Time for Chamber Shelf 1, 0.5% Chloride, Post-Cracked | 156 |
| B.29 | Cumulative Corrosion over Time for Chamber Shelf 1, 1.0% Chloride, Post-Cracked | 157 |
| B.30 | Cumulative Corrosion over Time for Chamber Shelf 1, 1.5% Chloride, Post-Cracked | 157 |
| B.31 | Cumulative Corrosion over Time for Chamber Shelf 1, 2.0% Chloride, Post-Cracked | 158 |
| B.32 | Cumulative Corrosion over Time for Chamber Shelf 1, 3.0% Chloride, Post-Cracked | 158 |
| B.33 | Cumulative Corrosion over Time for Chamber Shelf 2, 0.0% Chloride, Pre-Cracked | 159 |
| B.34 | Cumulative Corrosion over Time for Chamber Shelf 2, 0.5% Chloride, Pre-Cracked | 159 |
| B.35 | Cumulative Corrosion over Time for Chamber Shelf 2, 1.0% Chloride, Pre-Cracked | 160 |
| B.36 | Cumulative Corrosion over Time for Chamber Shelf 2, 1.5% Chloride, Pre-Cracked | 160 |
| B.37 | Cumulative Corrosion over Time for Chamber Shelf 2, 2.0% Chloride, Pre-Cracked | 161 |
| B.38 | Cumulative Corrosion over Time for Chamber Shelf 2, 3.0% Chloride, Pre-Cracked | 161 |
| B.39 | Cumulative Corrosion over Time for Chamber Shelf 3, 0.0% Chloride, Post-Cracked | 162 |
| B.40 | Cumulative Corrosion over Time for Chamber Shelf 3, 0.5% Chloride, Post-Cracked | 162 |
| B.41 | Cumulative Corrosion over Time for Chamber Shelf 3, 1.0% Chloride, Post-Cracked | 163 |
| C.8  | Half Cell Potential Readings for Bath 1, 3.0% Chloride, Pre-Cracked | 171 |
| C.9  | Half Cell Potential Readings for Bath 2, 0.0% Chloride, Pre-Cracked | 172 |
| C.10 | Half Cell Potential Readings for Bath 2, 0.5% Chloride, Pre-Cracked | 172 |
| C.11 | Half Cell Potential Readings for Bath 2, 1.0% Chloride, Pre-Cracked | 173 |
| C.12 | Half Cell Potential Readings for Bath 2, 1.5% Chloride, Pre-Cracked | 173 |
| C.13 | Half Cell Potential Readings for Bath 2, 2.0% Chloride, Pre-Cracked | 174 |
| C.14 | Half Cell Potential Readings for Bath 2, 3.0% Chloride, Pre-Cracked | 174 |
| C.15 | Half Cell Potential Readings for Bath 3, 0.0% Chloride, Post-Cracked | 175 |
| C.16 | Half Cell Potential Readings for Bath 3, 0.5% Chloride, Post-Cracked | 175 |
| C.17 | Half Cell Potential Readings for Bath 3, 1.0% Chloride, Post-Cracked | 176 |
| C.18 | Half Cell Potential Readings for Bath 3, 1.5% Chloride, Post-Cracked | 176 |
| C.19 | Half Cell Potential Readings for Bath 3, 2.0% Chloride, Post-Cracked | 177 |
| C.20 | Half Cell Potential Readings for Bath 3, 3.0% Chloride, Post-Cracked | 177 |
| C.21 | Half Cell Potential Readings for Bath 4, 0.0% Chloride, Post-Cracked | 178 |
| C.22 | Half Cell Potential Readings for Bath 4, 0.5% Chloride, Post-Cracked | 178 |
C.23 Half Cell Potential Readings for Bath 4, 1.0% Chloride, Post-Cracked 179
C.24 Half Cell Potential Readings for Bath 4, 1.5% Chloride, Post-Cracked 179
C.25 Half Cell Potential Readings for Bath 4, 2.0% Chloride, Post-Cracked 180
C.26 Half Cell Potential Readings for Bath 4, 3.0% Chloride, Post-Cracked 180
C.27 Half Cell Potential Readings for Chamber Shelf 1, 0.0% Chloride, Post-Cracked 181
C.28 Half Cell Potential Readings for Chamber Shelf 1, 0.5% Chloride, Post-Cracked 181
C.29 Half Cell Potential Readings for Chamber Shelf 1, 1.0% Chloride, Post-Cracked 182
C.30 Half Cell Potential Readings for Chamber Shelf 1, 1.5% Chloride, Post-Cracked 182
C.31 Half Cell Potential Readings for Chamber Shelf 1, 2.0% Chloride, Post-Cracked 183
C.32 Half Cell Potential Readings for Chamber Shelf 1, 3.0% Chloride, Post-Cracked 183
C.33 Half Cell Potential Readings for Chamber Shelf 2, 0.0% Chloride, Pre-Cracked 184
C.34 Half Cell Potential Readings for Chamber Shelf 2, 0.5% Chloride, Pre-Cracked 184
C.35 Half Cell Potential Readings for Chamber Shelf 2, 1.0% Chloride, Pre-Cracked 185
C.36 Half Cell Potential Readings for Chamber Shelf 2, 1.5% Chloride, Pre-Cracked 185
C.37 Half Cell Potential Readings for Chamber Shelf 2, 2.0% Chloride, Pre-Cracked 186
C.38 Half Cell Potential Readings for Chamber Shelf 2, 3.0% Chloride, Pre-Cracked 186
C.39 Half Cell Potential Readings for Chamber Shelf 3, 0.0% Chloride, Post-Cracked 187
C.40 Half Cell Potential Readings for Chamber Shelf 3, 0.5% Chloride, Post-Cracked 187
C.41 Half Cell Potential Readings for Chamber Shelf 3, 1.0% Chloride, Post-Cracked 188
C.42 Half Cell Potential Readings for Chamber Shelf 3, 1.5% Chloride, Post-Cracked 188
C.43 Half Cell Potential Readings for Chamber Shelf 3, 2.0% Chloride, Post-Cracked 189
C.44 Half Cell Potential Readings for Chamber Shelf 3, 3.0% Chloride, Post-Cracked 189
C.45 Half Cell Potential Readings for Chamber Shelf 4, 0.0% Chloride, Pre-Cracked 190
C.46 Half Cell Potential Readings for Chamber Shelf 4, 0.5% Chloride, Pre-Cracked 190
C.47 Half Cell Potential Readings for Chamber Shelf 4, 1.0% Chloride, Pre-Cracked 191
C.48 Half Cell Potential Readings for Chamber Shelf 4, 1.5% Chloride, Pre-Cracked 191
C.49 Half Cell Potential Readings for Chamber Shelf 4, 2.0% Chloride, Pre-Cracked 192
C.50 Half Cell Potential Readings for Chamber Shelf 4, 3.0% Chloride, Pre-Cracked 192
D.1 Chloride Content for Control Specimens 193
D.2 Chloride Content for Bath Specimens – 0.0% Chloride 193
D.3 Chloride Content for Bath Specimens – 0.5% Chloride 194
D.4  Figure D.4 – Chloride Content for Bath Specimens
      – 1.0% Chloride

D.5  Chloride Content for Bath Specimens – 1.5% Chloride

D.6  Chloride Content for Bath Specimens – 2.0% Chloride

D.7  Chloride Content for Bath Specimens – 3.0% Chloride

D.8  Chloride Content for Chamber Specimens
      – 0.0% Chloride

D.9  Chloride Content for Chamber Specimens
      – 0.5% Chloride

D.10 Chloride Content for Chamber Specimens
     – 1.0% Chloride

D.11 Chloride Content for Chamber Specimens
       – 2.0% Chloride

D.12 Chloride Content for Chamber Specimens
       – 3.0% Chloride

E.1  Surface Corrosion at Mid Section for 0.0%
      Chloride (Set #1)

E.2  Rib Loss at Mid Section for 0.0% Chloride (Set #1)

E.3  Surface Corrosion at Mid Section for 0.5%
      Chloride (Set #1)

E.4  Rib Loss at Mid Section for 0.5% Chloride (Set #1)

E.5  Surface Corrosion at Mid Section for 1.0%
      Chloride (Set #1)

E.6  Rib Loss at Mid Section for 1.0% Chloride (Set #1)

E.7  Surface Corrosion at Mid Section for 1.5%
      Chloride (Set #1)

E.8  Rib Loss at Mid Section for 1.5% Chloride (Set #1)

E.9  Surface Corrosion at Mid Section for 2.0%
      Chloride (Set #1)

xxiv
E.10  Rib Loss at Mid Section for 2.0% Chloride (Set #1)  203
E.11  Surface Corrosion at Mid Section for 3.0% Chloride (Set#1)  204
E.12  Rib Loss at Mid Section for 3.0% Chloride (Set #1)  204
E.13  Surface Corrosion at Mid Section for Average of all Chloride Contaminants (Set #1)  205
E.14  Rib Loss at Mid Section for Average of all Chloride Contaminants (Set #1)  205
E.15  Surface Corrosion at Mid Section for 0.0% Chloride (Set#2)  206
E.16  Rib Loss at Mid Section for 0.0% Chloride (Set #2)  206
E.17  Surface Corrosion at Mid Section for 0.5% Chloride (Set#2)  207
E.18  Rib Loss at Mid Section for 0.5% Chloride (Set #2)  207
E.19  Surface Corrosion at Mid Section for 1.0% Chloride (Set#2)  208
E.20  Rib Loss at Mid Section for 1.0% Chloride (Set #2)  208
E.21  Surface Corrosion at Mid Section for 1.5% Chloride (Set#2)  209
E.22  Rib Loss at Mid Section for 1.5% Chloride (Set #2)  209
E.23  Surface Corrosion at Mid Section for 2.0% Chloride (Set#2)  210
E.24  Rib Loss at Mid Section for 2.0% Chloride (Set #2)  210
E.25  Surface Corrosion at Mid Section for 3.0% Chloride (Set#2)  211
E.26  Rib Loss at Mid Section for 3.0% Chloride (Set #2)  211
E.27  Surface Corrosion at Mid Section for Average of all Chloride Contaminants (Set #2)  212
E.28 Rib Loss at Mid Section for Average of all Chloride Contaminants (Set #2)  

E.29 Time Step of Surface Corrosion for 0.0% Chloride Pre-Cracked Specimens  

E.30 Time Step of Rib Loss for 0.0% Chloride Pre-Cracked Specimens  

E.31 Time Step of Surface Corrosion for 0.5% Chloride Pre-Cracked Specimens  

E.32 Time Step of Rib Loss for 0.5% Chloride Pre-Cracked Specimens  

E.33 Time Step of Surface Corrosion for 1.0% Chloride Pre-Cracked Specimens  

E.34 Time Step of Rib Loss for 1.0% Chloride Pre-Cracked Specimens  

E.35 Time Step of Surface Corrosion for 1.5% Chloride Pre-Cracked Specimens  

E.36 Time Step of Rib Loss for 1.5% Chloride Pre-Cracked Specimens  

E.37 Time Step of Surface Corrosion for 2.0% Chloride Pre-Cracked Specimens  

E.38 Time Step of Rib Loss for 2.0% Chloride Pre-Cracked Specimens  

E.39 Time Step of Surface Corrosion for 3.0% Chloride Pre-Cracked Specimens  

E.40 Time Step of Rib Loss for 3.0% Chloride Pre-Cracked Specimens  

E.41 Time Step of Surface Corrosion for 0.0% Chloride Post-Cracked Specimens  

E.42 Time Step of Rib Loss for 0.0% Chloride Post-Cracked Specimens  

xxvi
E.43 Time Step of Surface Corrosion for 0.5% Chloride Post-Cracked Specimens 220
E.44 Time Step of Rib Loss for 0.5% Chloride Post-Cracked Specimens 220
E.45 Time Step of Surface Corrosion for 1.0% Chloride Post-Cracked Specimens 221
E.46 Time Step of Rib Loss for 1.0% Chloride Post-Cracked Specimens 221
E.47 Time Step of Surface Corrosion for 1.5% Chloride Post-Cracked Specimens 222
E.48 Time Step of Rib Loss for 1.5% Chloride Post-Cracked Specimens 222
E.49 Time Step of Surface Corrosion for 2.0% Chloride Post-Cracked Specimens 223
E.50 Time Step of Rib Loss for 2.0% Chloride Post-Cracked Specimens 223
E.51 Time Step of Surface Corrosion for 3.0% Chloride Post-Cracked Specimens 224
E.52 Time Step of Rib Loss for 3.0% Chloride Post-Cracked Specimens 224
F.1 Cumulative Mass Loss/Length for Control Specimens 225
F.2 Cumulative Mass Loss/Length for Bath 1, 0.0% Chloride Pre-Cracked Specimens 225
F.3 Cumulative Mass Loss/Length for Bath 1, 0.5% Chloride Pre-Cracked Specimens 226
F.4 Cumulative Mass Loss/Length for Bath 1, 1.0% Chloride Pre-Cracked Specimens 226
F.5 Cumulative Mass Loss/Length for Bath 1, 1.5% Chloride Pre-Cracked Specimens 227
F.6 Cumulative Mass Loss/Length for Bath 1, 2.0% Chloride Pre-Cracked Specimens 227
F.7  Cumulative Mass Loss/Length for Bath 1, 3.0% Chloride Pre-Cracked Specimens  228
F.8  Cumulative Mass Loss/Length for Bath 2, 0.0% Chloride Pre-Cracked Specimens  228
F.9  Cumulative Mass Loss/Length for Bath 2, 0.5% Chloride Pre-Cracked Specimens  229
F.10 Cumulative Mass Loss/Length for Bath 2, 1.0% Chloride Pre-Cracked Specimens  229
F.11 Cumulative Mass Loss/Length for Bath 2, 1.5% Chloride Pre-Cracked Specimens  230
F.12 Cumulative Mass Loss/Length for Bath 2, 2.0% Chloride Pre-Cracked Specimens  230
F.13 Cumulative Mass Loss/Length for Bath 2, 3.0% Chloride Pre-Cracked Specimens  231
F.14 Cumulative Mass Loss/Length for Bath 3, 0.0% Chloride Post-Cracked Specimens  231
F.15 Cumulative Mass Loss/Length for Bath 3, 0.5% Chloride Post-Cracked Specimens  232
F.16 Cumulative Mass Loss/Length for Bath 3, 1.0% Chloride Post-Cracked Specimens  232
F.17 Cumulative Mass Loss/Length for Bath 3, 1.5% Chloride Post-Cracked Specimens  233
F.18 Cumulative Mass Loss/Length for Bath 3, 2.0% Chloride Post-Cracked Specimens  233
F.19 Cumulative Mass Loss/Length for Bath 3, 3.0% Chloride Post-Cracked Specimens  234
F.20 Cumulative Mass Loss/Length for Bath 4, 0.0% Chloride Post-Cracked Specimens  234
F.21 Cumulative Mass Loss/Length for Bath 4, 0.5% Chloride Post-Cracked Specimens  235
<table>
<thead>
<tr>
<th>Page</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>F.22</td>
<td>Cumulative Mass Loss/Length for Bath 4, 1.0% Chloride Post-Cracked Specimens</td>
</tr>
<tr>
<td>F.23</td>
<td>Cumulative Mass Loss/Length for Bath 4, 1.5% Chloride Post-Cracked Specimens</td>
</tr>
<tr>
<td>F.24</td>
<td>Cumulative Mass Loss/Length for Bath 4, 2.0% Chloride Post-Cracked Specimens</td>
</tr>
<tr>
<td>F.25</td>
<td>Cumulative Mass Loss/Length for Bath 4, 3.0% Chloride Post-Cracked Specimens</td>
</tr>
<tr>
<td>F.26</td>
<td>Cumulative Mass Loss/Length for Chamber Shelf 1 0.0% Chloride, Post-Cracked Specimens</td>
</tr>
<tr>
<td>F.27</td>
<td>Cumulative Mass Loss/Length for Chamber Shelf 1 0.5% Chloride, Post-Cracked Specimens</td>
</tr>
<tr>
<td>F.28</td>
<td>Cumulative Mass Loss/Length for Chamber Shelf 1 1.0% Chloride, Post-Cracked Specimens</td>
</tr>
<tr>
<td>F.29</td>
<td>Cumulative Mass Loss/Length for Chamber Shelf 1 1.5% Chloride, Post-Cracked Specimens</td>
</tr>
<tr>
<td>F.30</td>
<td>Cumulative Mass Loss/Length for Chamber Shelf 1 2.0% Chloride, Post-Cracked Specimens</td>
</tr>
<tr>
<td>F.31</td>
<td>Cumulative Mass Loss/Length for Chamber Shelf 1 3.0% Chloride, Post-Cracked Specimens</td>
</tr>
<tr>
<td>F.32</td>
<td>Cumulative Mass Loss/Length for Chamber Shelf 2 0.0% Chloride, Pre-Cracked Specimens</td>
</tr>
<tr>
<td>F.33</td>
<td>Cumulative Mass Loss/Length for Chamber Shelf 2 0.5% Chloride, Pre-Cracked Specimens</td>
</tr>
<tr>
<td>F.34</td>
<td>Cumulative Mass Loss/Length for Chamber Shelf 2 1.0% Chloride, Pre-Cracked Specimens</td>
</tr>
<tr>
<td>F.35</td>
<td>Cumulative Mass Loss/Length for Chamber Shelf 2 1.5% Chloride, Pre-Cracked Specimens</td>
</tr>
<tr>
<td>F.36</td>
<td>Cumulative Mass Loss/Length for Chamber Shelf 2 2.0% Chloride, Pre-Cracked Specimens</td>
</tr>
</tbody>
</table>
F.37 Cumulative Mass Loss/Length for Chamber Shelf 2 3.0% Chloride, Pre-Cracked Specimens 243
F.38 Cumulative Mass Loss/Length for Chamber Shelf 3 0.0% Chloride, Post-Cracked Specimens 243
F.39 Cumulative Mass Loss/Length for Chamber Shelf 3 0.5% Chloride, Post-Cracked Specimens 244
F.40 Cumulative Mass Loss/Length for Chamber Shelf 3 1.0% Chloride, Post-Cracked Specimens 244
F.41 Cumulative Mass Loss/Length for Chamber Shelf 3 1.5% Chloride, Post-Cracked Specimens 245
F.42 Cumulative Mass Loss/Length for Chamber Shelf 3 2.0% Chloride, Post-Cracked Specimens 245
F.43 Cumulative Mass Loss/Length for Chamber Shelf 3 3.0% Chloride, Post-Cracked Specimens 246
F.44 Cumulative Mass Loss/Length for Chamber Shelf 4 0.0% Chloride, Pre-Cracked Specimens 246
F.45 Cumulative Mass Loss/Length for Chamber Shelf 4 0.5% Chloride, Pre-Cracked Specimens 247
F.46 Cumulative Mass Loss/Length for Chamber Shelf 4 1.0% Chloride Pre-Cracked Specimens 247
F.47 Cumulative Mass Loss/Length for Chamber Shelf 4 1.5% Chloride, Pre-Cracked Specimens 248
F.48 Cumulative Mass Loss/Length for Chamber Shelf 4 2.0% Chloride, Pre-Cracked Specimens 248
F.49 Cumulative Mass Loss/Length for Chamber Shelf 4 3.0% Chloride, Pre-Cracked Specimens 249
G.1 Visual Rating for Bath 1, 0.0% Chloride, Pre-Cracked 250
G.2 Mass Loss and Strength Loss for Bath 1, 0.0% Chloride, Pre-Cracked 250
G.3 Visual Rating for Bath 1, 0.5% Chloride, Pre-Cracked 251
G.4  Mass Loss and Strength Loss for Bath 1, 0.5% Chloride, Pre-Cracked

