Development of an Automated Electrical Impedance Tomography System and Its Implementation in Cementitious Materials

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DEVELOPMENT OF AN AUTOMATED ELECTRICAL IMPEDANCE TOMOGRAPHY SYSTEM AND ITS IMPLEMENTATION IN CEMENTITIOUS MATERIALS

A Dissertation
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
Civil Engineering

by
Tao Ruan
August 2016

Accepted by:
Dr. Amir Poursaeed, Committee Chair
Dr. Prasad Rangaraju
Dr. Brandon Ross
Dr. Taufiquar Khan
ABSTRACT

Electrical impedance tomography (EIT) based non-destructive evaluation showed great potentials in assessing the health condition of the new or existing civil infrastructures. Damages or anomalies that on the surface and embedded inside the structures exhibited as local conductivity changes and altered the path of electrical current flow. This investigation was focused on developing a new automated EIT system and employing EIT to identify the anomalies in cementitious materials structures.

This dissertation is structured as follows. First, common nondestructive evaluation (NDE) techniques including conductivity-based techniques were summarized as well as their advantages and disadvantages. Then the theories of EIT modality as well as inverse reconstruction algorithms were illustrated. Next, the development of the automated electrical tomography measurement system was presented which made it possible to complete thousands of measurements in a few minutes. The developed system has multiple portable measurement units that can be used on the objects with different geometries. Finally, experiments were designed and the results of the experimental works were discussed.

Laboratory experiments were carried out to explore the feasibility of implementing the EIT in assessing surface and subsurface damages in cementitious structures. With the aid of conductive paint, the tests were performed on both circular surfaces and a large polyester
transparent sheet. Damages with different geometries and sizes were identified. Furthermore, the feasibility of detecting subsurface (invisible) damages was investigated. With the aid of numerical simulation and inverse calculation, the locations of damages were identified and the sizes were qualitatively estimated. In addition, experiments were designed to assess the chloride distribution in concrete slabs. The results from the EIT tests were compared to results from half-cell potential (HCP) and four-point resistivity tests. The results corresponded very well and EIT reconstructed images showed clearer contrast.

Another application was to detect the distribution of steel fibers in steel reinforced mortar specimens using the EIT. The mortar specimens were cast with two different water to cementitious materials ratios 0.5 and 1.25, respectively. The fiber levels in volume percentages ranging from 0 to 2% with an increment of 0.5%. Comparative study was carried out with the aid of advanced photography techniques and image processing techniques. Results showed a great potential for the EIT method to be used in this application.

To summarize, EIT was proved to be a viable NDE tool for damage detection in cementitious structures. Despite the potentials of EIT in NDE of cementitious materials, challenges exist. First, cementitious materials are heavily heterogeneous with low electrical conductivity. Although conductive paint provided a relatively uniform conductivity field, it was only suitable for accessible surfaces of structures. For subsurface damage detection, the penetration of injected current was not deep enough for accurate damage detection, as
a result, only the damages with depths less than 30 mm can be detected. It seems that using more powerful current source could improve the image resolution. Another issue was the ill-posed feature of inverse analysis and more advanced algorithms are needed to enhance the performance and stability of the inverse problems compared to current approaches.
DEDICATION

To my loving parents, Hebang Ruan and Jinying Zhai, I dedicate this work to you. Thanks for giving me life, love and unconditional support throughout my life. All I have and will accomplish are only possible due to your love and sacrifices.
ACKNOWLEDGMENTS

I would like to thank the faculty and staff of the Glenn Department of Civil Engineering at Clemson University for their teaching, help, advice and support during my PhD study. In particular, I would like to express my utmost gratitude to my advisor, Dr. Amir Poursaeed, for his support and guidance throughout my dissertation work. In addition, I would also like to thank Dr. Prasada Rangaraju, Dr. Ross Brandon and Dr. Taufiquar Khan for their guidance and serving in my dissertation committee. I appreciate their generous help with their expertise and precious time. I would also like to thank Danny Metz, Scott Black, Samuel Biemann for their support in experiment preparation. I also appreciate the help from Lab Mates and friends Trent Dellinger, Zhengqi Li, Luay Alarab, Ling Ding, Zexu Qian and Xiaoyu Hu.

Finally, the financial support from Glen Department of Civil Engineering is gratefully acknowledged.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TITLE PAGE</td>
<td>i</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>DEDICATION</td>
<td>v</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xiii</td>
</tr>
<tr>
<td>NOMENCLATURE</td>
<td>xvii</td>
</tr>
<tr>
<td>I. INTRODUCTION</td>
<td>20</td>
</tr>
<tr>
<td>1.1 Background</td>
<td>20</td>
</tr>
<tr>
<td>1.2 Research objective</td>
<td>23</td>
</tr>
<tr>
<td>II. LITERATURE REVIEW</td>
<td>24</td>
</tr>
<tr>
<td>2.1 Brief review of the common NDE techniques for cementitious materials</td>
<td>24</td>
</tr>
<tr>
<td>2.2 Electrical properties of cementitious materials</td>
<td>28</td>
</tr>
<tr>
<td>2.3 Electrical impedance tomography</td>
<td>30</td>
</tr>
<tr>
<td>III. EIT THEORY AND RECONSTRUCTION ALGORITHM</td>
<td>32</td>
</tr>
</tbody>
</table>
Table of Contents (Continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Background</td>
<td>32</td>
</tr>
<tr>
<td>3.2</td>
<td>Theory</td>
<td>33</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Forward model</td>
<td>33</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Numerical implementation of CEM</td>
<td>35</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Derivation of Jacobian basing on CEM</td>
<td>38</td>
</tr>
<tr>
<td>3.2.4</td>
<td>Inverse calculation</td>
<td>41</td>
</tr>
<tr>
<td>3.2.5</td>
<td>Gauss-Newton method</td>
<td>42</td>
</tr>
<tr>
<td>3.2.6</td>
<td>Total Variation method</td>
<td>46</td>
</tr>
<tr>
<td>IV.</td>
<td>DEVELOPMENT OF THE AUTOMATED MEASUREMENT SYSTEM</td>
<td>50</td>
</tr>
<tr>
<td>4.1</td>
<td>Introduction</td>
<td>50</td>
</tr>
<tr>
<td>4.2</td>
<td>Component of the system</td>
<td>50</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Electrodes</td>
<td>51</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Measurement assembly</td>
<td>52</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Current source</td>
<td>53</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Switch system and multimeter</td>
<td>54</td>
</tr>
</tbody>
</table>
Table of Contents (Continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.3 Control platform</td>
<td>58</td>
</tr>
<tr>
<td>4.4 Data processing with EIDORS toolkit</td>
<td>60</td>
</tr>
<tr>
<td>V. SPECIMEN PREPARATION AND EXPERIMENTAL PROCEDURES</td>
<td>62</td>
</tr>
<tr>
<td>5.1 Surface damage with conductive paint</td>
<td>62</td>
</tr>
<tr>
<td>5.1 Subsurface damage detection</td>
<td>67</td>
</tr>
<tr>
<td>5.2 Steel fiber reinforced ultra-high performance concrete (SFRUHRC)</td>
<td>72</td>
</tr>
<tr>
<td>5.2.1 Fiber distribution of SFRUHPC</td>
<td>72</td>
</tr>
<tr>
<td>5.2.2 Materials</td>
<td>73</td>
</tr>
<tr>
<td>5.2.3 Mortar mixing</td>
<td>74</td>
</tr>
<tr>
<td>5.2.4 Photo acquisition and post-processing</td>
<td>76</td>
</tr>
<tr>
<td>5.2.5 Procedures of photo post-processing</td>
<td>77</td>
</tr>
<tr>
<td>5.3 Chloride detection in concrete slab</td>
<td>79</td>
</tr>
<tr>
<td>5.3.1 Half-cell potential measurement</td>
<td>82</td>
</tr>
<tr>
<td>5.3.2 Resistivity measurement</td>
<td>82</td>
</tr>
<tr>
<td>5.4 EIT testing</td>
<td>82</td>
</tr>
</tbody>
</table>
Table of Contents (Continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>VI. RESULTS AND DISCUSSIONS</td>
<td>85</td>
</tr>
<tr>
<td>6.1 Surface damage detection</td>
<td>85</td>
</tr>
<tr>
<td>6.2 Subsurface damage detection in two dimension</td>
<td>92</td>
</tr>
<tr>
<td>6.3 Assessment of steel fiber distribution in UHPC</td>
<td>99</td>
</tr>
<tr>
<td>6.3.1 Flowability test</td>
<td>99</td>
</tr>
<tr>
<td>6.3.2 Compressive strength test</td>
<td>100</td>
</tr>
<tr>
<td>6.3.3 Image analysis</td>
<td>103</td>
</tr>
<tr>
<td>6.3.4 Electrical impedance tomography measurement</td>
<td>107</td>
</tr>
<tr>
<td>6.4 Chloride diffusion in concrete slab</td>
<td>123</td>
</tr>
<tr>
<td>6.4.1 Half-cell potential and resistivity measurements</td>
<td>123</td>
</tr>
<tr>
<td>6.4.2 Electrical impedance tomography</td>
<td>127</td>
</tr>
<tr>
<td>VII. SUMMARY</td>
<td>131</td>
</tr>
<tr>
<td>7.1 Automated measurement system</td>
<td>131</td>
</tr>
<tr>
<td>7.2 Surface damage detection</td>
<td>131</td>
</tr>
<tr>
<td>7.3 Subsurface damage detection</td>
<td>132</td>
</tr>
</tbody>
</table>

x
Table of Contents (Continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.4 Fiber detection in UHPC</td>
<td>133</td>
</tr>
<tr>
<td>7.5 Chloride contaminated area detection</td>
<td>133</td>
</tr>
<tr>
<td>VIII. FUTURE WORK AND RECOMMENDATIONS</td>
<td>135</td>
</tr>
<tr>
<td>BIBLIOGRAPHY</td>
<td>137</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 5-1</td>
<td>Properties of the conductive nickel coating (MG Chemicals, 2015)</td>
<td>63</td>
</tr>
<tr>
<td>Table 5-2</td>
<td>Summarization of simulated damages on specimens coated with conductive paint</td>
<td>66</td>
</tr>
<tr>
<td>Table 5-3</td>
<td>Properties of silica fume</td>
<td>74</td>
</tr>
<tr>
<td>Table 5-4</td>
<td>Proportions of raw materials for 1 m$^3$ concrete (Unit: Kg)</td>
<td>75</td>
</tr>
<tr>
<td>Table 5-5</td>
<td>Proportions of raw materials for 1 m$^3$ concrete (Unit: Kg)</td>
<td>80</td>
</tr>
</tbody>
</table>
**LIST OF FIGURES**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 2-1</td>
<td>Wenner technique setup for measuring resistivity</td>
<td>29</td>
</tr>
<tr>
<td>Figure 3-1</td>
<td>Meshes with 256 triangle elements for 8 electrodes</td>
<td>36</td>
</tr>
<tr>
<td>Figure 3-2</td>
<td>Meshes with 256 triangle elements for 16 electrodes</td>
<td>37</td>
</tr>
<tr>
<td>Figure 3-3</td>
<td>Meshes with 256 triangle elements for 32 electrodes</td>
<td>37</td>
</tr>
<tr>
<td>Figure 3-4</td>
<td>Flow chart of EIT imaging using iterative GN algorithm</td>
<td>46</td>
</tr>
<tr>
<td>Figure 4-1</td>
<td>Portrait of spring contact probes with serrated tips</td>
<td>51</td>
</tr>
<tr>
<td>Figure 4-2</td>
<td>(a) 2D measurement units with 16 electrodes and (b) Performing measurement</td>
<td>52</td>
</tr>
<tr>
<td>Figure 4-3</td>
<td>(a) 2D measurement units with 32 electrodes and (b) Performing measurement</td>
<td>53</td>
</tr>
<tr>
<td>Figure 4-4</td>
<td>Schematic illustration of the 16 and 32 electrode arrangement for 2D measurement</td>
<td>54</td>
</tr>
<tr>
<td>Figure 4-5</td>
<td>Schematic illustration of the wiring diagram used to inject and switch current source to the adjacent electrodes and measure the potentials on the other pairs of electrodes</td>
<td>56</td>
</tr>
<tr>
<td>Figure 4-6</td>
<td>Photo of switch module</td>
<td>57</td>
</tr>
</tbody>
</table>
List of Figures (Continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 4-7</td>
<td>Photo of current source and switch system</td>
<td>57</td>
</tr>
<tr>
<td>Figure 4-8</td>
<td>Schematic representation of connections between different components of automated measurement system</td>
<td>59</td>
</tr>
<tr>
<td>Figure 4-9</td>
<td>Component of the system with the 2D measurement</td>
<td>59</td>
</tr>
<tr>
<td>Figure 5-1</td>
<td>Conductive paint covered specimens with longitudinal and circular artificial damage</td>
<td>64</td>
</tr>
<tr>
<td>Figure 5-2</td>
<td>Conductive paint covered specimens with zigzag artificial damage</td>
<td>65</td>
</tr>
<tr>
<td>Figure 5-3</td>
<td>Plastic sheet coated by conductive paint with damages in different geometries distributed on its surface</td>
<td>67</td>
</tr>
<tr>
<td>Figure 5-4</td>
<td>Schematic illustration of the specimens (a) damage created, using 0.1 mm Polypropylene transparent sheet, (b, c, d) damage created by saw cut and (e) damage created by a PVC pipe</td>
<td>71</td>
</tr>
<tr>
<td>Figure 5-5</td>
<td>Procedures of image processing and sample results</td>
<td>78</td>
</tr>
<tr>
<td>Figure 5-6</td>
<td>Photo of concrete slab with rebar labelled</td>
<td>81</td>
</tr>
<tr>
<td>Figure 5-7</td>
<td>Performing test on specimens with top surface coated by conductive paint.</td>
<td>83</td>
</tr>
<tr>
<td>Figure 5-8</td>
<td>Experiment setup for EIT test on top surface of concrete slab</td>
<td>84</td>
</tr>
</tbody>
</table>
List of Figures (Continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-1</td>
<td>Photo and reconstructed images for specimens with longitudinal anomalies</td>
<td>86</td>
</tr>
<tr>
<td>6-2</td>
<td>Photo and reconstructed images for specimens with circular anomalies</td>
<td>88</td>
</tr>
<tr>
<td>6-3</td>
<td>Photo and reconstructed images for specimens with zigzag anomalies</td>
<td>89</td>
</tr>
<tr>
<td>6-4</td>
<td>Painted plastic sheet with multiple anomalies and images reconstructed by (b) TV (c) GN</td>
<td>91</td>
</tr>
<tr>
<td>6-5</td>
<td>Reference specimen and (b) its reconstructed image</td>
<td>92</td>
</tr>
<tr>
<td>6-6</td>
<td>Photos and corresponding reconstructed images of specimens with damages created using embedded plastic sheet with (a) 10mm (b) 20mm and (c) 30mm, below the top surface</td>
<td>94</td>
</tr>
<tr>
<td>6-7</td>
<td>Photos and corresponding reconstructed images of specimens with single saw cut damage 10mm (a and b), 20mm (c), below the top surface</td>
<td>96</td>
</tr>
<tr>
<td>6-8</td>
<td>Photos and corresponding reconstructed images of specimens with double saw cut damage 10mm (a), 20mm (b), below the top surface</td>
<td>97</td>
</tr>
<tr>
<td>6-9</td>
<td>Specimen with circular damage and its reconstructed images</td>
<td>98</td>
</tr>
<tr>
<td>6-10</td>
<td>Flow diameter versus fiber percentage</td>
<td>100</td>
</tr>
<tr>
<td>6-11</td>
<td>Compressive strength of Mix A at 7 days</td>
<td>101</td>
</tr>
</tbody>
</table>
List of Figures (Continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-12</td>
<td>Compressive strength of Mix A at 28 days</td>
<td>101</td>
</tr>
<tr>
<td>6-13</td>
<td>Compressive strength of Mix B at 7 days</td>
<td>102</td>
</tr>
<tr>
<td>6-14</td>
<td>Compressive strength of Mix B at 28 days</td>
<td>102</td>
</tr>
<tr>
<td>6-15</td>
<td>Area ratio versus actual fiber content for both mix A and mix B</td>
<td>104</td>
</tr>
<tr>
<td>6-16</td>
<td>Normalized area ratio versus layer from top (layer 1) to bottom (layer 8) for Mix A</td>
<td>105</td>
</tr>
<tr>
<td>6-17</td>
<td>Fiber area percent versus layer from top (layer 1) to bottom (layer 8) for Mix B</td>
<td>106</td>
</tr>
<tr>
<td>6-18</td>
<td>Reconstructed image for specimen Mix A with 0.5% steel fiber</td>
<td>108</td>
</tr>
<tr>
<td>6-19</td>
<td>Mean conductivity difference for Mix A with 0.5% steel fiber</td>
<td>108</td>
</tr>
<tr>
<td>6-20</td>
<td>Reconstructed image for specimen Mix A with 1% steel fiber</td>
<td>109</td>
</tr>
<tr>
<td>6-21</td>
<td>Mean conductivity difference for Mix A with 1% steel fiber</td>
<td>110</td>
</tr>
<tr>
<td>6-22</td>
<td>Reconstructed images for specimen Mix A with 1.5% steel fiber</td>
<td>111</td>
</tr>
<tr>
<td>6-23</td>
<td>Mean conductivity difference for Mix A with 1.5% steel fiber</td>
<td>112</td>
</tr>
<tr>
<td>6-24</td>
<td>Reconstructed images for specimen Mix A with 2% fiber</td>
<td>113</td>
</tr>
<tr>
<td>6-25</td>
<td>Mean conductivity difference for Mix A with 2% steel fiber</td>
<td>114</td>
</tr>
</tbody>
</table>
**List of Figures (Continued)**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-26</td>
<td>Reconstructed images for specimen Mix B with 0.5% fiber</td>
<td>115</td>
</tr>
<tr>
<td>6-27</td>
<td>Mean conductivity difference for Mix B with 0.5% steel fiber</td>
<td>116</td>
</tr>
<tr>
<td>6-28</td>
<td>Reconstructed images for specimen Mix B with 1% fiber</td>
<td>117</td>
</tr>
<tr>
<td>6-29</td>
<td>Mean conductivity difference for Mix B with 1% steel fiber</td>
<td>118</td>
</tr>
<tr>
<td>6-30</td>
<td>Reconstructed images for specimen Mix B with 1.5% fiber</td>
<td>119</td>
</tr>
<tr>
<td>6-31</td>
<td>Mean conductivity difference for Mix B with 1.5% steel fiber</td>
<td>120</td>
</tr>
<tr>
<td>6-32</td>
<td>Reconstructed images for specimen Mix B with 2% steel fiber</td>
<td>121</td>
</tr>
<tr>
<td>6-33</td>
<td>Mean conductivity difference for Mix B with 2% steel fiber</td>
<td>122</td>
</tr>
<tr>
<td>6-34</td>
<td>Potential contour maps from half-cell potential test (Unit: mV) on the concrete slab</td>
<td>124</td>
</tr>
<tr>
<td>6-35</td>
<td>Resistivity contour plots from Wenner measurements (Unit: kΩ/cm²)</td>
<td>126</td>
</tr>
<tr>
<td>6-36</td>
<td>Contour plot of mean resistivity (Unit: Ω)</td>
<td>128</td>
</tr>
<tr>
<td>6-37</td>
<td>Mapping from EIT reconstructed images (dark blue means low conductivity)</td>
<td>129</td>
</tr>
<tr>
<td>6-38</td>
<td>Contour plot of the mean conductivity</td>
<td>130</td>
</tr>
</tbody>
</table>
NOMENCLATURE