G.5  Visual Rating for Bath 1, 1.0% Chloride, Pre-Cracked

G.6  Mass Loss and Strength Loss for Bath 1, 1.0% Chloride, Pre-Cracked

G.7  Visual Rating for Bath 1, 1.5% Chloride, Pre-Cracked

G.8  Mass Loss and Strength Loss for Bath 1, 1.5% Chloride, Pre-Cracked

G.9  Visual Rating for Bath 1, 2.0% Chloride, Pre-Cracked

G.10 Mass Loss and Strength Loss for Bath 1, 2.0% Chloride, Pre-Cracked

G.11 Visual Rating for Bath 1, 3.0% Chloride, Pre-Cracked

G.12 Mass Loss and Strength Loss for Bath 1, 3.0% Chloride, Pre-Cracked

G.13 Visual Rating for Bath 2, 0.0% Chloride, Pre-Cracked

G.14 Mass Loss and Strength Loss for Bath 2, 0.0% Chloride, Pre-Cracked

G.15 Visual Rating for Bath 2, 0.5% Chloride, Pre-Cracked

G.16 Mass Loss and Strength Loss for Bath 2, 0.5% Chloride, Pre-Cracked

G.17 Visual Rating for Bath 2, 1.0% Chloride, Pre-Cracked

G.18 Mass Loss and Strength Loss for Bath 2, 1.0% Chloride, Pre-Cracked

G.19 Visual Rating for Bath 2, 1.5% Chloride, Pre-Cracked

G.20 Mass Loss and Strength Loss for Bath 2, 1.5% Chloride, Pre-Cracked

G.21 Visual Rating for Bath 2, 2.0% Chloride, Pre-Cracked

xxxii
G.22 Mass Loss and Strength Loss for Bath 2, 2.0% Chloride, Pre-Cracked

G.23 Visual Rating for Bath 2, 3.0% Chloride, Pre-Cracked

G.24 Mass Loss and Strength Loss for Bath 2, 3.0% Chloride, Pre-Cracked

G.25 Visual Rating for Bath 3, 0.0% Chloride, Post-Cracked

G.26 Mass Loss and Strength Loss for Bath 3, 0.0% Chloride, Post-Cracked

G.27 Visual Rating for Bath 3, 0.5% Chloride, Post-Cracked

G.28 Mass Loss and Strength Loss for Bath 3, 0.5% Chloride, Post-Cracked

G.29 Visual Rating for Bath 3, 1.0% Chloride, Post-Cracked

G.30 Mass Loss and Strength Loss for Bath 3, 1.0% Chloride, Post-Cracked

G.31 Visual Rating for Bath 3, 1.5% Chloride, Post-Cracked

G.32 Mass Loss and Strength Loss for Bath 3, 1.5% Chloride, Post-Cracked

G.33 Visual Rating for Bath 3, 2.0% Chloride, Post-Cracked

G.34 Mass Loss and Strength Loss for Bath 3, 2.0% Chloride, Post-Cracked

G.35 Visual Rating for Bath 3, 3.0% Chloride, Post-Cracked

G.36 Mass Loss and Strength Loss for Bath 3, 3.0% Chloride, Post-Cracked

G.37 Visual Rating for Bath 4, 0.0% Chloride, Post-Cracked

G.38 Mass Loss and Strength Loss for Bath 4, 0.0% Chloride, Post-Cracked

G.39 Visual Rating for Bath 4, 0.5% Chloride, Post-Cracked
G.40  Mass Loss and Strength Loss for Bath 4, 0.5% Chloride, Post-Cracked 269
G.41  Visual Rating for Bath 4, 1.0% Chloride, Post-Cracked 270
G.42  Mass Loss and Strength Loss for Bath 4, 1.0% Chloride, Post-Cracked 270
G.43  Visual Rating for Bath 4, 1.5% Chloride, Post-Cracked 271
G.44  Mass Loss and Strength Loss for Bath 4, 1.5% Chloride, Post-Cracked 271
G.45  Visual Rating for Bath 4, 2.0% Chloride, Post-Cracked 272
G.46  Mass Loss and Strength Loss for Bath 4, 2.0% Chloride, Post-Cracked 272
G.47  Visual Rating for Bath 4, 3.0% Chloride, Post-Cracked 273
G.48  Mass Loss and Strength Loss for Bath 4, 3.0% Chloride, Post-Cracked 273
G.49  Visual Rating for Chamber Shelf 1, 0.0% Chloride, Post-Cracked 274
G.50  Mass Loss and Strength Loss for Chamber Shelf 1, 0.0% Chloride, Post-Cracked 274
G.51  Visual Rating for Chamber Shelf 1, 0.5% Chloride, Post-Cracked 275
G.52  Mass Loss and Strength Loss for Chamber Shelf 1, 0.5% Chloride, Post-Cracked 275
G.53  Visual Rating for Chamber Shelf 1, 1.0% Chloride, Post-Cracked 276
G.54  Mass Loss and Strength Loss for Chamber Shelf 1, 1.0% Chloride, Post-Cracked 276
G.55  Visual Rating for Chamber Shelf 1, 1.5% Chloride, Post-Cracked 277
G.56  Mass Loss and Strength Loss for Chamber Shelf 1, 1.5% Chloride, Post-Cracked 277
G.57 Visual Rating for Chamber Shelf 1, 2.0% Chloride, Post-Cracked

G.58 Mass Loss and Strength Loss for Chamber Shelf 1, 2.0% Chloride, Post-Cracked

G.59 Visual Rating for Chamber Shelf 1, 3.0% Chloride, Post-Cracked

G.60 Mass Loss and Strength Loss for Chamber Shelf 1, 3.0% Chloride, Post-Cracked

G.61 Visual Rating for Chamber Shelf 2, 0.0% Chloride, Pre-Cracked

G.62 Mass Loss and Strength Loss for Chamber Shelf 2, 0.0% Chloride, Pre-Cracked

G.63 Visual Rating for Chamber Shelf 2, 0.5% Chloride, Pre-Cracked

G.64 Mass Loss and Strength Loss for Chamber Shelf 2, 0.5% Chloride, Pre-Cracked

G.65 Visual Rating for Chamber Shelf 2, 1.0% Chloride, Pre-Cracked

G.66 Mass Loss and Strength Loss for Chamber Shelf 2, 1.0% Chloride, Pre-Cracked

G.67 Visual Rating for Chamber Shelf 2, 1.5% Chloride, Pre-Cracked

G.68 Mass Loss and Strength Loss for Chamber Shelf 2, 1.5% Chloride, Pre-Cracked

G.69 Visual Rating for Chamber Shelf 2, 2.0% Chloride, Pre-Cracked

G.70 Mass Loss and Strength Loss for Chamber Shelf 2, 2.0% Chloride, Pre-Cracked

G.71 Visual Rating for Chamber Shelf 2, 3.0% Chloride, Pre-Cracked

278

278

279

279

280

280

281

281

282

282

283

283

284

284

285
<table>
<thead>
<tr>
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<tbody>
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<td>G.72</td>
<td>Mass Loss and Strength Loss for Chamber Shelf 2, 3.0% Chloride, Pre-Cracked</td>
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</tr>
<tr>
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<td>Visual Rating for Chamber Shelf 3, 0.0% Chloride, Post-Cracked</td>
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</tr>
<tr>
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<tr>
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</tr>
<tr>
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<td>G.84</td>
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G.87 Visual Rating for Chamber Shelf 4, 0.5% Chloride, Pre-Cracked 293

G.88 Mass Loss and Strength Loss for Chamber Shelf 4, 0.5% Chloride, Pre-Cracked 293

G.89 Visual Rating for Chamber Shelf 4, 1.0% Chloride, Pre-Cracked 294

G.90 Mass Loss and Strength Loss for Chamber Shelf 4, 1.0% Chloride, Pre-Cracked 294

G.91 Visual Rating for Chamber Shelf 4, 1.5% Chloride, Pre-Cracked 295

G.92 Mass Loss and Strength Loss for Chamber Shelf 4, 1.5% Chloride, Pre-Cracked 295

G.93 Visual Rating for Chamber Shelf 4, 2.0% Chloride, Pre-Cracked 296

G.94 Mass Loss and Strength Loss for Chamber Shelf 4, 2.0% Chloride, Pre-Cracked 296

G.95 Visual Rating for Chamber Shelf 4, 3.0% Chloride, Pre-Cracked 297

G.96 Mass Loss and Strength Loss for Chamber Shelf 4, 3.0% Chloride, Pre-Cracked 297
1.0 Introduction

1.1 Background and Problem Statement
Deterioration of concrete bridges due to exposure to chloride attack is a major problem facing a number of state departments of transportation (DOT), including the North Carolina DOT (NCDOT). Use of deicing salts on roadways and bridges across the state, along with exposure to salt laden air and sea spray along the coastlines creates harsh environmental conditions and accelerates the corrosion process of concrete structures. This creates a greater need each year for the repair or replacement of corroding bridge structures across North Carolina, and is a very costly and labor-intensive venture for the NCDOT. Aside from the direct costs of repair or replacement, negative psychological effects on drivers, extended traffic delays during repair or replacement, possible safety hazards for workers and drivers, and reduced service life for bridges are all related to the deterioration of affected structures.

Since the early observations of corrosion damage to highway structures in the 1960’s, the need for cost effective corrosion protection has been more and more apparent (Weindgroff 1996). Since then, many corrosion protection methods have been developed in order to delay, slow, or stop the corrosion process. These include sealants for the exposed surface of the concrete, placing protective coatings on the reinforcement, using electrochemical means to protect the reinforcement and extract chlorides, and the use of corrosion inhibiting admixtures in the mix design.

1.2 Need for Research
Although the use of corrosion inhibiting admixtures have been implemented and their effectiveness for new concrete structures have been documented for quite some time, there has been little research conducted on the use of their sister products, surface applied corrosion inhibitors on existing concrete structures. Many companies that produce these surface applied corrosion inhibitors claim
that their products can delay, slow, stop, or even reverse the corrosion process in existing reinforced concrete structures. Due to the lack of independent research on these products, these claims have not been fully verified, especially to address the specific problems and conditions facing the NCDOT. The NCDOT has had experience with corrosion inhibiting admixtures such as calcium nitrite (NCHRP 10-45 2000) but has not implemented the use of surface treatments.

1.3 Objectives
This study was launched to address the major concerns of the NCDOT bridge maintenance regarding surface applied corrosion inhibitors, and the following objectives were identified:

- Determine the effectiveness of commercially available corrosion inhibitors for remediation purposes in delaying, slowing, or stopping corrosion in existing reinforced concrete.
- The assessment is to be conducted under controlled laboratory conditions of wet-dry submersion cycles and periodic salt-water spray in order to simulate severe corrosion environments encountered in the field over time.
- Compare the effectiveness of different corrosion inhibitor products at varying levels of chloride contamination representing the various stages of corrosion in reinforced concrete.
- Establish a threshold chloride content for the corrosion inhibitors, beyond which they are no longer useful to apply.
- Determine if the products have any detrimental effect on the concrete itself.
- Determine any potential application problems that may occur with the products that would make them difficult for the NCDOT to use. These may include ponding, extended time for absorption, or a change in texture of the surface characteristics such as slickness.
• Develop guidelines and specifications for use of surface applied corrosion inhibitors and impart this knowledge to the NCDOT for implementation.

1.4 Scope and Contents
Accelerated corrosion testing was conducted on 348 small-scale representations of bridge deck sections. Six different commercially available surface applied corrosion inhibitor products were tested in two separate harsh environments, wet/dry submersion cycles in a 15% chloride solution at 130°F, and periodic salt-water spray with 15% concentration at 130°F. Voltmeter, half cell potential, and environmental condition readings were taken during the accelerated environmental testing. Specimens were removed from the environment at timed intervals and autopsies were performed on the reinforcement in order for visual ratings, mass loss measurements, and tension tests to be conducted. Chloride content analysis tests were also performed at timed intervals throughout the tests.

This thesis consists of five chapters, including this introductory chapter. There is also an appendix with additional data on the accelerated corrosion tests.

Chapter 2 discusses the causes of corrosion and the chemical process that takes place. It also reviews the methods for corrosion protection that have been used successfully, and briefly discusses the limited research on surface applied corrosion inhibitors. The particular manufactures and products used in this research program are discussed, along with their product composition and perceived benefits.

Chapter 3 provides a detailed summary of the experimental setup and processes for this project. It discusses the methods of assessment used throughout the research and their relevance to the project.
Chapter 4 presents the data that was collected during the project as a graphical representation in order to uncover patterns and trends that would lead to possible conclusions.

Chapter 5 summarizes the findings and conclusions developed from this research and outlines the direction for possible further research.
2.0 Literature Review

2.1 Introduction
The most common durability problem in reinforced concrete structures today is the corrosion of the embedded steel (Bentur et al. 1997). Corrosion of reinforcement in concrete can produce cosmetic flaws such as staining or cracking. Much more severe, however, is the structural damage it can produce. Delamination, spalling, exposure of the steel, and reduction of the reinforcement cross-section can lead to serious safety hazards (Bentur et al. 1997). Repair and/or replacement of these seriously damaged structures can be very costly. It is estimated that the cost to repair bridge decks in the US alone are somewhere between $50 and $200 million each year (Bentur et al. 1997). It is therefore apparent that any method of delaying or stopping the corrosion process would be greatly beneficial to the civil and construction industry.

2.2 Causes of Corrosion
Although corrosion can occur in the absence of chlorides, chloride ions are the main cause for the corrosion of reinforcing steel in concrete (ACI 222R-96). It would seem obvious that to prevent corrosion, one could just produce concrete with no chlorides. Unfortunately, preventing corrosion is not as simple as eliminating all chlorides from the concrete mix. Although ACI 318-02 does specify maximum acceptable chloride contents under different conditions, it is often times impossible to fully eliminate chlorides altogether even in new construction. These ions can be found throughout nature. Even mix ingredients such as water and aggregate generally contain small amounts of chloride. Sometimes, chloride ions are intentionally added to the mix as a form of accelerant (ACI 222R-96). After casting, reinforced concrete can be further subjected to many forms of chloride invasion. Bridges and marine structures are especially vulnerable to chloride attack due to the use of deicing salts and salt laden air along the coastlines. When the chlorides are dissolved, they can migrate into the unprotected concrete just as pore water.
2.3 Mechanism of Corrosion

“The corrosion of steel in concrete is an electrochemical process in which both chemical reactions and flow of electrical current are involved” (Bentur et al. 1997). Four things must be present for corrosion to take place: an anode, a cathode, an electrical conductor, and an aqueous medium (ACI 222R-96). Electrons are produced at the anode by the anodic reaction and flow to the cathode where they are used in the cathodic reaction. This flow of electrons, along with the counter flow of ions in the external concrete pore solution make up the corrosion current (Bentur et al. 1997). Iron is oxidized to ferrous ions at the anode, i.e., the negative pole, as below:

\[
\text{Fe} \leftrightarrow \text{Fe}^{++} + 2\text{e}^{-} \quad (2.1)
\]

A serious problem occurs at the anode. When the anode loses electrons, there is a reduction in the area of the original steel. This reduced cross-section can lead to higher stress concentrations on the reinforcement and possibly failure. This is especially severe in prestressing tendons. The corrosion products are deposited onto the cathode. When this chemical reaction takes place, the corrosion products created have a volume that is several times greater than that of the original iron. This can also be a very serious problem, if the metal is embedded in concrete, as with reinforcing steel. The larger volume of the corrosion products can generate stresses on the surrounding concrete sufficient to cause severe cracking and spalling of the concrete. This is illustrated in Figure 2.1
Figure 2.1 – Effects of Corrosion on Reinforced Concrete as Displayed During this Research

The cathode is where the reduction occurs. The following is the cathodic reaction that takes place in concrete:

\[
\frac{1}{2} \text{H}_2\text{O} + \frac{1}{4}\text{O}_2 + \text{e}^- \Leftrightarrow \text{OH}^- \quad (2.2)
\]

These reactions can occur as macrocell corrosion or microcell corrosion. The difference between these two types of corrosion lies in the distance between the anode and the cathode. In a macrocell reaction, some distance separates the anode and cathode such that one section of reinforcement is losing mass while the other section is gaining the corrosion products. This is common in welded wire fabric or tied rebar mesh. When macrocell corrosion exists, with a known resistance, it is possible to measure the rate of corrosion (macrocell corrosion current) as will be discussed in the next chapter. In a microcell reaction, the anode and cathode are extremely close such that the mass is lost and corrosion products are deposited in essentially the same area of the reinforcement. Figure 2.2 shows both the macrocell and microcell corrosion.
Chloride ions facilitate the reactions at the anode and cathode by breaking down the passivating film around the rebar. Concrete naturally provides a protective environment for reinforcement. It creates a very strong alkaline environment (pH >10) in which a thin film of ferric oxide forms on the surface of the rebar and helps prevent the reinforcement from corroding (Pullar-Strecker 2002). This passive layer can be broken down by carbonation or by sufficient levels of chlorides. Figure 2.3 shows a diagram of the passive layer breakdown by chloride attack.