2D – two dimension

3D – three dimension

AC – alternate current

AET – automated electrical tomography

CM – cementitious material

CT – computer tomography

DAC – data acquisition

DC – direct current

EIT – electrical impedance tomography

EM – electromagnetic

FEM – finite element method

FRP – fiber reinforced polymer

GPR – ground penetration radar

GN – Gauss-Newton

HCP – half-cell potential

IR – infrared
NDE – non-destructive evaluation
NDT – non-destructive test
PDE – partial differential equations
PD-IPM – primal-dual interior point method
PVA – polyvinyl alcohol
RC – reinforced concrete
SHM – structural health monitoring
SFRUHPC – steel fiber reinforced ultra-high performance concrete
SIRT – simultaneous iterative reconstruction techniques
UGW – ultrasonic guided wave
UPE – ultrasonic pulse echo
TV – total variation
TSVD – truncated singular value decomposition
W/C – water-to-cement ratio
PP – polypropylene
PVC – polyvinyl chloride
CHAPTER ONE

INTRODUCTION

1.1 Background

Concrete is the most widely used construction material in the world. About 500 million tons of concrete was produced annually in United States. Compared to other construction materials, concrete has higher compressive strength, better durability and its raw materials are always available locally. However, degradation occurs due to a variety of reasons and the concrete damage is often the combination of many factors. Common factors contributing to the degradation of concrete are the corrosion of embedded steel rebar, chemical attack, alkali aggregate reaction and overload. According to Farrar and Worden, a damage can be defined as property change introduced into a system that will adversely affect the current and the future performance of that system (Farrar & Worden, 2007). In concrete structures, damages such as cracks and delaminations are important indicators of deterioration and they pose significant challenges on both new and existing structures. The damages in materials, including concrete materials, can grow and coalesce, leading to component and then structural level deficiencies (Farrar & Worden, 2007).

It is clear that an appropriate scheduled inspection and maintenance program lower the risk of catastrophic collapse and ensure the serviceability of the structures. Visual inspection is
the most commonly used technique; however, the efficiency greatly depends on the experience of the inspector and, in most cases, only damages expanding to the surface of structures can be captured. Therefore, effective damage assessment and health monitoring techniques are urgently needed.

Evaluation of the integrity of infrastructure is an essential procedure to assess the structural safety, durability and service capacities. The process of damage identification for civil infrastructures is always carried out in conjunction with disciplines including structural health monitoring (SHM) (Bently & Hatch, 2002), non-destructive evaluation (NDE) (Shull, 2002) and damage prognosis (Farrar, 2003). The goals of NDE and SHM are (1) to detect the existence of damages and what type of the damages exist in a structure; (2) to identify the locations of damages; (3) to quantitatively estimate the size of the damages and (4) to predict the impact of the damages on the structures and remaining service lives of such structures (Rytter, 1993; V. K. Sharma, 2009).

To assess the damages in structures, several damage detection techniques were proposed. These methodologies can be divided into structural scale and material scale. For damage detection at structural scale, vibration methods can be used and frequency information is extracted (Farrar & Worden, 2007). Typical objective features used in vibration methods are modal shapes, resonant frequencies, frequency response functions and modal assurance criterion. This method works well with damage occurred at component scale or system scale, such as, from earthquake or external impact. Nevertheless, it is challenging to extract
damage features corresponding to the local damages or gradual changes. Another challenge is that the frequency information will be superimposed from simultaneous presence of multiple damages. The other method focuses at material scale which is more accurate and promising for damage detection in concrete structures. More recently, modalities, such as ultrasonic techniques (Karaiskos et al., 2015; Kee & Zhu, 2013; Komlos et al., 1996; Song et al., 2007; Zhu et al., 2011), acoustic emission (Pour-Ghaz et al., 2011; Verstrynge et al., 2014), electromagnetic techniques (S. Na & Lee, 2012; Rhim & Buyukozturk, 1998), ultrasonic guided waves (B. L. Ervin et al., 2009; B. L. Ervin & Reis, 2008; D. Li et al., 2012; W. Na et al., 2002), X-ray (Elqra et al., 2007) and ground penetration radar (Maierhofer, 2003; X. Xie et al., 2013) were used for damage detection in concrete. However, many of these NDE modalities are expensive or have safety concerns, and some of them are difficult to implement in the field. Alternatively, conductivity-based NDE modalities, which are emerging with features of low cost, safe and ease of use in both laboratory and the fields, seem to be excellent NDE candidates for being used in damage detection in concrete structure.

In this work, the feasibility of implementing Electrical Impedance Tomography (EIT) in damage detection of cementitious structures was investigated. The idea of EIT was first suggested independently by Henderson and Webster (Henderson & webster, 1978) for medical imaging and by Lytle and Dines for geophysical imaging (Lytle & Dines, 1978). EIT is a non-invasive imaging radiation-free modality that uses the electrical properties of a material, from surface electrode measurements, inversely estimating the internal
resistivity/conductivity distribution within the material. Simplicity and low cost are the two main benefits of EIT, compared to other modalities, i.e. Magnetic Resonance Imaging (MRI) and Computerized Tomography Scanning (CT-Scan). It is also a safe method unlike tomography methods based on radiation, e.g. X-ray tomography.

1.2 Research objective

The research objective of this work was to study the feasibility of utilizing EIT method in assessing the damages and durability of concrete structures. To achieve this objective, the following endeavors were pursued:

1) Deriving an algorithm and customizing the mathematical model for implementation in cementitious materials,

2) Developing a portable and automated measurement system (including hardware and software) to perform the tests and to minimize the errors,

3) Investigating the feasibility of utilizing EIT technique to detect surface damage on specimens covered with conductive paint and reconstruct the 2D images,

4) Investigating the feasibility of utilizing EIT technique to detect subsurface damage on specimens and reconstruct 2D images,

5) Exploring the feasibility of detecting fiber distribution in ultra-high performance concrete, and

6) Utilizing EIT to evaluate chloride distribution in concrete slab.
2.1 Brief review of the common NDE techniques for cementitious materials

There are several techniques for evaluating the integrity of concrete structures. Visual inspection is one of the commonly used methods to evaluate the conditions of in-service structures. Visual inspection involves the assessment of surface cracks, spalling and other anomalies (Scott et al., 2003). While visual inspection is a very effective evaluation method, it only works for cracks that propagated to surface or surface spalling. It might take a long time for cracks propagating from interior to surface or spalling to become visible. In addition, all other hidden damages can also pose significant risks on the reliability and safety of the structures. Besides, only the human-accessible parts of the structures can be inspected by visual inspection, for example, the bottom of bridge decks over rivers cannot easily be visually inspected.

Chain dragging and hammer sounding are also widely used in evaluation of concrete structures (ASTM, 2012). Chain dragging finds the delamination zone and hammer hitting is used to determine the boundaries of such zone (Gucunski, 2013). The areas with delaminations underneath generate different sound compared to the sound concrete. This technique provides subjective results greatly depending on technician’s experience. Other
drawbacks of this method are that it is labor intensive and it does not work on bridge decks covered by asphalt layers.

Ultrasonic pulse echo (UPE) is a method basing on ultrasonic stress waves (Kohl & Streicher, 2006; Sansalone, 1993). The short-duration pulse is emitted from the probes made by piezoelectric materials, and then the reflected waves are captured and converted back to electrical signals. In this method, the transit time and amplitude ratio of pulse between emitted wave and received wave are of interest, and much shorter transit time obtained if the object under test has cracks or delaminations. The amplitude ratio can be used to estimate the extent of the deterioration. Laboratory experiments were performed using UPE to detect the internal damages in concrete and fiber reinforced polymer (FRP) - encased concrete structures (Mirmiran & Wei, 2001; Selleck et al., 1998; Suaris & Fernando, 1987). However, precise measurements are difficult to obtain. The intrinsic heterogeneity of reinforced concrete, the moisture content, aggregate gradation and sensor sensitivity always leads to errors for the tests. UPE was also utilized to explore the relationship between the strength gain and pulse velocity (Kewalramani & Gupta, 2006; Popovics, 2001; Voigt et al., 2003). UPE was also employed to monitor the setting process in high-performance concrete (Pessiki & Carino, 1988).

Ground penetration radar (GPR) is another nondestructive testing modality that relies on electromagnetic wave theory and damage is characterized by dielectric constant that differs from the sound concrete (Annan, 2009; Davis & Annan, 1989; Jol, 2008). The radargram
is used to output the health condition of the test object. One obvious advantage is that this method does not require the direct contact between antenna and the surface of structure. Besides, the traffic and other ambient noise have negligible influence on the accuracy of testing results. This is very important when testing the bridges with high volumes of traffic. GPR has been widely used in damage detections of concrete structures especially bridges (Barnes et al., 2008; Hugenschmidt & Mastrangelo, 2006; Kim, 2003; Maser, 1996; Wang et al., 2011). Chlorides and moisture distribution in concrete structures was also investigated by GPR (Hugenschmidt & Loser, 2008; Kalogeropoulos et al., 2011). The disadvantages of GPR are that heterogeneous property of concrete always scatters the GPR signals and it is challenging to interpret the radargram and achieve accurate information even by trained technicians.

Infrared (IR) thermography is an imaging modality that detects infrared energy emitted from an object, and exports it as temperature contour. The test procedures for bridge deck detection using IR thermography is described in ASTM D4788 (ASTM, 2013). The principle of IR thermography is to detect the irregular thermal anomalies by capturing IR radiation which is invisible to human eyes due to its longer wavelength compare to the sound surrounding (Gucunski, 2013). There are many field applications using IR thermography (Avdelidis et al., 2003; Poston et al., 1995; Stimolo, 2003). IR thermography was also applied on fiber reinforced polymer (FRP) composites to detect the delaminations between FRP and matrix (Cantini et al., 2013; Valluzzi et al., 2009). Additionally, IR thermography was employed to evaluate the historic masonry structures (Avdelidis &
Nevertheless, there are many factors leading to the errors in IR measurements. Energy loss in transmitting the radiation from object of interest and detector significantly depends on the test condition, and the accuracy of measurements largely depends on the ambient air temperature, as well as wind; distance and angle of vision also influence the accuracy of the thermal maps (Balaras & Argiriou, 2002).

Ultrasonic guided wave (UGW) is a nondestructive testing method that utilizes high frequency guided waves. The difference between guided waves and bulk waves is that the propagation of wave is confined by the boundaries. It means the boundary conditions need to be met in solving the equation of motion. In recent years, many studies basing on UGW have been carried out in the field of civil engineering. UGW was used as a tool to monitor the setting and strength gain of concrete (Borgerson & Reis, 2006, 2007; Pu et al., 2004; Reinhardt & Grosse, 2004). UGW was also used to estimate the corrosion in steel reinforced mortar (B. Ervin et al., 2006; B. L. Ervin et al., 2009; Reis et al., 2005; S. Sharma & Mukherjee, 2010). Rebar-concrete interface delamination was also assessed using UGW (D. Li et al., 2012; W. Na et al., 2002). Although, UGW seems to be a promising technique in NDE of civil infrastructures, there are still many challenges in field application. First, the heterogeneity of concrete leads to scattering and non-uniform energy leaks. Secondly, the interpretation of received signals is extremely difficult because either the wave packages superimposed or different wave modes with similar frequency coupled and there is no way to decompose those waves. Besides, the joints in concrete structures result in the
reflection, scattering and refraction of propagated waves, significantly lowering the accuracy of the measurements.

2.2 Electrical properties of cementitious materials

The electrical properties of concrete were investigated since the 1920s (Shimizu, 1928). The resistance of concrete can be measured by applying current and measuring the resulting potentials. There are two common measurement methods used in previous studies: (1) two electrodes setup for uniaxial specimen (W. J. McCarter et al., 2009) and (2) four electrodes method for surface measurement (Kessler et al., 2005; Presuel-Moreno et al., 2009; Wenner, 1916). For the former one, two circular disks or square metals are placed at each end of the cylinder, and the resistivity can be calculated as:

\[ \rho = \frac{R}{k} \]  

(2.1)

where \( \rho \) is the resistivity of the object under the test, \( R \) is the resistance of the media and \( k \) is the ratio of the cross section area to the length of specimen.

For the latter one, there are 4 equally spaced electrodes attached to the surface of the tests specimen. The two outer electrodes are used to inject current and two inner electrodes measure the electrical potential. As shown in Figure 2-1, four electrodes are equally spaced. A small alternating current is applied between the outer electrodes while potential is measured between the inner electrodes. The resistivity is then calculated by using the following equation:

\[ \rho = R \times k \]
\[ \rho = \frac{2\pi a V}{I} \]  

(2.2)

where \( \rho \) is the resistivity (\( \Omega \cdot \text{cm} \)), \( a \) is the distance between inner electrodes (cm) and \( V \) and \( I \) are RMS\(^1\) values or maximum values of voltage (volts) and current (amps), respectively.

![Figure 2-1 Wenner technique setup for measuring resistivity](image)

The electrical properties of the concrete were used for several applications including detecting setting time (Z. Li et al., 2007; Sant et al., 2006), assessing moisture content and saturation (Rajabipour et al., 2005; Weiss et al., 2012), assessing crack propagation (Pour-

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\(^1\) The value of an AC voltage is continually changing from zero up to the positive peak, through zero to the negative peak and back to zero again. Clearly for most of the time it is less than the peak voltage, so this is not a good measure of its real effect. Instead the root mean square value (RMS) which is 0.7 of the peak voltage or current is normally used.
Ghaz, 2011; Weiss et al., 2012) and characterizing chloride ion transport and penetration (Alonso et al., 1988; Polder & Peelen, 2002).

2.3 Electrical impedance tomography

The electrical properties of cementitious materials, using impedance technique, were first investigated by Hammond et al. (Hammond & Robson, 1955). The relationships between mix proportions and electrical properties of concrete were investigated and electrical model was proposed by Whittington et al. (Whittington et al., 1981). An improved method that eliminates polarization effects and capacitive reactance was proposed by Hugus et al. (Hughes et al., 1985), Hansson and Hansson carried out the experiments to measure the charge transportation and concrete resistance with both AC and DC methods (Hansson & Hansson, 1983). Electrical properties of cementitious materials was also used by McCarter et al. to monitor the moisture movement within such materials (W. McCarter & Garvin, 1989; W. McCarter et al., 2000). In addition to the application in conventional concrete structures, the effects of admixtures and other novel materials were also investigated by electrical methods (El-Enein et al., 1995; Ghrici et al., 2007; Papadakis, 2000; Shi, 2004). In recent years, inverse analysis and tomography were introduced and utilized to reconstruct the internal images of cementitious structures. EIT was used to detect damages in polymeric and steel fiber reinforced cementitious composites as well (Hou & Lynch, 2005a, 2005b, 2008). Du Plooy employed the EIT to explore the water and chloride ingress into concrete (Du Plooy et al., 2015). Karhunen et al. used EIT to detect various conductive
and non-conductive inclusions in concrete (Karhunen, Seppanen, Lehikoinen, Monteiro, et al., 2010). They also performed the studies on detecting cracks in concrete slabs and beams and the anomalies. EIT incorporated with conductive copper paint was used to detect surface damages on polymeric substrates and concrete beam (Hallaji et al., 2014). Hallaji et al. also used EIT for monitoring unsaturated moisture ingress within cement based materials (Hallaji et al., 2015).
3.1 Background

EIT is a modality that reconstructs the information of internal electrical properties of a cross section of an object, using multiple measurements from the periphery of that object (Pinheiro et al., 1999). By injecting known amplitude of current (AC or DC) and measuring the resulting electrical potential field at points sets on the boundary of the body, it is possible to "invert" such data to determine the conductivity or resistivity of the region of the body probed by the currents (National Research Council Institute Medicine, 1996). In EIT, an array of electrodes are positioned on the surface of the object and the electrodes are excited (by applying current) in pair and the potential values between the excited electrodes and the remaining ones are measured (Dyakowski et al., 2000).

The anomalies or defects inside structures lead to change of electrical properties of the object under the test. When electrical current applied externally, the electrical paths changed due to the presences of defects in the object, hence the defect could be detected. The objective of the EIT test is to identify, determine the locations, assess the dimensions and graphically present the anomalies in an object under the test.
3.2 Theory

3.2.1 Forward model

In order to inversely calculate the internal conductivity (admittivity, if in a complex case) distribution from joint information of the injected currents and resultant boundary potentials, a mathematic model that describes the relationships between current, potentials and material physical properties is required. By neglecting the capacitive and magnetic effects, the Maxwell’s equations can be simplified to the Poisson equation, which governing the steady state electrical field (Somersalo et al., 1992):

$$\nabla \cdot \sigma(x) \nabla u(x) = 0, x \in \Omega \quad (3.1)$$

Eq. (3.1) illustrates the relationship between the electrical field in a 3D domain and corresponding electrical potentials. The symbol \(x\) is 3D vector in domain \(\Omega\) and \(u\) is scalar electrical potential. The approximated model is considered accurate enough when DC or sufficiently low frequency AC is applied.