Figure 2.2 - Mechanism of Corrosion in Macrocell and Microcell
Investigations have shown that if this passive layer is broken down, conditions are ripe for corrosion in the reinforced concrete structure that is exposed to intermittent wetting and drying (ACI 222R-96). However, if the sections are fully saturated on a continuous basis, the rate of corrosion may be very slow. This is due to the lack of available oxygen to initiate the corrosion reaction. Research has shown that corrosion increases as the sodium chloride concentration increases until a threshold of concentration is reached. Beyond this threshold, the rate of corrosion decreases even with increased chloride ion concentration (ACI 222R-96).

2.4 Corrosion Prevention Methods
2.4.1 New Construction
There are many methods presently available that have been proven to slow or prevent corrosion. Through the years, practices have been developed for new construction that greatly increases the service life of structures. These include

Figure 2.3 - Chloride Attack on Steel Bars
establishing a minimum concrete cover over the rebar, developing initial chloride limits in mixes (as discussed previously), and lowering the permeability of the mixes.

Along with these general practices, more advanced corrosion protection methods have been developed for new construction. Corrosion inhibiting admixtures, such as calcium nitrite, have been proven to be a cost effective way to protect reinforcement when added to the initial concrete mix (El-Jazairi and Berke 1990). Sealants for concrete have also been developed and implemented in recent decades. These include waterproof membranes, Polymer impregnation, and various types of overlays (ACI 222R-96). Other methods of corrosion prevention for new construction have included coatings on rebar and different types of corrosion resistant rebar.

2.4.2 Existing Structures
For existing structures that were built before these preventative technologies could be implemented, corrosion protection is much more challenging. However, there is a continuously rising demand for rehabilitation techniques and protection methods for older, existing structures. Some structures are so severely damaged that topical treatments would be useless. In these severe cases, sections of the concrete can be removed and replaced with treated concrete, new reinforcement, and possibly a topcoat of sealer. In cases that are not as severe, electrochemical protection can be implemented. This is where chloride is actually extracted from the reinforced concrete by electrochemical means (Bentur et al. 1997). Another method of protection that has been successfully implemented in existing structures is cathodic protection. If applied properly, this method can prevent corrosion and stop corrosion that is already in progress (Bentur et al. 1997). This method utilizes an external sacrificial anode that gives up electrons and in turn protects the internal reinforcement by forcing it to act as the cathode.
2.4.3 Surface Applied Corrosion Inhibitors

All of the previously discussed methods have been tested and have proven themselves effective to slow or even stop the effects of corrosion. However, some of these methods can be costly and difficult to implement in existing construction. The construction and maintenance industries are always looking for more cost effective and easily implemented ways to prevent corrosion for existing structures exposed to harsh environments. One possible method is the use of chemical corrosion inhibitors applied to the exposed surface of the affected reinforced concrete. These products use much of the same technologies and chemicals developed for corrosion inhibiting admixtures. If proven effective in preventing or stopping the corrosion process, these surface applied chemicals could be a cost effective solution to prolonging the lifespan of affected structures.

Six companies and their latest surface applied corrosion inhibiting products were chosen to be the focus of this research project. These manufactures were Aquron, Axim, Cortec, Grace, Master Builders, and Sika. These companies were chosen because their familiarity to the NCDOT and their reputations in the concrete industry. Table 2.1 shows these manufacturers and their products used in this project.

Table 2.1 – Manufacturers and Their Corresponding Products Tested

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Product</th>
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<tr>
<td>Aquron</td>
<td>AQURON-7000/CPT 2000</td>
</tr>
<tr>
<td>Axim</td>
<td>AXIM Post III</td>
</tr>
<tr>
<td>Cortec</td>
<td>MCI 2020M/MCI 2022</td>
</tr>
<tr>
<td>Grace</td>
<td>Postrite</td>
</tr>
<tr>
<td>Master Builders/Chemrex</td>
<td>Sonocrete-Corrosion Inhibitor</td>
</tr>
<tr>
<td>Sika</td>
<td>FerroGard 903</td>
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</table>
The research team requested information on each of the products listed above. Specific chemical compositions of all products were not provided although requested. The following information was provided:

Aquron
- The Aquron 7000 System consists of two coats of a penetrant (Aquron 7000), and one coat of sealant (Aquron CPT 2000).
- Aquron 7000 is not a sodium silicate product.
- Aquron CPT 2000 is a colloidal silicate concrete treatment.
- The two products together form a homogeneous gel matrix that neutralizes and purges the chlorides to the surface by chemical attraction.
- The gel that is formed prevents further chloride contamination.
- It can be used as a remedial treatment or a preventative treatment for reinforced concrete structures (Aquron 2002).

Axim
- One coat of Axim Post III for a full treatment.
- Surface applied migrating corrosion inhibitor with a multi-component silane sealer.
- Silane sealer delays the ingress of chlorides.
- Axim Post III is suitable for existing and new (fully cured) reinforced concrete (Axim 1999).

Cortec
- One coat of MCI 2020M, and one coat of sealant MCI 2022.
- MCI 2020M is a water-based surface treatment migrating corrosion inhibitor.
- MCI 2022 is a penetrating, waterborne, vapor-permeable, water-repelling sealer for concrete and masonry.
• MCI 2022 is made of a low VOC blend of silane/siloxane emulsions and migrating corrosion inhibitors.
• For use on existing reinforced concrete structures (Cortec 2001).

Grace
• Three applications of Postrite.
• Postrite penetrates the concrete and protects the reinforcement by surrounding it with a corrosion inhibitor.
• Calcium nitrite based.
• Intended for the repair of concrete that has experienced damage due to chloride induced corrosion (Grace 1999).

Master Builders/ChemRex
• Sonocrete – Corrosion Inhibitor applied in two applications.
• Surface applied, water-based, migrating corrosion inhibitor containing no calcium nitrite.
• Forms a protective layer around the reinforcement that inhibits corrosion.
• For use on existing reinforced concrete structures (ChemRex 2002).

Sika
• FerroGard 903 requires two applications.
• It is a corrosion inhibiting impregnation coating for hardened concrete designed to penetrate the surface and then to diffuse in vapor or liquid form to the reinforcement.
• Forms a protective layer on the surface of the reinforcement.
• FerroGard 903 is a combination of amino alcohols and organic and inorganic corrosion inhibitors.
• Does not contain calcium nitrite.
• Maximum chloride content of structures intended for treatment is 6
lbs/yd$^3$.

- For use on existing reinforced concrete structures (Sika 2001).

It is obvious that there are many different methods that surface applied corrosion inhibitors use to prevent corrosion. Surface applied corrosion inhibitors can reduce the penetration of chlorides and carbon dioxide. With proper application, including monitoring and recoating, these corrosion inhibitors can contribute to the long-term good health of a structure exposed to corrosive environments (Pullar-Strecker 2002). It is difficult to compare different corrosion inhibitors due to a lack of accepted standard evaluation tests that can be applied to all types of inhibitors. It is necessary that a system of acceptable tests be developed for use in comparing corrosion inhibitors (Vermani and Clemena 1998). Continuing studies must be performed to evaluate surface applied corrosion inhibitors since most studies performed have been relatively recent and there is little long-term proof of their effectiveness (Pullar-Strecker 2002).
3.0 Experimental Procedure

3.1 Introduction
The main objective of this research project was to determine the effectiveness of six commercially available surface applied corrosion inhibitors. Reinforced concrete specimens were cast and then coated with one of the six corrosion inhibitor products tested. These products were donated by the corresponding manufacturers who were informed of the test matrix and parameters for approval prior to product application. Each product manufacturer was also invited to participate in the application process. Controlled cracking was induced either before or after the corrosion inhibitor products were applied, giving two sets of specimens: pre-cracked and post-cracked, respectively. Each specimen was duplicated once to ensure repeatability of the test results. These specimens were then placed in one of three testing environments. Two of the test environments were designed to accelerate corrosion using 15% salt-water solutions and a temperature of 130°F in either submersion wet/dry cycles or spray cycles. The third environment was considered the control environment and was kept at approximately 70°F and 50% relative humidity. The data collected throughout the experiment included corrosion current (voltmeter) readings, half cell potential readings, environmental condition readings, and chloride content analysis. Duplicate specimens were removed halfway through the testing and evaluated by visual assessments of corrosion, mass loss measurements, and strength reduction (tension) tests. At the end of the test, the remaining specimens were removed and evaluated in the same manner.

3.2 Test Preparation

3.2.1 Specimen Geometry
The reinforced concrete specimens used in the pilot test and in this research project were cast with identical dimensions: 2.5 in width, 2.0 in depth, and 14 in length. All specimens were reinforced with one ½ in diameter No. 4 Grade 60 steel bar (deformed bar) with ½ in concrete cover from the top surface, and 1.0 in
cover from the sides, as shown in Figure 3.1. The steel rebar extended from the concrete at both ends by 1.0 in. Stainless steel screws were drilled into one end of the rebar to allow for the necessary wiring for the corrosion assessment, i.e., voltmeter and half cell readings, during the test program. The bar ends were coated for a length of 2 in on either end using high temperature resistant epoxy paint to eliminate end corrosion effects.

![Specimen Geometry](image)

**Figure 3.1 - Specimen Geometry**
The specimen geometry was chosen to aid in the acceleration of the corrosion process, to simulate the approximate rebar cover in the existing concrete bridge decks in North Carolina, and to simplify the casting and handling of the specimens.

3.2.2 Slab Geometry
In order to produce the necessary crack patterns in the specimens, concrete slabs were designed and cast as support for the specimens. Each concrete slab was designed to hold seven specimens of the same chloride content, except for the slab for the control specimens, which held twelve specimens, i.e., two of each chloride content. The dimensions of each regular slab were as follows: 15 in width, 4 in depth, and 37.5 in length. The slabs contained a tied mesh of No. 3 deformed bars, vertical stainless steel threaded rods, and seven No. 8 bars to correspond with the seven specimens per slab. The vertical threaded rods were used in addition to the epoxy-coated plates to load each end of the specimen in order to induce the initial cracks. The No. 8 bars were necessary for monitoring of the corrosion current density. Each end of the No. 8 bars extended $\frac{1}{2}$ in out of either side of the slab. These bars, similar to the No. 4 bars in the specimens, were also coated with the same epoxy for a length of 2 in on either side. Also, similar to the specimens, one end of each No. 8 bar was equipped with a stainless steel screw.

3.2.3 Formwork and Casting
The formwork for the specimens and cubes are shown in Figures 3.2 and 3.3.
Figure 3.2 – Formwork for the Specimens

Figure 3.3 - Formwork for the Cubes
For the specimens and the cubes, six batches of concrete were cast, one for each chloride content. The appropriate amount of Sodium Chloride (NaCl) to achieve the correct initial chloride content by cement weight was added for each batch. Figure 3.4 shows the addition of the chloride during the mixing.

Figure 3.4 – Chloride Addition During Specimen and Cube Casting

The concrete was mixed in the laboratory, following a standard NCDOT mix. Figure 3.5 shows the casting of the specimens and the cubes.
The concrete for the slabs was ready mixed delivered to the laboratory, but followed the same mix proportions described earlier. Figure 3.6 shows the casting procedure for the slabs.
Small strips of approximately 1/8 in thick pre-cured carbon fiber reinforced polymer (FRP) were used as spacers under each specimen to create a height difference between the ends and the middle of the specimen. This allowed for tightening of the plates on each end to induce the necessary cracking. The choice of carbon FRP was to avoid corrosion of the spacer. Once the appropriate cracking was induced and the proper corrosion inhibitor products applied to each specimen, ½ in of grout was added on the top of each slab. The purpose for the grout was to provide continuity in the concrete between the specimens and the slabs so that an electrochemical current could freely pass between the two mediums. The grout was made of the same mix as the specimens, except that it did not contain any aggregates. Figure 3.7 shows the test setup.
A 100-ohm resistor was connected between the screws of each bar located in the slab to the screw in the corresponding bar in the specimen. Metal clips were used...
to connect the wire from the resistor on the bottom bar to the screw in the top bar. These resistors and the connecting wires were also coated with the same high temperature-resistant epoxy paint as the ends of the bars to protect them from the harsh environments. The resistors in conjunction with the grout provided the necessary connections for the macro-cell corrosion loop. The clips allowed disconnecting the resistors for half-cell measurements. A picture of the resistor connection can be seen in Figure 3.8.

![Resistor and Clip Connection](image)

**Figure 3.8 – Resistor and Clip Connection**

**3.2.5 Chloride Analysis Cubes**

In addition to the slabs and the specimens, 456 two-inch cubes were cast in preparation for this project. 210 cubes were placed in the bath environment, 210 were placed in the environmental chamber, 30 were placed in the control environment, and six initial cubes were tested immediately after casting and curing. The purpose of the cubes was to provide a sample of concrete to test for chloride content at timed intervals. These cubes were cast with the same chloride
contents as the specimens ranging from 0.0% to 3.0%, coated with the same corrosion inhibitor products, and placed in the same environments as the specimens. They were also coated with the epoxy paint on all sides except the top and bottom to mimic the specimens. At the end of each timed interval, one set of cubes was removed from its environment. Powder was then collected from the cubes by removing the epoxy paint and drilling at $\frac{1}{2}$ in from the top surface of each cube. The powder was placed in a sealed container until chloride analysis could be performed. The purpose for drilling at the $\frac{1}{2}$ in depth was to simulate the concrete conditions at the surface of the bar in the specimen. Each sealed powder sample was then taken to the Materials and Test Unit of the NCDOT, properly prepared using DOT standards, and titrated to determine the chloride content of each cube at the $\frac{1}{2}$ in level. This procedure was done at scheduled timed intervals of 1 month, 3 months, 6 months, 12 months, and 18 months of environmental exposure, along with six initial control cubes. Table 3.1 shows the cube test matrix.

Table 3.1 – Chloride Analysis Cube Matrix

<table>
<thead>
<tr>
<th>Chloride Content</th>
<th>CI Product</th>
<th>NO CI</th>
<th>Auron</th>
<th>Axim</th>
<th>Cortec</th>
<th>Grace</th>
<th>Master Builders</th>
<th>Sika</th>
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<tr>
<td>0.0%</td>
<td>16</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
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<tr>
<td>0.5%</td>
<td>16</td>
<td>10</td>
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<td>10</td>
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<td>1.0%</td>
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3.3 Pilot Tests
Two sets of pilot tests were carried out before preparing the specimens for the actual test program. These pilot tests were done on specimens with the same dimensions as the proposed test specimens. The first pilot test was carried out to determine the flexural response of the specimens. Strain gauges were placed on the top and bottom surfaces of the concrete specimens at their mid-span. Each specimen was then tested in three-point bending using the 220-kip MTS closed-loop universal testing machine. As expected, the specimens were over-reinforced and failed by crushing of concrete rather than yielding of steel bars. Figures 3.9 and 3.10 show the first pilot test setup and the failed specimen.

Figure 3.9 – Pilot Test Setup
The purpose of the second pilot test was to determine a simple, yet reliable and consistent method to induce similar crack patterns and similar strain levels in the specimens. Several specimens were equipped with strain gauges on the rebar before casting. The strain gauges were then connected to a strain indicator box. Additionally, DEMEC (Demountable Mechanical Strain Gauge) points were placed on the top surface of the concrete. Using these methods of measurement, each specimen was loaded by hand tightening the end plates. The cracks on the surface of the concrete specimens were monitored using magnifying glass and sufficient light. The first crack was observed at a strain of about 0.0007 in the embedded re-bar. The second crack was observed at a strain of about 0.0011 in the embedded re-bar. Repeatability of the data was confirmed on the various specimens. Therefore, it was decided that the appropriate and consistent strain level in the concrete was achieved when two cracks perpendicular to the length of the specimen and spanning the width of the specimen became visible. Figures 3.11, 3.12, and 3.13 show the second pilot test.
Figure 3.11 – Pilot Test 2: Setup with Strain Indicator Box

Figure 3.12 – Pilot Test 2: Using DEMEC Points and Dial Gauge
3.4 Test Setup

3.4.1 Test Parameters
The parameters of the final test matrix included six different levels of initial chloride contents (0.0%, 0.5%, 1.0%, 1.5%, 2.0%, and 3.0% of the weight of the cement in the mix), six different corrosion inhibitor products from six different manufacturers, pre-cracked and post-cracked conditions, duplicate specimens, and three environmental conditions. A total of 348 specimens were cast and used in the actual test program: 168 of these were located in four wet/dry baths, 168 specimens were placed in the environmental chamber, and 12 others in the control environment. Table 3.2 shows the overall test matrix and the selected corrosion inhibitor products.
<table>
<thead>
<tr>
<th>Corrosion Inhibitor (Manufacturer)</th>
<th>Environment</th>
<th>Number of Specimens</th>
<th>Total Number of Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Corrosion Inhibitor</td>
<td>Control Environment</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Wet/Dry Cycles</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Salt-Water Spray</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Salt-Water Spray</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>AXIM Post III (Axim Concrete Technologies)</td>
<td>Wet/Dry Cycles</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Salt-Water Spray</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>MCI 2020M/MCI2022 (Cortec Corporation)</td>
<td>Wet/Dry Cycles</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Salt-Water Spray</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Postrite (W.R. Grace and Company)</td>
<td>Wet/Dry Cycles</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Salt-Water Spray</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Sonocrete - Corrosion Inhibitor (Chemrex/Master Builders)</td>
<td>Wet/Dry Cycles</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Salt-Water Spray</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>FerroGard-903 (Sika Corporation)</td>
<td>Wet/Dry Cycles</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Salt-Water Spray</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Total Number of Specimens</td>
<td></td>
<td>58</td>
<td>58</td>
</tr>
</tbody>
</table>
3.4.2 Test Procedure
Of the seven specimens placed on each slab, the first served as the control specimen, and thus was not coated with any corrosion inhibitor. The remaining six were coated with one of the six products identified in Table 3.2 above. Each slab held only specimens of one particular percentage of initial chloride content. The ends of the specimens were color coded to identify the initial chloride content. Half of the specimens of each color code were cracked first. Then, the corrosion inhibitor products were applied on all specimens. Subsequently, the remaining specimens were cracked.