When considering the interactions between electrodes and medium surface, the complete electrode model (CEM) that was proposed and verified by Cheng et al. was proved to be most accurate (Cheng et al., 1989) approach. Later, Somersal et al. proved the existence and uniqueness of associated partial differential equation (PDE) with given boundary conditions (Somersalo et al., 1992). Assuming \(I_l\) is the current injected from the \(l\)th electrode, \(E_l\), with its contact impedance \(z_l\), \(V_l\) is the voltage on electrode \(E_l\), \(L\) is the
number of electrodes, $dS$ is oriented surface element and $\bar{n}$ is the outward unit normal vector, the boundary conditions are specified as follows:

$$V_l = u(x) + z_l \sigma \frac{\partial u(x)}{\partial \bar{n}}, x \in E_l, l = 1, 2, ..., L \quad (3.2)$$

$$I_l = \int_{E_l} \sigma \frac{\partial u(x)}{\partial \bar{n}} dS, S \in \bigcup_{l=1}^{L} E_l \quad (3.3)$$

$$\int \sigma \frac{\partial u(x)}{\partial \bar{n}} dS = 0, S \in \partial \Omega \setminus \bigcup_{l=1}^{L} e_l \quad (3.4)$$

Eq. (3.2) considers the constant potential on the electrodes and the contact impedances between electrodes and the medium; Eq. (3.3) discretizes the current pattern and fixes the total current through each electrode; and Eq. (3.4) shows that there is no current on the electrode-free surface.

Additionally, the ground level for potentials needs to be specified and the charge conservation law needs to be satisfied:

$$\sum_{l=1}^{L} I_l = 0 \quad (3.5)$$

$$\sum_{l=1}^{L} V_l = 0 \quad (3.6)$$

Given the conductivity and injected current, the forward problem is to solve the internal potential $u(x)$ and potential $U_l$ at electrodes. For Eq. (3.1)-(3.6), the analytical solutions
are only available for simplest case, thus, numerical finite element method is employed to solve the preceding equations set.

### 3.2.2 Numerical implementation of CEM

The CEM model can be formed numerically as following (Graham, 2007; Holder, 2004; Polydorides & Lionheart, 2002):

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}
\begin{bmatrix}
U \\
V
\end{bmatrix}
=
\begin{bmatrix}
0 \\
I
\end{bmatrix}
\]  
(3.7)

where \( A \) is admittance matrix, \( U \in N \) is a vector of domain potentials, \( V \in L \) is a vector of potentials on electrodes and \( I \) is a vector of current injections. \( A_{c1} \) is the global diffusion stiffness matrix, the local stiffness matrix is shown as

\[
A_{c1}(i,j) = \int_{\Omega} \sigma \nabla \phi_i \nabla \phi_j d\Omega_e \quad i, j = 1, \ldots, n
\]  
(3.8)

where \( \phi_i \) and \( \phi_j \) are the corresponding shape functions. The effect of contact impedance to nodes situated underneath the electrodes are taken into account by

\[
A_{c2}(i,j) = \sum_{l=1}^{L} \frac{1}{z_l} \int_{E_l} \phi_i \phi_j dS \quad i, j = 1, \ldots, n
\]  
(3.9)

The other two compartments have the form of:
\( A_e(i, j) = \frac{1}{(z_l)_j} \int_{E_l} \phi_l dS \quad (3.10) \)

\[
A_d(i, l) = \begin{cases} 
\frac{|E_l|}{z_l} & \text{for } i = l, i, j \in [1, L] \\
0 & \text{otherwise}
\end{cases} \quad (3.11)
\]

where \( |E_l| \) denotes the area of the surface of \( l \) th electrode. Using this method, the admittance matrix \( A \) is assembled through solving the natural boundary conditions and then augmented by complete electrode compartment \( A_e \) and \( A_d \).

In forward calculation, finite element method was adopted. The mesh samples in 2D generated with different fineness and electrodes numbers were shown in Figure 3-1 to 3-3. To avoid inverse crime, the numbers of elements in forward and inverse model used this study were 4096 and 1024, respectively.

![Figure 3-1 Meshes with 256 triangle elements for 8 electrodes](image)

*Figure 3-1 Meshes with 256 triangle elements for 8 electrodes*
Figure 3-2 Meshes with 256 triangle elements for 16 electrodes

Figure 3-3 Meshes with 256 triangle elements for 32 electrodes
3.2.3 Derivation of Jacobian basing on CEM

In this section, the derivation of Jacobian (sensitivity) matrix which relates the measured potentials and real conductivity is presented (Holder, 2004; Polydorides & Lionheart, 2002). The weak form of \( \nabla \cdot \sigma \nabla u = 0 \), for any \( \omega \) is

\[
\int_{\Omega} \sigma \nabla u \cdot \nabla \omega \, dV = \int_{\partial\Omega} \omega \sigma \frac{\partial u}{\partial n} \, dS
\]

(3.12)

where \( dV \) and \( dS \) are volume and surface elements. Substituting \( \omega \) with \( u \) yields to the power conservation formula

\[
\int_{\Omega} \sigma |\nabla u|^2 \, dV = \int_{\partial\Omega} u \sigma \frac{\partial u}{\partial n} \, dS
\]

(3.13)

Substituting Eq. (3.3) into Eq.(3.13) yields to

\[
\int_{\partial\Omega} u \sigma \frac{\partial u}{\partial n} \, dS = \sum_{l} \int_{E_l} \left(V_l - z_l \sigma \frac{\partial u}{\partial n} \right) \sigma \frac{\partial u}{\partial n} \, dS
\]

(3.14)

Combining Eq. (4.13) and Eq. (4.14) gives

\[
\int_{\Omega} \sigma |\nabla u|^2 \, dV + \sum_{l} \int_{E_l} z_l \left(\sigma \frac{\partial u}{\partial n} \right)^2 \, dS = \sum_{l} V_l I_l
\]

(3.15)

The first and second items in the left part of Eq. (3.15) stand for the power dissipated inside the medium and on surface electrode contacts, respectively. The right part stands for the
external power input. Assuming the injected current $I_l$ is constant and take perturbations $\sigma \rightarrow \sigma + \delta \sigma$, $u \rightarrow u + \delta u$ and $V_l \rightarrow V_l + \delta V_l$, keeping the first order term and ignoring higher order terms gives:

$$
\int_\Omega \delta \sigma |\nabla u|^2 \, dV + 2 \int_\Omega \sigma \nabla u \, dV + 2 \sum_l \int_{E_l} z_l \left( \frac{\partial u}{\partial n} \right) \delta \left( \frac{\partial u}{\partial n} \right) \, dS = \sum_l I_l \delta V_l
$$

(3.16)

Similarly, taking perturbations in Eq. (3.2) on the $l$th electrode $E_l$ provides

$$
\delta \left( \frac{\partial u}{\partial n} \right) = \frac{1}{z_l} (\delta V_l - \delta u)
$$

(3.17)

Using the weak formulation with $\omega = \delta u$ and substituting Eq. (3.17) in Eq. (3.16) leads to

$$
\int_\Omega \delta \sigma |\nabla u|^2 \, dV + 2 \sum_l \delta V_l \int_{E_l} \sigma \frac{\partial u}{\partial n} \, dS = \sum_l I_l \delta V_l
$$

(3.18)

By substituting Eq. (3.3) into the second item of Eq. (3.18), it can be simplified to $2 \sum_l I_l \delta V_l$, yielding the desired result

$$
\sum_l I_l \delta V_l = - \int_\Omega \delta \sigma |\nabla u|^2 \, dV
$$

(3.19)

To reveal the dependence of the potential on a vector of electrode currents $\mathbf{I} = (I_1, ..., I_L)$, the hypothetical measurement potential is written as $u(\mathbf{I}^m)$ while the potential for the $d$th
drive pattern is \( u(I^d) \). Applying the power perturbation formula Eq. (3.19) to \( u(I^d) + u(I^m) \) and \( u(I^d) - u(I^m) \) then subtracting each other gives

\[
\delta V_{dm} = -\int_\Omega \delta \sigma \nabla u(I^d) \cdot \nabla u(I^m) dV \tag{3.20}
\]

To calculate the Jacobian matrix one must choose a discretization of the conductivity. The simplest case is to take the conductivity to be piecewise constant on polyhedral elements. Considering \( \delta \sigma \) being the characteristic function of the \( i \)th element, the Jacobian (sensitivity matrix) for a fixed current pattern can be obtained

\[
\frac{\partial V_{dm}}{\partial \sigma_i} = -\int_\Omega \nabla u(I^d) \cdot \nabla u(I^m) dV = J \tag{3.21}
\]

Considering the observation noise either from equipment or environment:

\[
\delta V = J \delta \sigma + \varepsilon \tag{3.22}
\]

and

\[
\delta \sigma = J^{-1} \delta V + \varepsilon \tag{3.23}
\]

Where, \( \varepsilon \) is the combination of modelling error and measurement noise, \( \delta V = V(\sigma) - V(\sigma_0) \) and \( \delta \sigma = \sigma - \sigma_0 \) are the potentials and conductivity differences between two measurements (physical or finite element method).
3.2.4 *Inverse calculation*

The process of calculating images from captured data is called image reconstruction. There are two main challenges in reconstructing the images from EIT experimental data: non-locality and ill-posedness. In other images techniques, for example, CT-Scan, a collimated beam of radiation passed through the object under test in a straight line and the attenuation only affected by the anomaly on its path. However, in EIT, the change in the local conductivity affects the whole electrical field and imposes negligible effects on each measurement. Another challenge is the ill-posed nature, which makes the solving process extremely complicate. The physical problem is well-posed if for all admissible data, a unique solution exist and the solution depends continuously on the data (Hadamard, 2014). For well-posed problem, the solution is unique and continuously depends on the data. For ill-posed problems, however, there are many possible solutions for one set of data and small change or noise in the measured data might lead to significant changes in the solutions. The former criterion is not an issue since all materials have conductivity or resistivity. However, the later criterion creates the challenges for recovering the unknown conductivity from boundary measurements.