3.4.3 Application of Corrosion Inhibitors
Each corrosion inhibitor product was applied based on the recommended dosage rates in the vendor’s literature. If the rate was given as a range, the average value was chosen for this study. Most application rates were given in gallons per square foot of surface area. These values were converted to the surface area for each specimen and the exact amount of product was used for each application. To ensure the accuracy of the amount of product for each specimen, a syringe was used to administer the product and then a brush was used to distribute the product evenly on the surface of the specimen. For each different product, the instructions for the number of coats, drying time between coats, and the amount of each coat varied. During the application process, observations were recorded for each product. These observations included odor, color, and drying time of the product on the concrete surface, and the apparent slickness or change in the texture of the surface of the concrete. A list of the products, their application dosages, and the observations are provided in Table 3.3.
### Table 3.3 – Product Application Chart

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Aquron</th>
<th>Axim</th>
<th>Cortec</th>
<th>Grace</th>
<th>Master Builders (Chemrex)</th>
<th>Sika</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product</td>
<td>Aquron 7000 CPT 2000</td>
<td>Axim Post III</td>
<td>MCI 2020M MCI 2022</td>
<td>Postrite</td>
<td>Sonocrete Corrosion Inhibitor</td>
<td>Ferrogard - 903</td>
</tr>
<tr>
<td><strong>Applied Dosage</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primer</td>
<td>2 coats 200sq.ft/Gal</td>
<td>1 coat 200sq.ft/Gal</td>
<td>1 coat 150sq.ft/Gal</td>
<td>3 coats 150sq.ft/Gal</td>
<td>2 coats 150sq.ft/Gal</td>
<td>2 coats 100sq.ft/Gal</td>
</tr>
<tr>
<td>Sealer</td>
<td>1 coat 200sq.ft/Gal</td>
<td>None</td>
<td>1 coat 150sq.ft/Gal</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td><strong>Odor</strong></td>
<td>None</td>
<td>Very strong ammonia smell with noxious fumes</td>
<td>Mild ammonia smell</td>
<td>None</td>
<td>Ammonia smell</td>
<td>Very slight ammonia smell</td>
</tr>
<tr>
<td><strong>Drying Time</strong></td>
<td>15-30 minutes last coat - 1 hr</td>
<td>1 hour</td>
<td>15-30 minutes</td>
<td>30 minutes each</td>
<td>Last coat 1-2 hours</td>
<td>Last coat 1 hour</td>
</tr>
<tr>
<td><strong>Slickness</strong></td>
<td>Slightly for sealer until dried</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

### 3.4.4 Epoxy coating

Once the slabs and specimens were assembled and prepared with the corrosion inhibitors, one final step was needed before they could be exposed to the different environments. This step was applying the high temperature resistant epoxy coating to all of the sides of the slabs, specimens, and cubes, and to the top of the grouted slabs. The purpose for this coating was to prevent any influx of chlorides from entering the specimens or the cubes from the sides, and to force any such entry only from the top of the specimens and cubes. This was meant to simulate real life conditions of a typical section of a reinforced concrete bridge deck. The tops of the slab were coated also to prevent the penetration of chlorides to preserve the non-corroded condition of the reference bars located in the slabs. Figures 3.14 and 3.15 show the epoxy coating process.
Figure 3.14 - Epoxy Coating of the Slabs and Specimens

Figure 3.15 – Epoxy Coating of the Cubes
3.5 Exposure Environments
As stated earlier, three different environments were used in this research project; two to introduce an accelerated corrosion process, and the third as a control environment. The next section explains these different environments in detail.

3.5.1 Submersion Baths
Four watertight submersion baths were fabricated using timber, plywood, rubber pond liner, fiberglass insulation, and insulating foam. Each bath was designed to hold six slabs with seven specimens each, for a total of 42 specimens per bath. The baths were approximately 10 feet long by 4.5 feet wide and 1 foot deep. The experiment called for one week of submersion in 15% salt-water solution at 130°F-sustained temperature followed by one week of dry heat at the same temperature to further accelerate the corrosion. To achieve these temperature requirements, a water heater, thermostat, and circulating pump were installed in each bath for use during the submerged cycles. An industrial space heater was used for the dry cycles. Cubes were placed in one of the baths along with the slabs, five for each specimen for a total of 210 cubes. Once the slabs were loaded into the baths, water and salt was added to reach a 15% solution in two of the baths. The other two baths were exposed to dry heat. At the end of each week of exposure, the water was pumped from the wet baths to the dry baths, and the dry heat was introduced to the once-wet baths. Half of the specimens in the baths were removed at the end of six months. The duplicate set of specimens was removed at the end of the one-year exposure period. Figures 3.16 and 3.17 show the baths in wet and dry cycles.
Figures 3.16 – Loaded Bath in Wet Cycle
3.5.2 Environmental Chamber

The project first made use of the lab’s environmental chamber, which has the ability to range in temperature from $-105^\circ$ to $+180^\circ$ F, control humidity, and spray either salt water or potable water to simulate rain, or wet conditions. The slabs and 210 cubes were loaded into the chamber on aluminum shelves stacked four high with all specimens of the same chloride content on top of each other to
prevent any chloride diffusion from one slab to the other. The chamber was then programmed to run 15% salt-water spray cycles for four minutes at 130°F, and then run a dry cycle for 11 minutes at the same temperature, for a total cycle of 15 minutes. This cycle continued for five days out of the week, giving two days of shut down time to cool down the chamber and take the appropriate readings from week to week. Figure 3.18 shows the original environmental chamber.

Figure 3.18 – Original Environmental Chamber

This chamber ran the accelerated corrosion test for 18 days. At this time, severe leakage around the chamber base caused a halt in the test program. After much deliberation, it was decided to build a new chamber for immediate use. The new chamber was built much in the same way as the baths. The base dimensions and materials used were the same, the only difference being the height of the
chamber. As opposed to one foot, the chamber height had to accommodate four slabs high and allow for a person to enter in order to take readings. The chamber was built with a holding pool at the bottom for the 15% salt-water solution. A pump was placed in this holding pool and attached to a piping system that carried the water to spray pipes at the top of the chamber. Again, a water heater was used to reach the desired temperature. The slabs along with the cubes were loaded into the new chamber for continued testing. At the end of three months, the first set of specimens was removed from the chamber for evaluation. The remaining specimens were removed after six months of exposure. Figure 3.19 shows the assembled environmental chamber with the loaded specimens.

Figure 3.19 – Assembled Environmental Chamber
3.5.3 Control Environment

The control environment was inside in the lab, held at approximately 70°F and 50% relative humidity. Twelve specimens were located in this environment, two of each chloride content, all loaded on one slab. These specimens did not have any corrosion inhibitor products applied to them. The reason for this was to provide a reference of how the different chloride content specimens performed under no external extreme environmental conditions. Thirty cubes were also placed in this control environment, five for each chloride content. These cubes were tested at scheduled time intervals discussed earlier. At the end of one year, six specimens were removed from the control environment for evaluation. Figure 3.20 shows the control environment specimens.

Figure 3.20 – Control Environment Specimens
3.6 Data Collection During Exposure
A number of methods were utilized during the duration of this study to collect data for evaluation of the different corrosion inhibitor products. These methods are discussed in detail below.

3.6.1 Corrosion Current Measurements
The test specimens were set up so that a method of measurement using a known resistance in accordance with voltmeter readings could be used to determine the corrosion current density. This method, commonly referred to as voltmeter readings or corrosion current density data, has been utilized by other investigators as well and follows ASTM G 109 - 99 (West et al. 2002). For this method of measurement to work, a current has to develop between the corroding bar and a reference bar. There must also be a known resistance connecting these two bars. With a known resistance and the voltmeter readings, the simple equation \( V = IR \) (Voltage = Current x Resistance) can be solved for current, \( I = V/R \). The current can then be divided by the nominal area of the bar to provide a useful measurement known as the corrosion current density. The voltmeter readings were taken once each week for every specimen in all the environments. The data was collected and recorded in a spreadsheet for further analysis. Figure 3.21 shows the typical voltmeter reading procedure.
3.6.2 Half Cell Potential Measurements
Half cell potential measurements were also taken weekly for each specimen, following ASTM standard C-876. The reading device consists of essentially a voltmeter box connected to two leads, one being a simple connector wire, and the other, a copper-copper sulfate half cell electrode. The electrode consists of a copper rod submerged in an airtight sulfate/water solution. The surface of each concrete specimen was first wetted and then the moist electrode tip was placed on the wet surface for readings. The other lead wire was connected to the end of the corroded bar, after having detached it from the reference bar. The half cell data was collected in the same manner as the voltmeter readings and then recorded in a spreadsheet for further analysis. Figure 3.22 shows the typical half cell potential reading procedure.
3.6.3 Environmental Condition Measurements

Four different environmental condition measurements were taken on a weekly basis: salt-water concentration, pH, temperature, and humidity. The salt-water concentration was measured by taking a sample of each water reservoir from the baths and the chamber. The samples were then weighed and compared with a previously calibrated scale to measure chloride content. The purpose for this measurement was to maintain an approximate 15% salt-water solution at all times. If the solutions were not 15% at the time of measurement, the solution was either diluted or concentrated accordingly until a 15% solution was achieved. Figure 3.23 shows the typical salinity measurement procedure.
Each water reservoir was also subjected to pH measurements. Strips of pH indicator paper were submerged in each water reservoir and the color of the paper was then compared to a given pH scale. Figure 3.24 shows the pH measurements. This was monitored to give any warning of a chemical change in the salt-water solution.
Temperature measurements were taken during both the wet and dry cycles of corrosion testing, along with the control environment. The temperature was regulated to be approximately 130°F at all times in order to accelerate corrosion. Figure 3.25 shows the temperature measurements.
The final environmental condition that was monitored was the humidity in the control environment. A digital thermometer/humidity gauge was used to measure the relative humidity of the control environment. The control environment was kept at approximately 50% relative humidity.

### 3.6.4 Chloride Content Measurements

One important method to determine the effectiveness of the corrosion inhibitors is the chloride content analysis. As discussed earlier, drilled concrete powder samples were collected from the cubes at scheduled time intervals. These samples were tested at the NCDOT Materials and Test Unit following their standard test procedure which is a modification of ASTM C 1152. Under this procedure, samples were dried, prepared into a liquid solution, filtered, and then titrated. After calculations were performed using the titration data, the chloride content of each sample could be determined. Figures 3.26, 3.27, 3.28, and 3.29 show the various steps in the chloride analysis procedure.
Figure 3.26 – Cubes and Powder Ready for Chloride Analysis Testing

Figure 3.27 – Weighing the Dried Powder Samples
Figure 3.28 – Filtering Chloride Samples

Figure 3.29 – Titrating a Prepared Chloride Sample
3.7 Post-Exposure Measurements

As mentioned earlier, the duration of the accelerated corrosion testing was scheduled for 18 months for both the submersion baths and the spray chamber. As the tests progressed, it became clear to the research team that severe corrosion was occurring much earlier than expected. Therefore, it was decided to end the exposure of the specimens at different intervals. This was possible due to the duplicate specimens. The order the specimens were retrieved from their harsh environments were as follows: the first batch of the chamber was retrieved at the end of three months of exposure, the rest from the chamber at the end of six months, the first batch from the baths at the end of six months, and the remainder at the end of one year of accelerated corrosion testing. Each removed specimen was subjected to three post-exposure measurements: visual analysis, mass loss measurements, and tension tests, as discussed below.

3.7.1 Visual Corrosion Evaluations

Once the slabs were removed from the corrosive environments, the tested bars were recovered from each concrete specimen and evaluated visually using two quantifiable scales: percentage of surface area covered by corrosion and percentage of rib volume lost to corrosion. These percentages, although estimated only visually, provided a good basis of comparison. These evaluations were conducted by the same person for all bars. Randomly selected bars were assessed multiple times to ensure repeatability of the evaluations. Each bar was graphically divided into five different sections, two end sections and three middle sections. The purpose was to separate the amount of corrosion in the end sections of the bar from the corrosion in the middle sections, to ensure that various corrosion inhibitor products were not penalized for end effects that may have resulted from improper sealing. After surface rust evaluation, the bars were cleaned by light brushing using a non-wire brush, to evaluate rib loss in each section. Figure 3.30 shows the visual analysis procedure.
3.7.2 Mass Loss Measurements

The mass loss measurements in this study followed the ASTM standard G1 – 03. This standard provides a number of options for chemical cleaning of the rusted bars. After consulting several chemical experts, the standard using a mixture of 500ml-hydrochloric acid (HCl), 3.5g-hexamethylene tetramine (C₆H₁₂N₄), and 500ml-reagent water was chosen as the best option for this study. When soaked in this solution mixture, the bars would actually lose the majority of corrosion product to a chemical reaction with the liquid. Before this method could be utilized, the epoxied ends of the bars were cut off. The bars were soaked in the solution for 10-minute cycles, while weighing after each cycle until no significant mass loss could be recorded. For this study, four cycles provided the desired accuracy, as changes after 4 cycles were very negligible. Figures 3.31, 3.32, 3.33, and 3.34 show the various steps in the mass loss measurement process.
Figure 3.31 – Bars Submerged in Chemical Cleaning Solution

Figure 3.32 – Brushing Bars After the Chemical Bath
Figure 3.33 – Drying the Bars After the Chemical Bath

Figure 3.34 – Weighing a Bar After the Cleaning Process
3.7.3 Tension Tests
The last test to be performed on each individual bar was the tension test. The tension tests were performed in accordance with ASTM standard A 370 – 03a. Each bar was placed in the lab’s 220-kip MTS closed-loop universal testing machine under tension forces until failure. An extensometer was used for each test to measure the change in the length of the bar. The load-deflection graphs were generated for each specimen, and the loss of strength was measured in comparison with a control non-corroded bar. Figures 3.35, 3.36, and 3.37 show the various steps in the tension test.

Figures 3.35 – Tension Test Setup
Figure 3.36 – Extensometer Setup

Figure 3.37 – Bar After Failure in Tension
4.0 Analyses and Discussion

4.1 Introduction
As discussed in Chapter 3, a number of data sets were collected over the duration of this experiment. Measurements were taken before, during, and after the environmental exposure. The following sections will discuss these measurements and the findings based on this data.

4.2 Measurements and Results During Accelerated Testing

4.2.1 Corrosion Current Measurements and Results
Corrosion Current measurements were taken for each of the 348 specimens on a weekly basis using a voltmeter. The method for using the voltmeter to collect these measurements was discussed previously in Section 3.6.1, and generally followed ASTM G 109-99. These readings were collected and entered into a spreadsheet so that graphs could be developed and trends could be observed. The voltmeter readings, along with the known resistance of 100 Ohms, were used in accordance with ASTM G 102-89 (R 99) to determine corrosion rates for the specimens. This corrosion rate is calculated using Faraday’s Law as per ASTM G 102-89 (R99):

\[
CR = K_1 \left( \frac{i_{cor}}{\rho} \right) \left( \frac{W}{n} \right)
\]

(4.1)

Where:
CR = corrosion rate given in mm/year,

\[K_1 = 3.27 \times 10^{-3}, \text{ mm g/\(\mu\)A cm yr}\]

\[i_{cor} = \text{corrosion current density (\(\mu\)A/cm}^2) = (I_{cor}/A)\text{, where } I_{cor} = \text{total anodic current (\(\mu\)A), and } A = \text{exposed specimen area (cm}^2)\]

\[\rho = \text{density in g/cm}^3\]

\[W = \text{the atomic weight of the element, and}\]

\[n = \text{the number of electrons required to oxidize an atom of the element in the corrosion process, that is, the valence of the element}\]

Figures 4.1, 4.2, and 4.3 show typical graphs of the corrosion rate over time for specimens from the three environments; control, bath and chamber.
Figure 4.1 - Corrosion Rate for Control Specimens (Set #2)
Figure 4.2 - Corrosion Rate for Bath 2, 0.0% Chloride, Pre-Cracked
Figure 4.3 - Corrosion Rate for Chamber Shelf 3, 2.0% Chloride, Post-Cracked

Each of the graphs generated from this experiment for corrosion rate vs. time can be found in Appendix A. The gap in the chamber data was due to the shut down of the original chamber after some problems as discussed in Section 3.5.2 and for the time it took to complete the construction of the new chamber. The corrosion rate data can be interpreted as the instantaneous rate of corrosion at the particular time of voltage measurement. From the figures, it is obvious that the corrosion rate changes frequently over time for each specimen and a useful product comparison is not practical with these graphs. Fluctuations seen throughout for all three environments may indicate the start and end of each corrosion event. It was necessary to convert the corrosion rates for each specimen to a total corrosion measurement following ASTM G 109-99. This was done by integrating the corrosion rate data over time. Figures 4.4, 4.5, and 4.6
show the cumulative corrosion over time for the same specimens as the previous graphs. Graphs for other specimens are shown in Appendix B.

![Graph](image-url)

**Figure 4.4 - Cumulative Corrosion Over Time for Control Specimens (Set #2)**

For the control specimens, it is evident that the onset of corrosion is much later than in the bath and chamber environments. It is also clear that even at the end of the test program the amount of total corrosion of the control specimens was very little in comparison with the other environments, as was expected. All specimens display small amounts of corrosion, however there are several with initial chloride contents that display significantly more accumulated corrosion as compared to the others: these are 0.5%, 1.5%, and 3.0%. It is not clear why the 1.0% and 2.0% specimens display almost the same cumulative corrosion as the 0.0% specimens. In Set #1 of the control specimens (see Appendix B), on the
other hand, the 0.0%, 0.5%, and 1.0% specimens follow the same pattern of cumulative corrosion, while the 1.5%, 2.0%, and 3.0% specimens have significantly higher cumulative corrosion. The difference in the effect of the initial chloride content may be explained as follows:

- The levels of corrosion may be too low for non-accelerated corrosion, and therefore no real pattern of behavior for various chloride contents may exist after about one year.
- The resolution for this method of measurement may not be detailed enough to accurately detect corrosion at lower levels.
- Continued testing on these bars may be necessary to show any trends if they do exist.

It can, however, be concluded that different chloride levels do affect the onset of corrosion and can speed up the corrosion process based on these two sets of specimens.
Figure 4.5 - Cumulative Corrosion Over Time for Bath 2, 0.0% Chloride, Pre-Cracked
The cumulative corrosion graphs for both the bath and the chamber specimens, on the other hand, exhibit significant levels of corrosion in comparison with the control specimens. This was expected due to the severe nature of the accelerated testing environments. The graphs shown above indicate that the corrosion inhibitor products are more effective in slowing the corrosion process than if no corrosion inhibitor was used. Graphs for every specimen for total corrosion over time can be found in Appendix B. For many of these graphs, it may not differentiable as to which product(s) performed the best. Furthermore, there are anomalies where it is unclear whether the products even outperformed the control specimens. Furthermore, some of the graphs, especially those of the bath specimens, display negative cumulative corrosion. These negative values may be explained as follows:
• The reference bar is corroding more severely than the test bar, thus reversing the corrosion current and displaying a negative value (West et al. 2002).
• There is no macrocell developed between the reference bar and the test bar.
• The test bar is corroding, but the macrocell has developed only within the test bar itself.
• The test bar is corroding, but a microcell of corrosion has developed on the test bar.