The algorithm used in EIT image reconstruction can be divided into linear and nonlinear. In this study, the linear Gauss-Newton (GN) method and nonlinear Total Variation (TV) with Primal Dual-Interior Point (PD-IPM) method were adopted to perform inverse calculation.
3.2.5 *Gauss-Newton method*

Although EIT inverse problem is non-linear in nature, linearized approximations have proved to be useful and widely used (Adler et al., 2009; Cheney et al., 1990; Yorkey et al., 1987). The simplest approach is to find the minimum of:

\[
\sigma^* = \text{argmin} \| V_m - F(\sigma) \|^2 
\]  

(3.24)

where \( V_m \) denotes the measured potentials from the experiment and \( F(\sigma) \) denotes the forward operator. Assume that the matrix \( F \) maps the boundary measurements \( V \) to conductivity distribution \( \sigma \), then

\[
V_m = F(\sigma) + \epsilon 
\]  

(3.25)

where \( \epsilon \) is the measurement noise. The Taylor polynomial at \( \sigma_0 \) is

\[
V_m(\sigma) = V_m(\sigma_0) + V_m'(\sigma_0)(\sigma - \sigma_0) 
\]  

(3.26)

\[+ O(\sigma - \sigma_0) \]

where \( \sigma_0 \) is reference conductivity and \( \sigma \) is the conductivity after change of state. Neglecting the higher order \( O(\sigma - \sigma_0) \) and taking perturbation yield to

\[
\delta V_m = J \delta \sigma + n 
\]  

(3.27)
where \( J \) is Jacobian matrix and \( n \) is measurement noise. Assuming \( \sigma_r \) is reference conductivity, and the Jacobian matrix can be defined as

\[
[J]_{ij} = \frac{\partial|V_m|_i}{\partial|\sigma|_j} \bigg|_{\sigma_r}
\]

(3.28)

Jacobian matrix depends on the number of elements in the finite element model (FEM), current injection pattern and complete electrode models. The number of unknown variable \( n_N \) (elements in FEM) is much larger than number of the measurements \( n_{meas} \); therefore, the matrix is underdetermined and regulation methods are employed to overcome the ill-posed issue. There are several regularization methods used for EIT, such as truncated singular value decomposition (TSVD), simultaneous iterative reconstruction techniques (SIRT) and Gauss-Newton (GN) method. All linear methods are similar in structure and different parameters are used. Iterative Gauss-Newton method is employed in this study because of its high efficiency, and its capability in implementation in fast and real-time imaging. By adding Tikhonov information (prior information), the solution become the minimization of

\[
\sigma^* = \|V^* - J\Delta\sigma\|^2 + \alpha\|T\sigma\|^2
\]

(3.29)

The objective function of GN method in terms of general Tikhonov regularization can be expressed as in a more explicit form in sum of quadratic norms (Graham, 2007)
\[ \|V^* - J\Delta\sigma\|_{\Sigma_n^{-1}}^2 + \|\sigma^* - \sigma_0\|_{\Sigma_\sigma^{-1}}^2 \]  \tag{3.30}

where \( V^* \) is the difference between simulated and measured potentials, \( \sigma^* \) and \( \sigma_0 \) are conductivity change and its expected value for all elements, respectively. \( \Sigma_n \) and \( \Sigma_\sigma \) represent the covariance matrix of the measurement noise and expected conductivity, respectively. Let \( \sigma_n \) and \( \sigma_x \) are the average amplitude of measurement noise and conductivity change, respectively, \( S = \sigma_n^2 \Sigma_n \) models the measurement accuracy, for uncorrelated noise and difference imaging, since the same number of electrodes are used in both simulated and measurement systems, thus, \( S = I \) - identity matrix. The regularization matrix \( P = \sigma_x^2 \Sigma_\sigma \) aims to model the unlikelihood of image elements (Adler et al., 2007). Then the one-step solution for Eq. (3.30) can be obtained as

\[ \sigma^* = \left( \frac{1}{\sigma_n^2} f^T S^{-1} f + \frac{1}{\sigma_x^2} P^{-1} \right)^{-1} f^T \frac{1}{\sigma_n^2} S^{-1} V^* \]  \tag{3.31}

Considering \( \lambda = \sigma_n / \sigma_x \), which is defined as regularization hyperparameter, Eq. (3.31) becomes:

\[ \sigma^* = (f^T S^{-1} f + \lambda^2 P^{-1})^{-1} f^T S^{-1} V^* \]  \tag{3.32}

The steps used to apply the iterative Gauss-Newton method are summarized as following

1) Select an initial approximation of conductivity as prior information (real conductivity of material is used in this research).
2) Based on the known current injection and geometry of the object, simulated measurements are obtained through solving the forward problem.

3) Calculate the change in conductivity $\sigma^*$, using Eq. (3.32).

4) Update the conductivity of the object

$$\sigma_{k+1} = \sigma_k + \Delta \sigma$$  \hspace{1cm} (3.33)

5) Update the admittance matrix $A$.

6) Consequentially, the Jacobian will be updated as well as the simulated potentials.

7) Select the rule to terminate the iteration, either define a threshold or set the numbers of iterations. If the rule cannot be met, return to step 2 and the iteration will be terminated when the rule is met.

8) Output is the reconstructed conductivity.

Figure 3-4 graphically shows the flow chart of whole process of EIT difference imaging using iterative Gauss-Newton method.
Figure 3-4 Flow chart of EIT imaging using iterative GN algorithm

3.2.6 Total Variation method

The PD-IPM is an algorithm based on TV functional, which was first proposed by Rudin et Al. and implemented in EIT by Chan et. al and Borsic et al. (Andrea Borsic et al., 2007; Gagne et al., 1998; Rudin et al., 1992). Its advantage over linear reconstruction algorithms is its capacity to preserve or restore discontinuities in reconstructed profiles since it does not apply smoothing on the reconstructed images. This character is important in nondestructive evaluation of civil structures. By using TV function, however, one needs to find the minimum of a non-differentiable function that cannot be directly solved by traditional optimization algorithms. Therefore, the time and hardware cost are significantly higher than linear methods.
The objective of the discretized TV regularized inverse problem with linear forward operator (denoted as primal problem) is to find the minimum of

$$\frac{1}{2} \| F(\sigma) - V_m \|^2 + \alpha \Sigma_j |L_j \sigma| \quad (P)$$

where $F$ is forward operator, $L$ is a discretization of gradient operator, $j$ stands the $j$th edge in the mesh, $V_m$ is measured potentials, and $\alpha$ is the hyperparameter that controlling the level of applied regularization.

The dual problem seeks to find the maximum of

$$\frac{1}{2} \| F(\sigma) - V_m \|^2 + \alpha y^T L \sigma \quad (D)$$

where $y \in R$ are primal variables and $\|y_i\| < 1$. Subtracting Eq. (3.35) from Eq. (3.34) provides the primal-dual gap and applies complementary condition, which nulls the primal-dual gap

$$\Sigma_j |L_j \sigma| - y^T L \sigma = 0 \quad (3.36)$$

Similarly, the numerical implementation (Andrea Borsic et al., 2007) of PD-IPM algorithm to calculate the non-linear solution seeks the minimum of

$$\frac{1}{2} \| F(\sigma) - V_m \|^2 + \alpha TV(\sigma) \quad (3.37)$$
where \( TV(\sigma) \) is the total variation of a conductivity image, defined as

\[
TV(\sigma) = \int_{\Omega} |\nabla \sigma| d\Omega \tag{3.38}
\]

The non-linear equations set of PD-IPM can be written as

\[
J^T (F(\sigma) - V_m) + \alpha L^T \sigma = 0 \tag{3.39}
\]

\[
L\sigma - Ey = 0 \tag{3.40}
\]

where \( J = \frac{\partial F(\sigma)}{\partial \sigma} \) denotes the Jacobian of forward operator \( F(\sigma) \) and it is severely rank deficient, and \( E \) is a diagonal matrix defined by

\[
E = diag(\sqrt{||L_i\sigma||^2 + \beta}), i = 1,2,...,n \tag{3.41}
\]

where \( \beta > 0 \) is smoothness parameter. Too small \( \beta \) always lead to divergence considering the fact that TV regularized problem is non-differentiable. In this study, the initial \( \beta \) was set to 0.001 and decreased for each iteration.