To determine if the reference bars were corroding, a sampling of reference bars were excavated at the conclusion of the test and examined for corrosion. Little or no corrosion was found on the reference bars examined. This leaves the explanation that there was either a macrocell or microcell developed on the test bar itself. This can be verified by the graphs of the half cell readings that will be discussed later. The standard for the half cell graphs specify values more negative than -0.35V to be indicative of a 90% probability of corrosion. By comparing the graphs for the half cell readings with the cumulative corrosion graphs, it can be determined if the test bar is corroding at the time of negative cumulative corrosion readings. If the test bar is corroding, then the data for corrosion current and cumulative corrosion for that particular specimen is rendered spurious. Furthermore, the scatter in data for this method may be due to the deviation from the set specifications in the ASTM standard that was used. ASTM G 109-99 states “this test method may not properly rank the performance of different corrosion inhibitors, especially at concrete covers over the steel of less than 40mm (1.5 in)”. The concrete cover used in this experiment was 0.5 in. This was chosen based on the data supplied by the NCDOT to represent the shallower concrete cover in existing bridge decks in North Carolina. It is also a possibility that, although the voltmeter data may be useful in determining whether the specimens are corroding or not, it may not have the precision that is
necessary to compare different corrosion inhibitor products with one another. Based on these findings, it is clear that the corrosion current method alone does not provide adequate information in distinguishing the performances of different products.

4.2.2 Half Cell Readings and Results
As with the voltmeter readings, half cell readings were taken each week for every specimen tested. This data collection was based on ASTM C 876 – 91 (R 99), as discussed in detail in Section 3.6.2. All of these readings were collected and entered into a spreadsheet so that useful graphs could be developed and any trends in the data would be found. Figures 4.7, 4.8, and 4.9 show typical half cell data over time for the control, bath, and chamber environments, respectively.

![Figure 4.7 - Half Cell Readings for Control Specimens (Set #2)](image-url)
Figure 4.8 - Half Cell Readings for Bath 2, 0.0% Chloride, Pre-Cracked
As mentioned earlier, the gap in the chamber data was due to the switch from the original chamber to the new chamber. ASTM standard C 876 –91 (R 99) provides the following limits as guidance for half cell potential data:

- Measured Potential > -0.20 V: Greater than 90% probability that no corrosion is occurring in that area at the time of measurement
- -0.20 V ≤ Measured Potential ≤ -0.35 V: Corrosion activity in the area of measurement is uncertain
- Measured Potential < -0.35 V: Greater than 90% probability that corrosion is occurring in that area at the time of measurement

As expected, no corrosion was measured for the control environment specimens by the half cell method.
Based on the above stated limits, the bath specimens began to exhibit a high probability of corrosion after approximately one month of accelerated testing. The bath specimens for the most part stay within this region for the remainder of the accelerated test program except to fluctuate into the uncertain range on occasion and very rarely into the range of low probability of corrosion. The cyclic fluctuations that are exhibited by the half cell graphs for the bath specimens were observed to occur due to the one-week wet and one week dry cycles. Much higher potentials were generally observed directly after the wet cycles. Conversely, lower potentials were observed following a week in the dry cycle for the same specimen. This phenomenon occurred even with proper wetting of the concrete surface prior to taking measurements after each cycle. This may be attributed to the fact that the electrical current being measured could travel through the saturated concrete with more ease than it could through the dry concrete, despite a fully wetted surface.

The chamber specimens display many of the same trends as those in the baths. Similar to the specimens in the baths, there was a high probability of corrosion observed after just about one month of accelerated environmental exposure for most specimens. Most specimens fluctuated in and out of the high probability and uncertain regions, and occasionally into the low probability range. There were more occurrences of chamber specimens in the uncertain range than in the bath specimens. This was most likely due to the severity of the bath environment, as compared with the chamber. Unlike the baths, there is no real cyclic trend observed because readings were taken in the chamber under similar saturation conditions each week.

While a number of trends were observed with the half cell data, there is no clear indication as to which corrosion inhibitor products performed the best. This is primarily due to the nature of this data. The data provides the probability that
corrosion is or is not occurring, but it does not provide to what extent the corrosion occurs. For example, two specimens may have very different potentials both more negative than −0.35 V and therefore both have a 90% probability that corrosion is occurring. The standard does not state that the more negative, the more probable corrosion, but rather gives only the limits listed above. This leads to the conclusion that no comparison may be directly drawn between the performances of different corrosion inhibitors based solely on the half cell potential data. The half cell potential data can be used to determine the probability of corrosion only.

It is important to note that there are many factors that affect the accuracy of half cell potential readings, including temperature, light, and cleanliness of the electrode (Ansuini & Dimond 1994). These factors, along with the precision of the half cell readings make it impractical to determine the performance of the corrosion inhibitor products from this measurement alone. The full set of graphs of half cell potentials over time for all specimens can be seen in Appendix C.

4.2.3 Environmental Readings and Results
The environmental readings taken during this testing program included salt-water concentration, pH, temperature, and humidity. These readings, similar to the voltmeter and half cell readings, were taken on a weekly basis. The details for collecting the environmental data were described in Section 3.6.3. Figure 4.10 shows the change in salinity over time for the baths and the chamber.
Figure 4.10 - Salinity Over Time for Bath and Chamber Environments

Although slight changes in salinity occur periodically, it is evident that the average remains relatively close to the target 15% NaCl concentration. Furthermore, adjustments were made every time a change was observed. The target pH for the water used in this project was a neutral range from 6-8. Figure 4.11 shows the change in pH over time for the baths and the chamber.
It is clear from this graph that the pH of the salt-water solutions had no significant fluctuations over time. This means that the alkalinity of the solution did not change over time, which in turn indicates that the pH of the solution itself should not affect the accelerated corrosion test results. ACI 222R-96 states that the alkalinity of concrete actually protects the reinforcing steel from low levels of chloride attack by forming a protective barrier on the surface of the steel. The range for this protection is considered a pH value between 8 and 13. At pH levels above or below this, the layer of protection around the steel can be more readily broken down and corrosion is more likely to occur. As shown in the above graph, at no time during the experiments, the pH level in any of the environments entered into the range between 8 and 13.

The target temperature for the specimens in the baths and chamber was 130°F for
both the wet and dry cycles of the tests in order to further accelerate the corrosion process. Figure 4.12 shows temperature vs. time for the baths and chamber environment.

![Figure 4.12 - Temperature Over Time for Bath and Chamber Environments](image)

It can be observed that fluctuations in temperature occurred frequently over time, but the average temperature was kept relatively close to the target of 130°F.

The only environment for which the humidity was measured was the control environment. The target humidity for this environment was set at 50% RH. Figure 4.13 shows the humidity and temperature changes over time for the control environment.
Based on this graph, it is clear that the humidity fluctuated considerably over time. It was very difficult to regulate humidity in the control environment. Although fluctuations are large, the average value for the relative humidity was still close to 50%. The temperature, however, was kept very close to the target of 70°F for the control environment.

4.3 Post-Exposure Measurements and Results

4.3.1 Chloride Content Analysis and Results

Chloride content analysis tests were performed on 324 – 2” cubes: 6 initial cubes, 90 after one month of exposure, 90 after 3 months of exposure, another 90 after 6 months of exposure, and finally 48 after 12 months of exposure, the latter for baths and control only. The method of testing for chloride content was discussed.
in detail in Section 3.6.4. The purpose of these tests was to measure the chloride ion concentration at the level of the rebar (1/2 in below the concrete surface) based on the weight of the concrete. Based on titration results, calculations were performed to determine the percent Chloride ion by weight of concrete in the sample. These calculations were based on the NCDOT Materials and Test Unit Procedure C-4.0, “Chloride Analysis on Bridge Concrete (Potentiometric Titration Method)”. As mentioned in Chapter 3, this test method was based on ASTM standard C 1152. It is very important that these calculations are not confused with the initial chloride contamination percentages. As mentioned in Chapter 3, the initial chloride contamination levels were based on the weight of dry cement in the mix only. The percent chloride ion concentration found by titration methods identifies the percent concentration based upon the weight of the cured concrete. The difference between these two percentages is roughly a factor of 10, obviously the percentage based on weight of dry cement being the higher. Figure 4.14 shows the change in chloride ion percentages over time for the control environment.
Figure 4.14 - Chloride Content for Control Specimens

The control specimens display the behavior that would be expected. The higher the initial chloride content, the higher the chloride ion percentage tested. There is slight overlap between the 1.0% and 1.5% at one month, but that may be attributed to the collection of the sample of powder, which may or may not include part of the aggregates. Figure 4.15 shows the chloride content for several bath specimens.
It was observed that most of the 1.5% bath samples tested returned results with lower chloride contents than that of the control specimen, i.e., with no corrosion inhibitor. This indicates that those with lower tested chloride contents performed better at preventing additional chloride influx over the course of the accelerated testing program. The graph for the 1.5% bath specimens displays closely clustered chloride analysis results. This clustered phenomenon occurs more predominately with higher initial chloride contaminations. The bath specimens at 0.0% and 0.5% initial chloride contamination, on the other hand, display more scattered data with only a few products performing better than the control specimen. The high spread between the no corrosion inhibitor and those products that display lower chloride contents indicate a better product performance over the control. However, as the initial chloride contents increase beyond 0.5%, the data spread decreases significantly indicating a drop from 50%
improved performance to 30% for the 1.0% initial chloride specimens. This increased performance reduces even further to a range of 10-15% for the 1.5%-3.0% initial chloride specimens. From this data, it is obvious that as the level of chloride contamination increases, the effectiveness of the corrosion inhibitors decreases.

**Figure 4.16 - Chloride Content for Chamber Specimens – 0.0% Chloride**

Based on the chamber 0.0% specimens, it is clear that all corrosion inhibitor products are more successful in preventing chloride contamination than if no corrosion inhibitor was applied. The graph shown here displays highly scattered results. This indicates that the effectiveness of the corrosion inhibitors was much higher than if the data was clustered. Similar to the baths, when the initial chloride contamination is increased, the less scattered the data becomes. This leads to the same conclusion that the corrosion inhibitors become less effective at higher levels of initial chloride contamination. Unlike the baths, however, the
chloride contamination seems to stabilize over time. In the baths, this trend was not observed, but rather there was a consistent increase in the level of chloride of the specimens over the course of the testing program. This may be attributed to the harsher nature of the bath environment. Due to the frequent wet/dry cycles in the baths, higher corrosion results were observed along with higher overall chloride contaminations. It is believed that if the specimens were tested for a longer period of time, eventually the same level of corrosion and chloride contamination as the baths could have been reached in the chamber. All products displayed chloride contaminations below that of the control specimen for most data points, especially at the lower initial chloride contamination levels. As the level of initial chloride increased, it was evident that every corrosion inhibitor became less effective. As time progressed and as the initial chloride contamination levels increased, most products became less effective to the point that no significant difference was noticed compared to the control specimen. All of the chloride content graphs can be found in Appendix D.

4.3.2 Visual Ratings: Analysis and Results

After the accelerated environmental testing was concluded, the specimens were removed from their respective environments and each piece of test rebar was extracted from the concrete. A visual rating system was used to collect data from each bar regarding percent surface corrosion and percent rib loss. This visual rating system was explained in Section 3.7.1. Once this data was compiled, graphs were made comparing the different corrosion inhibitor products at all stages of removal. There were two methods of data collection for the visual evaluations: surface rust assessment and rib loss assessment. These evaluations were performed for both the mid-sections and the end-sections of each test bar. As discussed in Chapter 3, the bars were divided into five segments – two end-sections, and three mid-sections. The data was collected and grouped as end-sections and mid-sections for comparison. The purpose of this distinction was to
determine if end effects for the bars were significant. A sampling of these graphs for surface rust percentage in the end-sections can be seen in Figures 4.17 and 4.18.

**Figure 4.17 - % Surface Corrosion at Endsections for 1.0% Chloride (Set #1)**
Figure 4.17 shows the first set of specimens taken from the chamber at the end of three months, and from the baths at the end of six months. Figure 4.18 shows the second set of specimens taken from the chamber and bath at the end of six months and one year, respectively. From these graphs, it is obvious that although corrosion did occur in the endsections of the specimens, the same amount of surface rust occurred for nearly all specimens regardless of which corrosion inhibitor, if any, was applied. There is no significant difference in the amount of surface rust for any specimen in the same data set. This same trend was observed in the rib loss graphs for the end-sections, as well. A sampling of the end-section rib loss graphs are shown in Figures 4.19 and 4.20.
Figure 4.19 - % Rib Loss at Endsections for 1.0% Chloride (Set #1)
Once again, Figure 4.19 displays the first set of specimens removed from the chamber at the end of three months, and from the baths at the end of six months. Figure 4.18 shows the second set of specimens removed from the chamber and bath at the end of six months and one year, respectively. These two sets of data, both for surface rust and rib loss show the same trends: there is no significant difference in the performance of any corrosion inhibitor products at the end sections as compared to the control specimen. This is a very important observation because from this observation it can be concluded that the end section surface rust and rib loss can be disregarded as a factor possibly affecting the performance of the corrosion inhibitors. This conclusion also validates the next steps in the test procedure, which focuses only on the mid-section of test bars for further analysis of the corrosion inhibitors.

Figure 4.20 - % Rib Loss at Endsections for 1.0% Chloride (Set #2)
For the analysis of the corrosion inhibitor products, only the data for the mid-sections was used. The visual evaluation for the midsection of the bars gave data that was much more distinct and functional in comparing different corrosion inhibitor products. Figures 4.21-26 show a sampling of the surface rust comparison graphs for the mid-sections of the bars.

Figure 4.21 - % Surface Corrosion at Midsection for 0.0% Chloride (Set #1)
Figure 4.22 - % Surface Corrosion at Midsection for 1.5% Chloride (Set #1)
Figures 4.21, 4.22, and 4.23 are all of the first set of specimens removed from the chamber and baths at three and six months, respectively, as discussed earlier. The following figures, 4.24, 4.25, and 4.26, are graphs of the second set of specimens removed from the chamber and baths at six months and one year, respectively.

Figure 4.23 - % Surface Corrosion at Midsection for 3.0% Chloride (Set #1)
Figure 4.24 - % Surface Corrosion at Midsection for 0.0% Chloride
(Set #2)
Figure 4.25 - % Surface Corrosion at Midsection for 1.5% Chloride
(Set #2)
From these graphs, several trends can be observed. One trend that is quite clear is that at 0.0% initial chloride content, there is a very distinct difference in the performance of the corrosion inhibitors. Also, at this level of chloride contamination, it can be said that almost all corrosion inhibitor products perform better than the control specimens. As the level of chloride contamination is increased to 1.5%, there is an increase in the percentage of surface rust, as would be expected. At this level, however, there is less of a difference between the performance of the specimens with and without corrosion inhibitor products. However, several products appear to continue working well even at this high level of chloride contamination. As the level of initial chloride contamination increases from 1.5% to 3.0%, it is observed that the surface rust percentage actually decreases in some cases. At first thought, this is a very peculiar
phenomenon. This may be due to the solution reaching an optimum chloride contamination level, beyond which there is little or no difference in the advance of the corrosion process. In some cases, the corrosion activity documented is less at higher levels of chloride contamination beyond the optimum chloride level (Smith et al. 1992). It is also clear that the performance of the corrosion inhibitors average out and appear to be close to the same level or below the performance of the specimens with no corrosion inhibitor applied. There are a few exceptions as would be expected. Based on these graphs, it can be determined that at this level of initial chloride contamination (3.0%), no corrosion inhibitor products are effective. The surface corrosion graphs for the mid-sections can be found in Appendix E.

Another useful comparison for the visual evaluations is the performance of the same products at the same level of chloride contamination over the course of the accelerated testing program. Because of the timed removal of specimens at four different stages in the corrosion program, it is possible to compare these different stages to see how the products performed over time. Figure 4.27 shows the mid-section surface rust evaluations over the four stages of accelerated testing for the 0.0% specimens.
This graph represents corrosion at different stages of exposure for each specimen. It is believed that the wet/dry cycles in the baths provided a much more aggressive environment than the periodic salt water spray in the chamber, and therefore, the specimens that were removed from the chamber after six months did not show as much corrosion as those in the baths. These graphs provide the important data over time of continued exposure for each corrosion inhibitor. It can be observed that most specimens at the 0.0% initial chloride contamination level do exhibit an increase in the percent surface rust over the time of exposure, as was expected. As with all data in this project, there are exceptions. These may be attributed to natural variations due to sample size. If the sample size was large enough, it is expected that average surface corrosion would exhibit an increase over time for most all specimens. At the earliest stage
of exposure, all of the specimens with corrosion inhibitors perform better than the control specimen for the 0.0% specimens for both pre-cracked and post-cracked specimens. This is also true at the second stage (removal from chamber at six months) for the 0.0% specimens. At the third stage, there only two outliers to this trend. Finally, at the fourth stage (removal from the bath after 12 months), all specimens with corrosion inhibitors display less surface rust than their control counterparts at 0.0% initial chloride contamination.

These same observations also hold true at the 0.5% initial chloride contamination level. However, at the 1.0% initial chloride level and above, the difference between the performance of the corrosion inhibitors and no corrosion inhibitor specimens greatly decreases. Therefore, it can be concluded from this data that the effectiveness of the corrosion inhibitors decreases after the initial chloride contamination level of 0.5%, regardless of the time of environmental exposure.