Then, the inverse problem can be solved iteratively by Gauss-Newton method. The conductivity update can be written as (A. Borsic et al., 2010)

\[
\delta \sigma_k = -(J_k^T J_k + \alpha L^T L)^{-1}(J_k^T (F(\sigma_k) - V_d) - \alpha L^T L \sigma_k) \tag{3.42}
\]
where $V_d = V(\sigma_k) - V(\sigma_{k-1})$, $k$ is the iteration number and $k = 1, 2, \ldots$. The iteration ends until the difference is smaller than the preset threshold.

Generally, performing reconstruction with TV functional regularizations is more expensive in hardware and time when compared to linear approaches. However, the non-linear algorithms always capture the sharp conductivity changes that will be missed in linear algorithms. Nonetheless, GN algorithms are more robust than TV methods, since GN using $l_2$ norm, which is more robust than $l_1$ norm that used in TV algorithms. Besides, the images reconstructed by GN algorithms always biased towards smoother since $l_2$ norm tends to have a smaller value (Zhou et al., 2015).
CHAPTER FOUR

DEVELOPMENT OF THE AUTOMATED MEASUREMENT SYSTEM

4.1 Introduction

An automatic measurements system was developed to perform the experiments in this study. In conducting the EIT, one of the main challenges is that running the test is time consuming since hundreds of potentials measurements are needed for a single image reconstruction. In addition, in most previous studies (Hallaji et al., 2014, 2015; Karhunen, Seppanen, Lehikoinen, Blunt, et al., 2010; Karhunen, Seppanen, Lehikoinen, Monteiro, et al., 2010), the electrodes were permanently installed on the surface of the object under investigation and in many of them the injection of current, switching electrodes and voltages measurements were performed manually or semi-automatically. Therefore, a LabView based automatic EIT measurement system with portable probes was designed and used to conduct EIT in this study. Each measurement takes 1/10 seconds and the data collection can be done in a few minutes.

4.2 Component of the system

The EIT system mainly consists of array of electrodes, current source, data acquisition system and image reconstruction software.
4.2.1 Electrodes

Electrodes are usually arranged equi-spacially around the region of interest. However, the electrodes are usually fixed in most of the previously used systems. In this study, portable electrode measurement unit was designed and built for 2D imaging system. Serrated tip spring test pins were used as the electrodes. The serrated design of these electrodes with many parallel points of contact provides redundant paths for current to flow through. This design maximizes the contact between each electrode and the surface of the specimen which as a result eliminates the necessity of permanently attaching the electrodes to the surface of the specimen. This assures good contact in most circumstances except human skin or fragile surface because of its sharpness. Figure 4-1 shows the examples of spring test pins used in this study.

![Figure 4-1 Portrait of spring contact probes with serrated tips](image_url)
4.2.2 Measurement assembly

For 2D measurement, a 150 × 150 × 10 mm plastic sheet was used as the electrode holder for both 32 pins and 16 pins setups. 32 or 16 equi-spacially holes were drilled around a circle with the diameter of 86 mm and electrodes were inserted and fixed in the holes, using epoxy glue. A wire was then soldered to the other end of each electrode for electrical connections and measurements. Figure 4-2 and 4-3 shows the details of measurement unit with 16 and 32 electrodes, respectively.

![Figure 4-2](image1.jpg)  (a) 2D measurement units with 16 electrodes and  (b) Performing measurement
Current source was utilized to inject current between electrode 1 and 2, and boundary potentials were measured between electrode pair 1-2, 2-3, …, 15-16, 16-1, for 16 electrode setup and 1-2, 2-3, …, 31-32, 32-1, for 32 electrodes setup. In this way total 16 or 32 potential readings were taken in each current injection. Then current injection was switched to the next adjacent pair of electrodes i.e. electrode 2 and 3. In this way total $16 \times 16 = 256$ and $32 \times 32 = 1024$ potential readings are captured for 16 and 32 electrodes, respectively and used as the potential database for one object. However, the potentials captured involved with current-carrying electrodes were not used in the following calculations and removed at the beginning of data processing, leading to 208 (for 16 electrodes) or 928 for 32 electrodes) effective potentials for reconstruction. Obviously, the time required for
obtaining this number of measurements, manually, was large. In this automatic system, the total required time the potential measurements, including the switching current between electrodes, was approximately 20 seconds for 16 and 80 seconds for 32 electrodes setup, respectively.

Figure 4-4 Schematic illustration of the 16 and 32 electrode arrangement for 2D measurement

4.2.4 Switch system and multimeter

The measurement system was consisted of four main components: current source, multimeter, switch system and computer. The digital multimeter and switching system adopted in this study included a Keithley model 2750 digital multimeter, data acquisition, switching and data-logging mainframe with five slots for inserting the plug-in switch/control modules. Each slot supports a series of multiplexer, matrix, or control modules. The role of the mainframe was to communicate between channels. Two separate sets of multiplexer modules were used to apply current and to measure potential. To eliminate the possible interactions between positive and negative currents, the positive and
negative outputs of the current source were connected to the independent sets of channel, i.e. positive to the first 20 channels (channels 1 to 20) and negative to the second set of 20 channels (channels 21 to 40) on one of the 7708 modules. Thus, for example, to apply positive current on electrode 1 and negative current on electrode 2, channels 1 and 21 were closed simultaneously, while the other channels stayed open. After closing the designated channels for current injection on each adjacent pair of electrodes, the potential values, resulted from the current injection on the rest of the electrodes were measured, using separate module. Figure 4-4 schematically illustrates the configuration for current injection and switching and potential measurements for 16 electrodes. Figure 4-6 shows one of the switch modules and Figure 4-7 shows the current source and switch system. If larger number of electrodes is required, more modules can be combined together to provide the appropriate number of channels.
Figure 4-5  Schematic illustration of the wiring diagram used to inject and switch current source to the adjacent electrodes and measure the potentials on the other pairs of electrodes.
Figure 4-6  Photo of switch module

Figure 4-7  Photo of current source and switch system
To combine the abovementioned components, the software, named Automated Electrical Tomography (AET), was developed using LabVIEW. This software automatically selected the electrodes for current injection, connected the current source to the electrodes by closing the appropriate channels, and then run the potential measurements on the mainframe for the rest of the electrodes. After completion of each current injection, the AET, opened all channels, switched the current injection to the next electrode pair and repeated until all the measurements were ended. The system also measured the contact resistance which included the resistance between electrodes and the surface of the object under the test, the wires and the switching system. This resistance was considered later in constructing the image from the voltage measurements. AET is capable to run the measurements continuously or with a preset interval. This feature is especially useful if the change in resistivity/conductivity with time in the material under test is of interest, i.e. monitoring chloride diffusion and moisture movement.

4.3 Control platform

The AET was used to control the measurement system. As mentioned above, certain channels were closed to realized eject current on one pair adjacent electrode pairs and simultaneously potentials between every adjacent electrode pairs were captured. Figure 4-8 shows the schematic diagram of the relationship between different components of the measurement system and the actual measurement components are shown in Figure 4-9.
Data was output in text format and imported to the MATLAB code to reconstruct the image. More details of the system can be found in the paper (Ruan & Poursae, 2016).

Figure 4-8  Schematic representation of connections between different components of automated measurement system

Figure 4-9  Component of the system with the 2D measurement
4.4 Data processing with EIDORS toolkit

The EIT image reconstructions were accomplished by EIDORS toolkit developed by Polydorides and Lionheart (Polydorides & Lionheart, 2002). The toolkit was first proposed to reconstruct images in medical field with the aim to portrait the conductivity distribution of the object under investigation. The reconstruction can be divided into two main steps: (i) forward problem and (ii) inverse problem. Before solving the inverse problem, one needs to obtain the electrical fields in order to calculate the Jacobian matrix. For simple geometries and homogeneous materials with uniform conductivity, the electrical field can be analyzed theoretically. However, that is not the case for the object presented in this work. The low conductivity and heterogeneous features of cementitious materials pose the challenge and therefore the forward problem cannot be solved analytically. Therefore, finite element method (FEM) was used. As mentioned earlier, another challenge is the ill-posed nature of inverse problem. Considering 16 electrode setup and 1024 elements mesh as example, one can collect 256 potential measurements through every adjacent electrode pair and only 208 useful measurements left by removing potentials captured with current-involving electrodes. The objective is to get the 1024 solutions from 208 known variables and this leads to the indeterministic problem. Thus, in this study prior information and regularization techniques were employed to help solutions converge. The procedures of image reconstruction can be summarized as:

1) Set basic parameters, e.g. number of electrodes, mesh density and current amplitude,
2) Create the forward model with initial conductivity guess,

3) Set parameters for forward calculation, e.g. solve algorithm,

4) Solve the forward problem upon known current amplitude, current injection and potentials measurement pattern,

5) Load experimental data to substitute data from simulation,

6) Create the inverse model,

7) Set parameters for inverse calculation, e.g. prior information, hyperparameter, number of iterations,

8) Get the solutions for each element,

9) Show the images in appropriate format and save.