The second method of visual evaluation involved estimating a percent rib loss in the mid-section for each specimen. This was carried out after the surface rust evaluations and a light cleaning with a non-wire bristle brush had taken place. The following figures 4.28, 4.29, and 4.30 show a sampling of the rib loss graphs for the first set of specimens removed from their environments.
Figure 4.28 - % Rib Loss in Midsections for 0.0% Chloride (Set #1)
Figure 4.29 - % Rib Loss in Midsections for 1.5% Chloride (Set #1)
Figure 4.30 - % Rib Loss in Midsections for 3.0% Chloride (Set #1)

Figures 4.31, 4.32, and 4.33 show the percent rib loss for a sampling of the second set of specimens removed from their testing environments.
Figure 4.31 - % Rib Loss in Midsections for 0.0% Chloride (Set #2)
Figure 4.32 - % Rib Loss in Midsections for 1.5% Chloride (Set #2)
Figure 4.33 - % Rib Loss in Midsections for 3.0% Chloride (Set #2)

Although the numbers are lower, the rib loss graphs show the same trend as the surface rust graphs. These lower numbers were expected since it requires more corrosion activity to remove ribs than it does for corrosion to appear only on the surface. Many of the same trends observed for the surface rust graphs could be observed in the rib loss graphs. For instance, at 0.0% initial chloride, many of the specimens with the corrosion inhibitor products seem to exhibit less rib loss than the specimens without the corrosion inhibitors. Again, as this rises to 1.5%, the effectiveness of the corrosion inhibitor products diminishes, and some products appear to be even less effective than with no corrosion inhibitor at all. As the initial chloride level moves up to 3.0%, the rib loss again tends to decrease just as surface rust did at this point. These graphs also exhibit a similar averaging effect for the values of all specimens. Again, this peculiar phenomenon may be due to the realization of threshold chloride content level prior to the 3.0%
level, as discussed previously. Once again it can be determined that at this level of initial chloride contamination, no corrosion inhibitor products are effective.

As with the surface rust assessment, it is useful to compare the mid-section rib loss graphs for the same specimens over time stepped intervals. Figure 4.34 shows the time step data for rib loss of the 0.0% specimens.

The time step rib loss graphs show similar trends to those of the time step surface corrosion graphs. Most specimens show an increase in rib loss as the time steps progress at the lower levels of initial chloride contamination. However, some differences do exist. Unlike the surface corrosion graphs, there are few products that exhibit an increase in rib loss at the 0.0% and 0.5% chloride levels than do the specimens with no inhibitor products. Similar to the surface corrosion
graphs, the rib loss time step data shows little effectiveness beyond 0.5% for the corrosion inhibitor products.

4.3.3 Mass Loss Measurements and Results
After visual evaluations were concluded for each of the specimens, chemical mass loss measurements were conducted. This method followed the standards set forth in ASTM G1-03, as described in detail in Section 3.7.2. The data from these tests were recorded in a spreadsheet, and graphs were developed for each specimen based on the overall mass loss per length after the chemical cleanings. These were compared to the overall mass loss per length for the control specimens to determine the significance of the amount of metal lost. Figures 4.35, 4.36, and 4.37 show a sampling of the mass loss data for the control, bath, and chamber specimens.
Figure 4.35 – Cumulative Mass Loss/Length for Control Specimens

For the control specimens, the cumulative mass losses per unit length were very little as would be expected. The 2.0% specimen was the only specimen that displayed comparable mass losses to the accelerated environmental testing. But even this specimen displayed low mass losses in comparison. As with all specimens in the chemical cleaning process, there is a very high difference after the first cleaning, beyond which the mass losses level out and little changes can be detected.
Figure 4.36 – Cumulative Mass Loss/Length for Bath 4, 0.0% Chloride, Post-Cracked Specimens

The above graph for the wet/dry bath shows that the most mass losses occurred on the specimen with no corrosion inhibitor applied, with the other specimens displaying less mass losses. Therefore, it can be concluded that all corrosion inhibitor products are effectively preventing corrosion. This trend is true for almost every specimen at the 0.0% and 0.5% initial chloride contamination levels. As the initial chloride contamination level increases beyond 0.5%, this trend starts to dissipate, just as noted in visual evaluations. Between 1.0% and 1.5% initial chloride contamination, the corrosion inhibitor products still appear to be useful to some extent, but to a lesser degree. When the initial chloride contamination increases to 2.0% and 3.0%, the performance of the corrosion inhibitors are much more sporadic. However, at the 3.0% level some products still perform better than the no corrosion inhibitor specimens, but it is not
consistent enough to draw any solid conclusions.

Figure 4.37 – Cumulative Mass Loss/Length for Chamber 0.0% Chloride, Shelf 3, Post-Cracked Specimens

As with the previous graph of the bath specimens, the above graph for the chamber shows that the most mass losses occurred on the specimen with no corrosion inhibitor applied, with the other specimens displaying less mass losses. Also similar to the bath specimens, this trend is true for almost every specimen at the 0.0% and 0.5% initial chloride contamination levels. As the initial chloride contamination level increases beyond 0.5%, it is more difficult to determine which products, if any perform consistently well. At the 1.0% initial chloride contamination levels, several products perform sporadically better than the no corrosion inhibitor specimen. At both the 1.0% and 1.5% initial chloride contamination, the corrosion inhibitor products still appear to be useful to some
extent, but to a lesser degree. At the 1.5% initial chloride level, there were no corrosion inhibitors that performed consistently well. When the initial chloride contamination increases to 2.0% and 3.0%, the performance of the corrosion inhibitors are increasingly arbitrary. All of the mass loss graphs can be found in Appendix F.

It is important to note that the chemical cleaning process to measure mass loss does not give a good indication of the damage incurred by pitting corrosion. The chemical cleaning is not able to fully remove pitting corrosion in some cases according to ASTM G1-03. In order for the effects of pitting corrosion to be determined, and to corroborate the visual analysis and mass loss conclusions, it was deemed necessary to conduct tension tests on all of the specimens.

4.3.4 Tension Tests and Results
The last set of data collected for this experiment was the tension tests. These tests were conducted in accordance with ASTM A370-03a. The purpose of these tests was to determine the extent of corrosion in general, and pitting corrosion in particular. The tension test procedure was discussed in detail in Section 3.7.3. The data from the tension tests were collected and entered into a spreadsheet so that graphs could be developed for comparison purposes. A typical load deflection curve of the tension test data is shown in Figure 4.38. The most significant value on the graph is the peak load, which was used to compare the loss of cross section in various rebars.
From these tension tests, a percent strength loss was calculated based upon the tension test data from a control bar. These graphs can be seen in Figures 4.39 and 4.40.
Figure 4.39 – Percent Strength Loss Based on Tension Tests for Bath 3, 0.0% Chloride, Post-Cracked

It should be stated that “strength loss” in this section actually refers to a reduction in peak load of the rebar caused by metal loss due to corrosion effects, not a strength loss based on material properties. The term “strength loss” is used in this section to differentiate between the tension tests and the chemical mass loss tests. For the graph shown above, the specimen with no corrosion inhibitor product demonstrates the highest strength loss. This indicates that the specimens with corrosion inhibitors were more effective in preventing corrosion. However, this trend is not observed for many of the bath specimens. Despite this anomaly, several products do consistently show better results than that of the specimen with no corrosion inhibitor. There is no apparent pattern though to the usefulness of the products for the bath specimens.
Figure 4.40 – Percent Strength Loss Based on Tension Tests for Chamber 0.5% Chloride, Shelf 4, Pre-Cracked

The figure shown above shows the percent strength loss for a set of chamber specimens. The no corrosion inhibitor specimen displays higher percent strength loss than the rest of the specimens in this figure. As with the bath specimens this trend does not hold true for most data sets. The specimens at 0.0% and 0.5% initial chloride contamination have a higher occurrence of this trend, as expected. Some products still appear to be effective at levels above 0.5% initial chloride contamination.

4.4 Cross Comparison for Post-Exposure Data

The most useful data collected for this project was done after the accelerated environmental testing was concluded. These analysis tools included the visual ratings (both surface corrosion and rib loss), chemical mass loss measurements,
and tension testing. By conducting all four analyses and comparing the results, it was possible to verify the performance of the corrosion inhibitors. This was a necessary and very useful step in this research project since the data collected during the accelerated environmental exposure could only confirm if the bars were corroding but not to what extent with any degree of accuracy. Figures 4.41 through 4.44 show a comparison of the visual rating graphs with the mass loss/strength loss graphs for one set of specimens from both the bath and chamber environments.

**Figure 4.41 – Visual Ratings for Bath 2, 0.0% Chloride, Pre-Cracked Specimens**
Although each graph is on a very different scale, it is evident that the same pattern of behavior exists for the corrosion inhibitors in both graphs. The specimen with no corrosion inhibitor performs worst in both visual rating analysis as well as mass loss/strength loss analysis. Most graphs for the bath data exhibit the same pattern of behavior for both visual ratings and mass loss/strength loss graphs when compared side by side. There are, of course, a few exceptions to this pattern. The next two figures show similar graphs for the chamber specimens.
Figure 4.43 – Visual Ratings for Chamber 0.5% Chloride, Shelf 2, Pre-Cracked Specimens
The same pattern of behavior is exhibited by these two graphs as was for the bath specimens. The mass loss and strength loss data confirm the visual rating data. This is very significant because it verifies the methods of data collection and analysis that was used for this project. For both these graphs, the specimen with no corrosion inhibitor product exhibits the worst performance.

Some of the same results were found with these comparative data sets as the earlier analyses. As the initial chloride contamination level increased, the effectiveness of all corrosion inhibitor products decreased. Along with this, the difference between the performance of the specimens with no corrosion inhibitor products and those with the products also diminished. Although all products show improvement over the control specimens in the lower levels of chloride.
contamination and earlier stages of exposure, some products seem to show more consistent results than others. All of these graphical comparisons between the visual ratings and the mass/strength loss can be found in Appendix G.
5.0 Summary and Conclusions

5.1 Summary
Corrosion of existing reinforced concrete structures is a serious problem facing most state DOTs today, NCDOT not being the exception. Many methods of corrosion protection have been proven effective over the years, but can be costly and difficult to implement. If the manufacturers’ claims were substantiated that surface applied corrosion inhibitors could delay, slow, or stop corrosion on existing reinforced concrete structures, there could be a cost effective and simple solution to the corrosion problem in the inventory of the state DOTs.

This research project tested six commercially available surface applied corrosion inhibitor products under simulated field conditions and accelerated corrosion environments to determine the extent of their effectiveness. Each manufacturer of the products tested was made aware of the test matrix and parameters prior to the test and was invited to participate in the product application process. The products tested were donated by their respective manufacturers.

5.2 Conclusions
It was found that overall; corrosion inhibitor products that were tested did initially help delay and slow the corrosion process. As would be expected however, none of these products totally stopped or reversed the corrosion process, as claimed by some of the manufacturers. As expected, all products tested were more effective at lower levels of initial chloride contamination. Each product tested would be effective if applied on fully hardened new concrete with initial chloride content levels below those levels specified by ACI 318-02 to induce corrosion. For almost all specimens, as the time of accelerated corrosion testing increased, the amount of corrosion also increased.

Neither the macrocell corrosion current nor the half cell potential data provided adequate distinction in determining the extent of corrosion in various test
specimens, and therefore, could not be used to compare the effectiveness of the corrosion inhibitor products. The macrocell corrosion current data can be useful if a macrocell has developed between the reference bar and the test bar. Even then, the resolution of this method appeared to be too low to generate a good product comparison. The half cell potential data can be useful in relaying the probability of corrosion, and not the extent of corrosion. Therefore, it could not provide with any degree of certainty a comparison of the corrosion inhibitor products. As a result, further steps were deemed necessary to evaluate the effectiveness of the corrosion inhibitor products.

By conducting visual ratings of the test bars, it was concluded that the end effects of the bars were negligible, and only the mid-sections of the bars which were fully embedded inside the concrete, were needed for further analysis.

It was concluded that a threshold chloride content does exist between 1.5% and 3.0% initial chloride contamination (by weight of cement), beyond which the addition of chloride does not increase the severity of corrosion. This was observed by the averaging effect displayed from the visual ratings.

Beyond 0.5% initial chloride contamination (by weight of cement), there is little effectiveness observed in the performance of almost all corrosion inhibitors. Therefore, it can be concluded that there is no significant benefit in applying any of the tested corrosion inhibitors to the surface of reinforced concrete when the chloride contamination levels are above 0.5% by weight of cement, or about 0.05% by weight of concrete.

Although chemical mass loss measurements confirmed most trends observed through visual ratings, they could not indicate severity of pitting corrosion. Therefore, it was deemed necessary to conduct tension tests on the rebar to determine the effects of pitting corrosion.
Each product tested proved its effectiveness by inhibiting corrosion to a certain extent. Some products tested performed better under the specific test conditions than did others. Further parameters should be considered when determining which product(s) should be implemented into the NCDOT's rehabilitation program. These include: cost of the product in a single application (including materials, labor, traffic control, and alternative traffic routing) and time to subsequent applications. An optimization of these parameters may indicate that the most cost effective product is not the most effective or vice versa. The benefit of the product applied should be weighed against the financial investment to apply and reapply the product, and an optimization of these parameters should be reached before choosing which product to apply.

ACI 222 gives the following chloride limits for new construction: Prestressed concrete – 0.08%, reinforced concrete in wet conditions – 0.10%, reinforced concrete in dry conditions 0.20%. These numbers are for acid-soluble chloride based on the weight of concrete and are from ASTM 1152. These numbers roughly correlate to chloride contents by weight of cement of 0.8%, 1.0%, and 2.0%, respectively. For this experiment, the limits for reinforced concrete in wet conditions should be considered. This supports the experimental findings that the corrosion inhibitors should be limited to 0.5% initial chloride contamination by weight of cement.

5.3 Suggestions for Further Research
Although this research effort provided ample justifications to establish conclusions for the products tested, there are other surface applied corrosion inhibitor products on the market, which require further investigation. During further similar to this project, it would be beneficial to investigate the following suggestions:

- In this particular project, the effects of pre-cracking and post-cracking were not quantified and appeared to be negligible due to several issues
– the minute size of the cracks (two hairline cracks), the lack of sufficient concrete cover (1/2” as opposed to 2”), the severity of the corrosive environment, and the rapid onset of the corrosion process. Therefore, it cannot be determined from this experiment whether cracked or un-cracked decks would be more suitable for the corrosion inhibitor application.

- Other methods of determining the results of cracking on the effectiveness of surface applied corrosion inhibitors should be investigated.

- The total submersion and exposure to the accelerated corrosive environment caused rapid deterioration of resistor wires, loading plates, and any exposed metal components that were not made of stainless steel, including the components of the enclosed environments.

- It is suggested that the corrosive environment be contained to only the surface of the specimens being tested or that only non-corrosive metals be used in the untested components to avoid such problems.

The research can benefit from chemical analysis of the composition of the corrosion inhibitor products and physical characteristics of the products. Once the active ingredients and physical characteristics of the more effective products are determined, the state DOTs can develop their own specifications for such products. They could also develop test methods for acceptance of such products.

Even with further testing, it is recommended that DOTs begin using these products on a trial basis and take detailed accounts of their performance in order to determine the effectiveness in actual field conditions. It is suggested that candidates for these field trials be chosen based on chloride analysis testing and the likelihood of exposure to corrosive environments. Those structures with results from chloride analysis testing of 0.5% chloride contamination (by cement
weight) or below would be considered good candidates for use of these products on a trial basis. The more severe the environment of the trial basis, the faster corrosion would occur and data could be collected.

Finally, an issue that needs further consideration is the correlation of the accelerated corrosion testing with the actual field conditions. While a number of research projects have attempted to address this issue, it remains unclear as to how many years of real time exposure could be simulated by a limited number of accelerated corrosion testing in the laboratory. This issue could also affect the re-application regime of corrosion inhibitor products on concrete surface.
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Sika, “Sika FerroGard® 903: Penetrating Corrosion Inhibiting, Impregnation

Figure A.1 – Corrosion Rate for Control Set #1

Figure A.2 – Corrosion Rate for Control Set #2
Figure A.3 – Corrosion Rate for Bath 1, 0.0% Chloride, Pre-Cracked

Figure A.4 – Corrosion Rate for Bath 1, 0.5% Chloride, Pre-Cracked
Figure A.5 – Corrosion Rate for Bath 1, 1.0% Chloride, Pre-Cracked

Figure A.6 – Corrosion Rate for Bath 1, 1.5% Chloride, Pre-Cracked
Figure A.7 – Corrosion Rate for Bath 1, 2.0% Chloride, Pre-Cracked

Figure A.8 – Corrosion Rate for Bath 1, 3.0% Chloride, Pre-Cracked
Figure A.9 – Corrosion Rate for Bath 2, 0.0% Chloride, Pre-Cracked

Figure A.10 – Corrosion Rate for Bath 2, 0.5% Chloride, Pre-Cracked
Figure A.11 – Corrosion Rate for Bath 2, 1.0% Chloride, Pre-Cracked

Figure A.12 – Corrosion Rate for Bath 2, 1.5% Chloride, Pre-Cracked
Figure A.13 – Corrosion Rate for Bath 2, 2.0% Chloride, Pre-Cracked

Figure A.14 – Corrosion Rate for Bath 2, 3.0% Chloride, Pre-Cracked
Figure A.15 – Corrosion Rate for Bath 3, 0.0% Chloride, Post-Cracked

Figure A.16 – Corrosion Rate for Bath 3, 0.5% Chloride, Post-Cracked
Figure A.17 – Corrosion Rate for Bath 3, 1.0% Chloride, Post-Cracked

Figure A.18 – Corrosion Rate for Bath 3, 1.5% Chloride, Post-Cracked
Figure A.19 – Corrosion Rate for Bath 3, 2.0% Chloride, Post-Cracked

Figure A.20 – Corrosion Rate for Bath 3, 3.0% Chloride, Post-Cracked
Figure A.21 – Corrosion Rate for Bath 4, 0.0% Chloride, Post-Cracked

Figure A.22 – Corrosion Rate for Bath 4, 0.5% Chloride, Post-Cracked
Figure A.23 – Corrosion Rate for Bath 4, 1.0% Chloride, Post-Cracked

Figure A.24 – Corrosion Rate for Bath 4, 1.5% Chloride, Post-Cracked
Figure A.25 – Corrosion Rate for Bath 4, 2.0% Chloride, Post-Cracked

Figure A.26 – Corrosion Rate for Bath 4, 3.0% Chloride, Post-Cracked
Figure A.27 – Corrosion Rate for Chamber Shelf 1, 0.0% Chloride, Post-Cracked

Figure A.28 – Corrosion Rate for Chamber Shelf 1, 0.5% Chloride, Post-Cracked
Figure A.29 – Corrosion Rate for Chamber Shelf 1, 1.0% Chloride, Post-Cracked

Figure A.30 – Corrosion Rate for Chamber Shelf 1, 1.5% Chloride, Post-Cracked
Figure A.31 – Corrosion Rate for Chamber Shelf 1, 2.0% Chloride, Post-Cracked

Figure A.32 – Corrosion Rate for Chamber Shelf 1, 3.0% Chloride, Post-Cracked
Figure A.33 – Corrosion Rate for Chamber Shelf 2, 0.0% Chloride, Pre-Cracked

Figure A.34 – Corrosion Rate for Chamber Shelf 2, 0.5% Chloride, Pre-Cracked
Figure A.35 – Corrosion Rate for Chamber Shelf 2, 1.0% Chloride, Pre-Cracked

Figure A.36 – Corrosion Rate for Chamber Shelf 2, 1.5% Chloride, Pre-Cracked
Figure A.37 – Corrosion Rate for Chamber Shelf 2, 2.0% Chloride, Pre-Cracked

Figure A.38 – Corrosion Rate for Chamber Shelf 2, 3.0% Chloride, Pre-Cracked
Figure A.39 – Corrosion Rate for Chamber Shelf 3, 0.0% Chloride, Post-Cracked

Figure A.40 – Corrosion Rate for Chamber Shelf 3, 0.5% Chloride, Post-Cracked
Figure A.41 – Corrosion Rate for Chamber Shelf 3, 1.0% Chloride, Post-Cracked

Figure A.42 – Corrosion Rate for Chamber Shelf 3, 1.5% Chloride, Post-Cracked
Figure A.43 – Corrosion Rate for Chamber Shelf 3, 2.0% Chloride, Post-Cracked

Figure A.44 – Corrosion Rate for Chamber Shelf 3, 3.0% Chloride, Post-Cracked
Figure A.45 – Corrosion Rate for Chamber Shelf 4, 0.0% Chloride, Pre-Cracked

Figure A.46 – Corrosion Rate for Chamber Shelf 4, 0.5% Chloride, Pre-Cracked
Figure A.47 – Corrosion Rate for Chamber Shelf 4, 1.0% Chloride, Pre-Cracked

Figure A.48 – Corrosion Rate for Chamber Shelf 4, 1.5% Chloride, Pre-Cracked
Figure A.49 – Corrosion Rate for Chamber Shelf 4, 2.0% Chloride, Pre-Cracked

Figure A.50 – Corrosion Rate for Chamber Shelf 4, 3.0% Chloride, Pre-Cracked
APPENDIX B

Figure B.1 – Cumulative Corrosion Over Time for Control Set #1

Figure B.2 – Cumulative Corrosion Over Time for Control Set #2
Figure B.3 – Cumulative Corrosion Over Time for Bath 1, 0.0% Chloride, Pre-Cracked

Figure B.4 – Cumulative Corrosion Over Time for Bath 1, 0.5% Chloride, Pre-Cracked
Figure B.5 – Cumulative Corrosion Over Time for Bath 1, 1.0% Chloride, Pre-Cracked

Figure B.6 – Cumulative Corrosion Over Time for Bath 1, 1.5% Chloride, Pre-Cracked
Figure B.7 – Cumulative Corrosion Over Time for Bath 1, 2.0% Chloride, Pre-Cracked

Figure B.8 – Cumulative Corrosion Over Time for Bath 1, 3.0% Chloride, Pre-Cracked
Figure B.9 – Cumulative Corrosion Over Time for Bath 2, 0.0% Chloride, Pre-Cracked

Figure B.10 – Cumulative Corrosion Over Time for Bath 2, 0.5% Chloride, Pre-Cracked
Figure B.11 – Cumulative Corrosion Over Time for Bath 2, 1.0% Chloride, Pre-Cracked

Figure B.12 – Cumulative Corrosion Over Time for Bath 2, 1.5% Chloride, Pre-Cracked
Figure B.13 – Cumulative Corrosion Over Time for Bath 2, 2.0% Chloride, Pre-Cracked

Figure B.14 – Cumulative Corrosion Over Time for Bath 2, 3.0% Chloride, Pre-Cracked
Figure B.15 – Cumulative Corrosion Over Time for Bath 3, 0.0% Chloride, Post-Cracked

Figure B.16 – Cumulative Corrosion Over Time for Bath 3, 0.5% Chloride, Post-Cracked
Figure B.17 – Cumulative Corrosion Over Time for Bath 3, 1.0% Chloride, Post-Cracked

Figure B.18 – Cumulative Corrosion Over Time for Bath 3, 1.5% Chloride, Post-Cracked
Figure B.19 – Cumulative Corrosion Over Time for Bath 3, 2.0% Chloride, Post-Cracked

Figure B.20 – Cumulative Corrosion Over Time for Bath 3, 3.0% Chloride, Post-Cracked
Figure B.21 – Cumulative Corrosion Over Time for Bath 4, 0.0% Chloride, Post-Cracked

Figure B.22 – Cumulative Corrosion Over Time for Bath 4, 0.5% Chloride, Post-Cracked
Figure B.23 – Cumulative Corrosion Over Time for Bath 4, 1.0% Chloride, Post-Cracked

Figure B.24 – Cumulative Corrosion Over Time for Bath 4, 1.5% Chloride, Post-Cracked
Figure B.25 – Cumulative Corrosion Over Time for Bath 4, 2.0% Chloride, Post-Cracked

Figure B.26 – Cumulative Corrosion Over Time for Bath 4, 3.0% Chloride, Post-Cracked

155
Figure B.27 – Cumulative Corrosion Over Time for Chamber Shelf 1, 0.0% Chloride, Post-Cracked

Figure B.28 – Cumulative Corrosion Over Time for Chamber Shelf 1, 0.5% Chloride, Post-Cracked
Figure B.29 – Cumulative Corrosion Over Time for Chamber Shelf 1, 1.0% Chloride, Post-Cracked

Figure B.30 – Cumulative Corrosion Over Time for Chamber Shelf 1, 1.5% Chloride, Post-Cracked
Figure B.31 – Cumulative Corrosion Over Time for Chamber Shelf 1, 2.0% Chloride, Post-Cracked

Figure B.32 – Cumulative Corrosion Over Time for Chamber Shelf 1, 3.0% Chloride, Post-Cracked
Figure B.33 – Cumulative Corrosion Over Time for Chamber Shelf 2, 0.0% Chloride, Pre-Cracked

Figure B.34 – Cumulative Corrosion Over Time for Chamber Shelf 2, 0.5% Chloride, Pre-Cracked
Figure B.35 – Cumulative Corrosion Over Time for Chamber Shelf 2, 1.0% Chloride, Pre-Cracked

Figure B.36 – Cumulative Corrosion Over Time for Chamber Shelf 2, 1.5% Chloride, Pre-Cracked
Figure B.37 – Cumulative Corrosion Over Time for Chamber Shelf 2, 2.0% Chloride, Pre-Cracked

Figure B.38 – Cumulative Corrosion Over Time for Chamber Shelf 2, 3.0% Chloride, Pre-Cracked
Figure B.39 – Cumulative Corrosion Over Time for Chamber Shelf 3, 0.0% Chloride, Post-Cracked

Figure B.40 – Cumulative Corrosion Over Time for Chamber Shelf 3, 0.5% Chloride, Post-Cracked
Figure B.41 – Cumulative Corrosion Over Time for Chamber Shelf 3, 1.0% Chloride, Post-Cracked

Figure B.42 – Cumulative Corrosion Over Time for Chamber Shelf 3, 1.5% Chloride, Post-Cracked
Figure B.43 – Cumulative Corrosion Over Time for Chamber Shelf 3, 2.0% Chloride, Post-Cracked

Figure B.44 – Cumulative Corrosion Over Time for Chamber Shelf 3, 3.0% Chloride, Post-Cracked
Figure B.45 – Cumulative Corrosion Over Time for Chamber Shelf 4, 0.0% Chloride, Pre-Cracked

Figure B.46 – Cumulative Corrosion Over Time for Chamber Shelf 4, 0.5% Chloride, Pre-Cracked
Figure B.47 – Cumulative Corrosion Over Time for Chamber Shelf 4, 1.0% Chloride, Pre-Cracked

Figure B.48 – Cumulative Corrosion Over Time for Chamber Shelf 4, 1.5% Chloride, Pre-Cracked
Figure B.49 – Cumulative Corrosion Over Time for Chamber Shelf 4, 2.0% Chloride, Pre-Cracked

Figure B.50 – Cumulative Corrosion Over Time for Chamber Shelf 4, 3.0% Chloride, Pre-Cracked
Figure C.1 – Half Cell Potential Readings for Control Set #1

Figure C.2 – Half Cell Potential Readings for Control Set #2
Figure C.3 – Half Cell Potential Readings for Bath 1, 0.0% Chloride, Pre-Cracked

Figure C.4 – Half Cell Potential Readings for Bath 1, 0.5% Chloride, Pre-Cracked
Figure C.5 – Half Cell Potential Readings for Bath 1, 1.0% Chloride, Pre-Cracked

Figure C.6 – Half Cell Potential Readings for Bath 1, 1.5% Chloride, Pre-Cracked
Figure C.7 – Half Cell Potential Readings for Bath 1, 2.0% Chloride, Pre-Cracked

Figure C.8 – Half Cell Potential Readings for Bath 1, 3.0% Chloride, Pre-Cracked
Figure C.9 – Half Cell Potential Readings for Bath 2, 0.0% Chloride, Pre-Cracked

Figure C.10 – Half Cell Potential Readings for Bath 2, 0.5% Chloride, Pre-Cracked
Figure C.11 – Half Cell Potential Readings for Bath 2, 1.0% Chloride, Pre-Cracked

Figure C.12 – Half Cell Potential Readings for Bath 2, 1.5% Chloride, Pre-Cracked
Figure C.13 – Half Cell Potential Readings for Bath 2, 2.0% Chloride, Pre-Cracked

Figure C.14 – Half Cell Potential Readings for Bath 2, 3.0% Chloride, Pre-Cracked
Figure C.15 – Half Cell Potential Readings for Bath 3, 0.0% Chloride, Post-Cracked

Figure C.16 – Half Cell Potential Readings for Bath 3, 0.5% Chloride, Post-Cracked
Figure C.17 – Half Cell Potential Readings for Bath 3, 1.5% Chloride, Post-Cracked

Figure C.18 – Half Cell Potential Readings for Bath 3, 1.5% Chloride, Post-Cracked
Figure C.19 – Half Cell Potential Readings for Bath 3, 2.0% Chloride, Post-Cracked

Figure C.20 – Half Cell Potential Readings for Bath 3, 3.0% Chloride, Post-Cracked
Figure C.21 – Half Cell Potential Readings for Bath 4, 0.0% Chloride, Post-Cracked

Figure C.22 – Half Cell Potential Readings for Bath 4, 0.5% Chloride, Post-Cracked
Figure C.23 – Half Cell Potential Readings for Bath 4, 1.0% Chloride, Post-Cracked

Figure C.24 – Half Cell Potential Readings for Bath 4, 1.5% Chloride, Post-Cracked
Figure C.25 – Half Cell Potential Readings for Bath 4, 2.0% Chloride, Post-Cracked

Figure C.26 – Half Cell Potential Readings for Bath 4, 3.0% Chloride, Post-Cracked
Figure C.27 – Half Cell Potential Readings for Chamber Shelf 1, 0.0% Chloride, Post-Cracked

Figure C.28 – Half Cell Potential Readings for Chamber Shelf 1, 0.5% Chloride, Post-Cracked
Figure C.29 – Half Cell Potential Readings for Chamber Shelf 1, 1.0% Chloride, Post-Cracked

Figure C.30 – Half Cell Potential Readings for Chamber Shelf 1, 1.5% Chloride, Post-Cracked
Figure C.31 – Half Cell Potential Readings for Chamber Shelf 1, 2.0% Chloride, Post-Cracked

Figure C.32 – Half Cell Potential Readings for Chamber Shelf 1, 3.0% Chloride, Post-Cracked
Figure C.33 – Half Cell Potential Readings for Chamber Shelf 2, 0.0% Chloride, Pre-Cracked

Figure C.34 – Half Cell Potential Readings for Chamber Shelf 2, 0.5% Chloride, Pre-Cracked
Figure C.35 – Half Cell Potential Readings for Chamber Shelf 2, 1.0% Chloride, Pre-Cracked

Figure C.36 – Half Cell Potential Readings for Chamber Shelf 2, 1.5% Chloride, Pre-Cracked
Figure C.37 – Half Cell Potential Readings for Chamber Shelf 2, 2.0% Chloride, Pre-Cracked

Figure C.38 – Half Cell Potential Readings for Chamber Shelf 2, 3.0% Pre-Cracked
Figure C.39 – Half Cell Potential Readings for Chamber Shelf 3, 0.0% Chloride, Post-Cracked

Figure C.40 – Half Cell Potential Readings for Chamber Shelf 3, 0.5% Chloride, Post-Cracked
Figure C.41 – Half Cell Potential Readings for Chamber Shelf 3, 1.0% Chloride, Post-Cracked

Figure C.42 – Half Cell Potential Readings for Chamber Shelf 3, 1.5% Chloride, Post-Cracked
Figure C.43 – Half Cell Potential Readings for Chamber Shelf 3, 2.0% Chloride, Post-Cracked

Figure C.44 – Half Cell Potential Readings for Chamber Shelf 3, 3.0% Chloride, Post-Cracked
Figure C.45 – Half Cell Potential Readings for Chamber Shelf 4, 0.0% Chloride, Pre-Cracked

Figure C.46 – Half Cell Potential Readings for Chamber Shelf 4, 0.5% Chloride, Pre-Cracked
Figure C.47 – Half Cell Potential Readings for Chamber Shelf 4, 1.0% Chloride, Pre-Cracked

Figure C.48 – Half Cell Potential Readings for Chamber Shelf 4, 1.5% Chloride, Pre-Cracked
Figure C.49 – Half Cell Potential Readings for Chamber Shelf 4, 2.0% Chloride, Pre-Cracked

Figure C.50 – Half Cell Potential Readings for Chamber Shelf 4, 3.0% Chloride, Pre-Cracked
APPENDIX D

Figure D.1 – Chloride Content for Control Specimens

Figure D.2 – Chloride Content for Bath Specimens – 0.0% Chloride
Figure D.3 – Chloride Content for Bath Specimens – 0.5% Chloride

Figure D.4 – Chloride Content for Bath Specimens – 1.0% Chloride
Figure D.5 – Chloride Content for Bath Specimens – 1.5% Chloride

Figure D.6 – Chloride Content for Bath Specimens – 2.0% Chloride
Figure D.7 – Chloride Content for Bath Specimens – 3.0% Chloride

Figure D.8 – Chloride Content for Chamber Specimens – 0.0% Chloride
Figure D.9 – Chloride Content for Chamber Specimens – 0.5% Chloride

Figure D.10 – Chloride Content for Chamber Specimens – 1.0% Chloride
Figure D.11 – Chloride Content for Chamber Specimens 2.0% Chloride

Figure D.12 – Chloride Content for Chamber Specimens – 3.0% Chloride
APPENDIX E

Figure E.1 Surface Corrosion at Mid Section for 0.0% Chloride (Set#1)

Figure E.2 Rib Loss at Mid Section for 0.0% Chloride (Set #1)
Figure E.3 Surface Corrosion at Mid Section for 0.5% Chloride (Set#1)

Figure E.4 Rib Loss at Mid Section for 0.5% Chloride (Set #1)
Figure E.5 Surface Corrosion at Mid Section for 1.0% Chloride (Set#1)

Figure E.6 Rib Loss at Mid Section for 1.0% Chloride (Set #1)
Figure E.7 Surface Corrosion at Mid Section for 1.5% Chloride (Set #1)

Figure E.8 Rib Loss at Mid Section for 1.5% Chloride (Set #1)
Figure E.9 Surface Corrosion at Mid Section for 2.0% Chloride (Set#1)

Figure E.10 Rib Loss at Mid Section for 2.0% Chloride (Set #1)
Figure E.11 Surface Corrosion at Mid Section for 3.0% Chloride (Set #1)

Figure E.12 Rib Loss at Mid Section for 3.0% Chloride (Set #1)
Figure E.13 Surface Corrosion at Mid Section for Average of all Chloride Contaminants (Set#1)

Figure E.14 Rib Loss at Mid Section for Average of all Chloride Contaminants (Set#1)
Figure E.15 Surface Corrosion at Mid Section for 0.0% Chloride (Set #2)

Figure E.16 Rib Loss at Mid Section for 0.0% Chloride (Set #2)
Figure E.17 Surface Corrosion at Mid Section for 0.5% Chloride (Set #2)

Figure E.18 Rib Loss at Mid Section for 0.5% Chloride (Set #2)
Figure E.19 Surface Corrosion at Mid Section for 1.0% Chloride (Set #2)

Figure E.20 Rib Loss at Mid Section for 1.0% Chloride (Set #2)
Figure E.21 Surface Corrosion at Mid Section for 1.5% Chloride (Set#2)

Figure E.22 Rib Loss at Mid Section for 1.5% Chloride (Set #2)
Figure E.23 Surface Corrosion at Mid Section for 2.0% Chloride (Set#2)

Figure E.24 Rib Loss at Mid Section for 2.0% Chloride (Set #2)
Figure E.25 Surface Corrosion at Mid Section for 3.0% Chloride (Set #2)

Figure E.26 Rib Loss at Mid Section for 3.0% Chloride (Set #2)
Figure E.27 Surface Corrosion at Mid Section for Average of all Chloride Contaminants (Set#2)

Figure E.28 Rib Loss at Mid Section for Average of all Chloride Contaminants (Set#2)
Figure E.29 Time Step of Surface Corrosion for 0.0% Chloride Pre-Cracked Specimens

Figure E.30 Time Step of Rib Loss for 0.0% Chloride Pre-Cracked Specimens
Figure E.31 Time Step of Surface Corrosion for 0.5% Chloride Pre-Cracked Specimens

Figure E.32 Time Step of Rib Loss for 0.5% Chloride Pre-Cracked Specimens
Figure E.33 Time Step of Surface Corrosion for 1.0% Chloride Pre-Cracked Specimens

Figure E.34 Time Step of Rib Loss for 1.0% Chloride Pre-Cracked Specimens
Figure E.35 Time Step of Surface Corrosion for 1.5% Chloride Pre-Cracked Specimens

Figure E.36 Time Step of Rib Loss for 1.5% Chloride Pre-Cracked Specimens
Figure E.37 Time Step of Surface Corrosion for 2.0% Chloride Pre-Cracked Specimens

Figure E.38 Time Step of Rib Loss for 2.0% Chloride Pre-Cracked Specimens
Figure E.39 Time Step of Surface Corrosion for 3.0% Chloride Pre-Cracked Specimens

Figure E.40 Time Step of Rib Loss for 3.0% Chloride Pre-Cracked Specimens
Figure E.41 Time Step of Surface Corrosion for 0.0% Chloride Post-Cracked Specimens

Figure E.42 Time Step of Rib Loss for 0.0% Chloride Post-Cracked Specimens
Figure E.43 Time Step of Surface Corrosion for 0.5% Chloride Post-Cracked Specimens

Figure E.44 Time Step of Rib Loss for 0.5% Chloride Post-Cracked Specimens
Figure E.45 Time Step of Surface Corrosion for 1.0% Chloride Post-Cracked Specimens

Figure E.46 Time Step of Rib Loss for 1.0% Chloride Post-Cracked Specimens
Figure E.47 Time Step of Surface Corrosion for 1.5% Chloride Post-Cracked Specimens

Figure E.48 Time Step of Rib Loss for 1.5% Chloride Post-Cracked Specimens
Figure E.49 Time Step of Surface Corrosion for 2.0% Chloride Post-Cracked Specimens

Figure E.50 Time Step of Rib Loss for 2.0% Chloride Post-Cracked Specimens
Figure E.51 Time Step of Surface Corrosion for 3.0% Chloride Post-Cracked Specimens

Figure E.52 Time Step of Rib Loss for 3.0% Chloride Post-Cracked Specimens
APPENDIX F

Figure F.1 – Cumulative Mass Loss/Length for Control Specimens

Figure F.2 – Cumulative Mass Loss/Length for Bath 1, 0.0% Chloride Pre-Cracked Specimens
Figure F.3 – Cumulative Mass Loss/Length for Bath 1, 0.5% Chloride Pre-Cracked Specimens

Figure F.4 – Cumulative Mass Loss/Length for Bath 1, 1.0% Chloride Pre-Cracked Specimens
Figure F.5 – Cumulative Mass Loss/Length for Bath 1, 1.5% Chloride Pre-Cracked Specimens

Figure F.6 – Cumulative Mass Loss/Length for Bath 1, 2.0% Chloride Pre-Cracked Specimens
Figure F.7 – Cumulative Mass Loss/Length for Bath 1, 3.0% Chloride Pre-Cracked Specimens

Figure F.8 – Cumulative Mass Loss/Length for Bath 2, 0.0% Chloride Pre-Cracked Specimens
Figure F.9 – Cumulative Mass Loss/Length for Bath 2, 0.5% Chloride Pre-Cracked Specimens

Figure F.10 – Cumulative Mass Loss/Length for Bath 2, 1.0% Chloride Pre-Cracked Specimens
Figure F.11 – Cumulative Mass Loss/Length for Bath 2, 1.5% Chloride Pre-Cracked Specimens

Figure F.12 – Cumulative Mass Loss/Length for Bath 2, 2.0% Chloride Pre-Cracked Specimens
Figure F.13 – Cumulative Mass Loss/Length for Bath 2, 3.0% Chloride Pre-Cracked Specimens

Figure F.14 – Cumulative Mass Loss/Length for Bath 3, 0.0% Chloride Post-Cracked Specimens
Figure F.15 – Cumulative Mass Loss/Length for Bath 3, 0.5% Chloride Post-Cracked Specimens

Figure F.16 – Cumulative Mass Loss/Length for Bath 3, 1.0% Chloride Post-Cracked Specimens
Figure F.17 – Cumulative Mass Loss/Length for Bath 3, 1.5% Chloride Post-Cracked Specimens

Figure F.18 – Cumulative Mass Loss/Length for Bath 3, 2.0% Chloride Post-Cracked Specimens
Figure F.19 – Cumulative Mass Loss/Length for Bath 3, 3.0% Chloride Post-Cracked Specimens

Figure F.20 – Cumulative Mass Loss/Length for Bath 4, 0.0% Chloride Post-Cracked Specimens
Figure F.21 – Cumulative Mass Loss/Length for Bath 4, 0.5% Chloride Post-Cracked Specimens

Figure F.22 – Cumulative Mass Loss/Length for Bath 4, 1.0% Chloride Post-Cracked Specimens
Figure F.23 – Cumulative Mass Loss/Length for Bath 4, 1.5% Chloride Post-Cracked Specimens

Figure F.24 – Cumulative Mass Loss/Length for Bath 4, 2.0% Chloride Post-Cracked Specimens
Figure F.25 – Cumulative Mass Loss/Length for Bath 4, 3.0% Chloride Post-Cracked Specimens

Figure F.26 – Cumulative Mass Loss/Length for Chamber Shelf 1 0.0% Chloride, Post-Cracked Specimens
Figure F.27 – Cumulative Mass Loss/Length for Chamber Shelf 1 0.5% Chloride, Post-Cracked Specimens

Figure F.28 – Cumulative Mass Loss/Length for Chamber Shelf 1 1.0% Chloride, Post-Cracked Specimens
Figure F.29 – Cumulative Mass Loss/Length for Chamber Shelf 1
1.5% Chloride, Post-Cracked Specimens

Figure F.30 – Cumulative Mass Loss/Length for Chamber Shelf 1
2.0% Chloride, Post-Cracked Specimens
Figure F.31 – Cumulative Mass Loss/Length for Chamber Shelf 1
3.0% Chloride, Post-Cracked Specimens

Figure F.32 – Cumulative Mass Loss/Length for Chamber Shelf 2
0.0% Chloride, Pre-Cracked Specimens
Figure F.33 – Cumulative Mass Loss/Length for Chamber Shelf 2 0.5% Chloride, Pre-Cracked Specimens

Figure F.34 – Cumulative Mass Loss/Length for Chamber Shelf 2 1.0% Chloride, Pre-Cracked Specimens
Figure F.35 – Cumulative Mass Loss/Length for Chamber Shelf 2
1.5% Chloride, Pre-Cracked Specimens

Figure F.36 – Cumulative Mass Loss/Length for Chamber Shelf 2
2.0% Chloride, Pre-Cracked Specimens
Figure F.37 – Cumulative Mass Loss/Length for Chamber Shelf 2
3.0% Chloride, Pre-Cracked Specimens

Figure F.38 – Cumulative Mass Loss/Length for Chamber Shelf 3
0.0% Chloride, Post-Cracked Specimens
Figure F.39 – Cumulative Mass Loss/Length for Chamber Shelf 3
0.5% Chloride, Post-Cracked Specimens

Figure F.40 – Cumulative Mass Loss/Length for Chamber Shelf 3
1.0% Chloride, Post-Cracked Specimens
**Figure F.41** – Cumulative Mass Loss/Length for Chamber Shelf 3
1.5% Chloride, Post-Cracked Specimens

**Figure F.42** – Cumulative Mass Loss/Length for Chamber Shelf 3
2.0% Chloride, Post-Cracked Specimens
Figure F.43 – Cumulative Mass Loss/Length for Chamber Shelf 3
3.0% Chloride, Post-Cracked Specimens

Figure F.44 – Cumulative Mass Loss/Length for Chamber Shelf 4
0.0% Chloride, Pre-Cracked Specimens
Figure F.45 – Cumulative Mass Loss/Length for Chamber Shelf 4 0.5% Chloride, Pre-Cracked Specimens

Figure F.46 – Cumulative Mass Loss/Length for Chamber Shelf 4 1.0% Chloride, Pre-Cracked Specimens
Figure F.47 – Cumulative Mass Loss/Length for Chamber Shelf 4
1.5% Chloride, Pre-Cracked Specimens

Figure F.48 – Cumulative Mass Loss/Length for Chamber Shelf 4
2.0% Chloride, Pre-Cracked Specimens
Figure F.49 – Cumulative Mass Loss/Length for Chamber Shelf 4
3.0% Chloride, Pre-Cracked Specimens
Figure G.1 – Visual Ratings for Bath 1, 0.0% Chloride, Pre-Cracked

Figure G.2 – Mass Loss and Strength Loss for Bath 1, 0.0% Chloride, Pre-Cracked
Figure G.3 – Visual Ratings for Bath 1, 0.5% Chloride, Pre-Cracked

Figure G.4 – Mass Loss and Strength Loss for Bath 1, 0.5% Chloride, Pre-Cracked
**Figure G.5 – Visual Ratings for Bath 1, 1.0% Chloride, Pre-Cracked**

**Figure G.6 – Mass Loss and Strength Loss for Bath 1, 1.0% Chloride, Pre-Cracked**
Figure G.7 – Visual Ratings for Bath 1, 1.5% Chloride, Pre-Cracked

Figure G.8 – Mass Loss and Strength Loss for Bath 1, 1.5% Chloride, Pre-Cracked
Figure G.9 – Visual Ratings for Bath 1, 2.0% Chloride, Pre-Cracked

Figure G.10 – Mass Loss and Strength Loss for Bath 1, 2.0% Chloride, Pre-Cracked
Figure G.11 – Visual Ratings for Bath 1, 3.0% Chloride, Pre-Cracked

Figure G.12 – Mass Loss and Strength Loss for Bath 1, 3.0% Chloride, Pre-Cracked
Figure G.13 – Visual Ratings for Bath 2, 0.0% Chloride, Pre-Cracked

Figure G.14 – Mass Loss and Strength Loss for Bath 2, 0.0% Chloride, Pre-Cracked
Figure G.15 – Visual Ratings for Bath 2, 0.5% Chloride, Pre-Cracked

Figure G.16 – Mass Loss and Strength Loss for Bath 2, 0.5% Chloride, Pre-Cracked
Figure G.17 – Visual Ratings for Bath 2, 1.0% Chloride, Pre-Cracked

Figure G.18 – Mass Loss and Strength Loss for Bath 2, 1.0% Chloride, Pre-Cracked
Figure G.19 – Visual Ratings for Bath 2, 1.5% Chloride, Pre-Cracked

Figure G.20 – Mass Loss and Strength Loss for Bath 2, 1.5% Chloride, Pre-Cracked
Figure G.21 – Visual Ratings for Bath 2, 2.0% Chloride, Pre-Cracked

Figure G.22 – Mass Loss and Strength Loss for Bath 2, 2.0% Chloride, Pre-Cracked
Figure G.23 – Visual Ratings for Bath 2, 3.0% Chloride, Pre-Cracked

Figure G.24 – Mass Loss and Strength Loss for Bath 2, 3.0% Chloride, Pre-Cracked
Figure G.25 – Visual Ratings for Bath 3, 0.0% Chloride, Post-Cracked

Figure G.26 – Mass Loss and Strength Loss for Bath 3, 0.0% Chloride, Post-Cracked
Figure G.27 – Visual Ratings for Bath 3, 0.5% Chloride, Post-Cracked

Figure G.28 – Mass Loss and Strength Loss for Bath 3, 0.5% Chloride, Post-Cracked
Figure G.29 – Visual Ratings for Bath 3, 1.0% Chloride, Post-Cracked

Figure G.30 – Mass Loss and Strength Loss for Bath 3, 1.0% Chloride, Post-Cracked
Figure G.31 – Visual Ratings for Bath 3, 1.5% Chloride, Post-Cracked

Figure G.32 – Mass Loss and Strength Loss for Bath 3, 1.5% Chloride, Post-Cracked
Figure G.33 – Visual Ratings for Bath 3, 2.0% Chloride, Post-Cracked

Figure G.34 – Mass Loss and Strength Loss for Bath 3, 2.0% Chloride, Post-Cracked
Figure G.35 – Visual Ratings for Bath 3, 3.0% Chloride, Post-Cracked

Figure G.36 – Mass Loss and Strength Loss for Bath 3, 3.0% Chloride, Post-Cracked
Figure G.37 – Visual Ratings for Bath 4, 0.0% Chloride, Post-Cracked

Figure G.38 – Mass Loss and Strength Loss for Bath 4, 0.0% Chloride, Post-Cracked
Figure G.39 – Visual Ratings for Bath 4, 0.5% Chloride, Post-Cracked

Figure G.40 – Mass Loss and Strength Loss for Bath 4, 0.5% Chloride, Post-Cracked
Figure G.41 – Visual Ratings for Bath 4, 1.0% Chloride, Post-Cracked

Figure G.42 – Mass Loss and Strength Loss for Bath 4, 1.0% Chloride, Post-Cracked
Figure G.43 – Visual Ratings for Bath 4, 1.5% Chloride, Post-Cracked

Figure G.44 – Mass Loss and Strength Loss for Bath 4, 1.5% Chloride, Post-Cracked
Figure G.45 – Visual Ratings for Bath 4, 2.0% Chloride, Post-Cracked

Figure G.46 – Mass Loss and Strength Loss for Bath 4, 2.0% Chloride, Post-Cracked
Figure G.47 – Visual Ratings for Bath 4, 3.0% Chloride, Post-Cracked

Figure G.48 – Mass Loss and Strength Loss for Bath 4, 3.0% Chloride, Post-Cracked
Figure G.49 – Visual Ratings for Chamber Shelf 1, 0.0% Chloride, Post-Cracked

Figure G.50 – Mass Loss and Strength Loss for Chamber Shelf 1, 0.0% Chloride, Post-Cracked
Figure G.51 – Visual Ratings for Chamber Shelf 1, 0.5% Chloride, Post-Cracked

Figure G.52 – Mass Loss and Strength Loss for Chamber Shelf 1, 0.5% Chloride, Post-Cracked
Figure G.53 – Visual Ratings for Chamber Shelf 1, 1.0% Chloride, Post-Cracked

Figure G.54 – Mass Loss and Strength Loss for Chamber Shelf 1, 1.0% Chloride, Post-Cracked
Figure G.55 – Visual Ratings for Chamber Shelf 1, 1.5% Chloride, Post-Cracked

Figure G.56 – Mass Loss and Strength Loss for Chamber Shelf 1, 1.5% Chloride, Post-Cracked
Figure G.57 – Visual Ratings for Chamber Shelf 1, 2.0% Chloride, Post-Cracked

Figure G.58 – Mass Loss and Strength Loss for Chamber Shelf 1, 2.0% Chloride, Post-Cracked
Figure G.59 – Visual Ratings for Chamber Shelf 1, 3.0% Chloride, Post-Cracked

Figure G.60 – Mass Loss and Strength Loss for Chamber Shelf 1, 3.0% Chloride, Post-Cracked
Figure G.61 – Visual Ratings for Chamber Shelf 2, 0.0% Chloride, Pre-Cracked

Figure G.62 – Mass Loss and Strength Loss for Chamber Shelf 2, 0.0% Chloride, Pre-Cracked
Figure G.63 – Visual Ratings for Chamber Shelf 2, 0.5% Chloride, Pre-Cracked

Figure G.64 – Mass Loss and Strength Loss for Chamber Shelf 2, 0.5% Chloride, Pre-Cracked
Figure G.65– Visual Ratings for Chamber Shelf 2, 1.0% Chloride, Pre-Cracked

Figure G.66 – Mass Loss and Strength Loss for Chamber Shelf 2, 1.0% Chloride, Pre-Cracked

282
Figure G.67 – Visual Ratings for Chamber Shelf 2, 1.5% Chloride, Pre-Cracked

Figure G.68 – Mass Loss and Strength Loss for Chamber Shelf 2, 1.5% Chloride, Pre-Cracked
Figure G.69 – Visual Ratings for Chamber Shelf 2, 2.0% Chloride, Pre-Cracked

Figure G.70 – Mass Loss and Strength Loss for Chamber Shelf 2, 2.0% Chloride, Pre-Cracked
Figure G.71 – Visual Ratings for Chamber Shelf 2, 3.0% Chloride, Pre-Cracked

Figure G.72 – Mass Loss and Strength Loss for Chamber Shelf 2, 3.0% Chloride, Pre-Cracked
Figure G.73 – Visual Ratings for Chamber Shelf 3, 0.0% Chloride, Post-Cracked

Figure G.74 – Mass Loss and Strength Loss for Chamber Shelf 3, 0.0% Chloride, Post-Cracked
Figure G.75 – Visual Ratings for Chamber Shelf 3, 0.5% Chloride, Post-Cracked

Figure G.76 – Mass Loss and Strength Loss for Chamber Shelf 3, 0.5% Chloride, Post-Cracked
Figure G.77 – Visual Ratings for Chamber Shelf 3, 1.0% Chloride, Post-Cracked

Figure G.78 – Mass Loss and Strength Loss for Chamber Shelf 3, 1.0% Chloride, Post-Cracked
Figure G.79 – Visual Ratings for Chamber Shelf 3, 1.5% Chloride, Post-Cracked

Figure G.80 – Mass Loss and Strength Loss for Chamber Shelf 3, 1.5% Chloride, Post-Cracked
Figure G.81 – Visual Ratings for Chamber Shelf 3, 2.0% Chloride, Post-Cracked

Figure G.82 – Mass Loss and Strength Loss for Chamber Shelf 3, 2.0% Chloride, Post-Cracked
Figure G.83 – Visual Ratings for Chamber Shelf 3, 3.0% Chloride, Post-Cracked

Figure G.84 – Mass Loss and Strength Loss for Chamber Shelf 3, 3.0% Chloride, Post-Cracked
Figure G.85 – Visual Ratings for Chamber Shelf 4, 0.0% Chloride, Pre-Cracked

Figure G.86 – Mass Loss and Strength Loss for Chamber Shelf 4, 0.0% Chloride, Pre-Cracked
Figure G.87 – Visual Ratings for Chamber Shelf 4, 0.5% Chloride, Pre-Cracked

Figure G.88 – Mass Loss and Strength Loss for Chamber Shelf 4, 0.5% Chloride, Pre-Cracked
Figure G.89 – Visual Ratings for Chamber Shelf 4, 1.0% Chloride, Pre-Cracked

Figure G.90 – Mass Loss and Strength Loss for Chamber Shelf 4, 1.0% Chloride, Pre-Cracked
Figure G.91 – Visual Ratings for Chamber Shelf 4, 1.5% Chloride, Pre-Cracked

Figure G.92 – Mass Loss and Strength Loss for Chamber Shelf 4, 1.5% Chloride, Pre-Cracked
Figure G.93 – Visual Ratings for Chamber Shelf 4, 2.0% Chloride, Pre-Cracked

Figure G.94 – Mass Loss and Strength Loss for Chamber Shelf 4, 2.0% Chloride, Pre-Cracked
Figure G.95 – Visual Ratings for Chamber Shelf 4, 3.0% Chloride, Pre-Cracked

Figure G.96 – Mass Loss and Strength Loss for Chamber Shelf 4, 3.0% Chloride, Pre-Cracked