The median of reconstructed conductivity of all elements was chosen to be the reference level of the output images. The reference level for each reconstructed image was presented at the middle of color bar right to each image. The reference level was also used as the threshold to filter unnecessary values. Since the presence of damages in concrete structures leads to conductivity loss, therefore, all values greater than median was forced to be the median. As a result, the conductivity values on the images are relative values not absolute values; for example, the conductivity loss of the area with the number 4 on the color scale is 2 times more than the area with number 2 in the color scale.
5.1 Surface damage with conductive paint

To verify the practicality of the EIT in detecting surface damages, three different experiments were carried out. First, 100 mm × 200 mm (4 × 8 in.) cylindrical paste specimens with water-to-cement ratio of 0.45 were cast and wet cured for 72 hours. After curing, the specimens were taken out and put in the lab for 24 hours. Then these specimens were cut into slices with the thickness of 50 mm and the top surfaces were coated by aerosol nickel based conductive paint, with the specification described in Table 5-1. Masking tape was used to create anomalies with different sizes and shapes. Specimens with longitudinal and circular anomalies shown in Figure 5-1.
Table 5-1 Properties of the conductive nickel coating (MG Chemicals, 2015).

<table>
<thead>
<tr>
<th>Properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service Temperature</td>
<td>-40 to +120 oC</td>
</tr>
<tr>
<td><strong>Uncured paint</strong></td>
<td></td>
</tr>
<tr>
<td>Viscosity at 25oC</td>
<td>100 cP</td>
</tr>
<tr>
<td>Density</td>
<td>1.24 g/mL</td>
</tr>
<tr>
<td>Flash point</td>
<td>-18 oC</td>
</tr>
<tr>
<td><strong>Cured paint</strong></td>
<td></td>
</tr>
<tr>
<td>Volume Resistivity</td>
<td>0.0042 Ω.cm</td>
</tr>
<tr>
<td>Surface Resistance 1 × coat (~1.50 mil)</td>
<td>≤0.7 Ω/sq or 1.4 S/m</td>
</tr>
</tbody>
</table>

The lengths of longitudinal anomalies were 50 mm and the widths were 1 mm, 3 mm and 5 mm. Similarly, two perpendicular stripes were created to test whether the technique was capable to identify both anomalies simultaneously. The diameters of circular anomalies were increased from 10 mm to 25 mm at the increment of 5 mm.
In addition to longitudinal and circular anomalies, more complicated case, zigzag type damages were prepared. The leg lengths for zigzags were 20 mm and 40 mm, respectively. The procedure of preparing zigzag anomalies was the same as aforementioned for regular
damages. Figure 5-2 presented the photos of specimens with zigzag anomalies. Table 5-2 summarized all the conductive paint coated specimens used in this work.

*Figure 5-2 Conductive paint covered specimens with zigzag artificial damage*
Table 5-2  
*Summarization of simulated damages on specimens coated with conductive paint*

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Damage type</th>
<th>Damage size</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stripe</td>
<td>L: 50 mm W: 1 mm</td>
<td>Vertical</td>
</tr>
<tr>
<td>2</td>
<td>Stripe</td>
<td>L: 50 mm W: 3 mm</td>
<td>Vertical</td>
</tr>
<tr>
<td>3</td>
<td>Stripe</td>
<td>L: 50 mm W: 5 mm</td>
<td>Vertical</td>
</tr>
<tr>
<td>4</td>
<td>Stripe</td>
<td>L: 50 mm W: 3 mm</td>
<td>Horizontal &amp; Vertical</td>
</tr>
<tr>
<td>5</td>
<td>Circular</td>
<td>D: 10 mm</td>
<td>3 o'clock</td>
</tr>
<tr>
<td>6</td>
<td>Circular</td>
<td>D: 15 mm</td>
<td>3 o'clock</td>
</tr>
<tr>
<td>7</td>
<td>Circular</td>
<td>D: 20 mm</td>
<td>3 o'clock</td>
</tr>
<tr>
<td>8</td>
<td>Circular</td>
<td>D: 25 mm</td>
<td>3 o'clock</td>
</tr>
<tr>
<td>9</td>
<td>Zigzag</td>
<td>L: 20 mm per leg</td>
<td>Horizontal</td>
</tr>
<tr>
<td>10</td>
<td>Zigzag</td>
<td>L: 40 mm per leg</td>
<td>Horizontal</td>
</tr>
</tbody>
</table>

To illustrate the capability of the portable unit to scan a large surface, the polyester transparent sheet with the dimension of 215.9 mm × 355.6 mm (8.5 in. × 11 in.) was also employed. Tapes were cut into stripes and circles and attached on the sheet at designated position to simulate damages. The surface of the sheet was then coated with the conductive nickel paint. As the result, the covered surface with the tape remained un-painted, while the rest of the surface was covered with a layer of paint, as shown in Figure 5-3. The portable measurement unit was positioned at different locations on the surface, as shown with the dashed lines in Figure 5-3.
5.1 Subsurface damage detection

In order to investigate the feasibility of the EIT to detect subsurface (invisible) damages in mortar structures, a set of $100 \times 200$ mm (diameter and height) mortar cylinders with water-to-cement ratio of 0.45 and 40 volume percent of fine aggregates were cast. The specimens were demolded 24 hours after casting and then wet cured for 7 days. After curing, each cylinder was cut into 4 pieces with the height of approximately 50 mm. The specimens
were left in the lab for 24 hours before performing the test. To simulate damages with different geometries and sizes four groups of specimens were prepared as followings:

Group I: In this group no damage was created on the specimens and used as the reference

Group II: In this group a polypropylene (PP) sheet, with the thickness of approximately 0.1 mm, was inserted in each mold and then mortar was cast. The sheets were inserted in three different levels in the molds to provide 10 mm, 20 mm and 30 mm distances between the top of the sheet edge to the top of the specimen. Schematic illustration of the specimens is shown in Figure 5-4a.

Group III: In this group a 3 mm saw blade was used to simulate damage with 3 mm width. Specimens were cut to create two levels of damages: 10 mm and 20 mm from the cut level to the top of the specimens. Three different combinations were used: One single cut, two parallel cuts and two cross cuts. Schematic illustrations of the specimens are shown in
Group IV: A PVC pipe with the diameter of 22 mm was embedded in the molds, 10 mm from the top of the specimen before casting to create the circular damage. Schematic illustration of the specimens is shown in Figure 5-4b and d.
Figure 5-4e.
Figure 5-4  Schematic illustration of the specimens (a) damage created, using 0.1 mm Polypropylene transparent sheet, (b, c, d) damage created by saw cut and (e) damage created by a PVC pipe
5.2 Steel fiber reinforced ultra-high performance concrete (SFRUHRC)

5.2.1 Fiber distribution of SFRUHPC

Development of modern infrastructure construction demands for high performance concrete including high strength, toughness and durability (Farnam et al., 2010; T. Xie & Ozbakkaloglu, 2015).

In 1990’s ultra-high performance fiber reinforced concrete was developed by the addition of supplementary materials, elimination of coarse aggregates, very low water to binder ratio (less than 0.25), application of super-plasticizer and addition of fine steel fiber reinforcement, (Gao, Molyneaux, and Patnaikuni, 2008). It is a special cement based material which behaves like a low porosity ceramic material and is densely packed that exhibits increased mechanical performance due to high stress and strain relationship,

Typical fibers used to reinforce concrete are steel fibers of different shapes and dimensions; glass fibers, and synthetic fibers including polypropylene, polyethylene, polyolefin and polyvinyl alcohol; carbon fibers (Brandt, 2009). Steel fibers are the most common fibers in producing ultra-high performance fiber reinforced concrete. In order to assure the reinforcing function of the fibers, uniform distribution of the fibers is necessary. However, the fibers distribution is influenced by many factors including fiber diameter, length, shape as well as the matrix composition and casting method. The fiber distribution in the structures determines the mechanical performance and reinforcement efficiency. Therefore, it is imperative to assess the distribution of fibers in the concrete. X-ray
computed tomography was harnessed to explore the fiber uniformity in concrete slabs and precast walls (Liu et al., 2013; Ponikiewski et al., 2015a, 2015b; Suuronen et al., 2013). However, as aforementioned, X-ray tomography based evaluation methods not only are expensive, but also they involve safety issues. Mason et. al performed a comprehensive study to determine the fiber orientation by non-destructive alternate current impedance spectroscopy (Mason et al., 2002). Lataste et. al utilized electrical resistance as factor to examine the steel fiber distribution in concrete slab (Lataste et al., 2008). Magnetic inductance was also used by Ferrara et. al to determine the steel fiber dispersion in concrete slab structures. In this study, the EIT was used to determine the fiber distribution in ultra-high performance steel fiber reinforced concrete.

5.2.2 Materials

Type III cement produced by ARGOS Cement Company was used to prepare the specimens. The cement was sieved by No. 50 sieve to remove the clump. Silica fume was added to the mixture with the specifications shown in Table 5-3.
Table 5-3  Properties of silica fume

<table>
<thead>
<tr>
<th>Term</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity (g/mm$^3$)</td>
<td>2.20</td>
</tr>
<tr>
<td>Surface area (m$^2$/kg)</td>
<td>20000</td>
</tr>
<tr>
<td>Particle size (μm)</td>
<td>0.15</td>
</tr>
<tr>
<td>Loss on ignition (%)</td>
<td>2.00</td>
</tr>
<tr>
<td>SiO$_2$ (%)</td>
<td>95.5</td>
</tr>
<tr>
<td>Fe$_2$O$_3$ (%)</td>
<td>0.30</td>
</tr>
<tr>
<td>Al$_2$O$_3$ (%)</td>
<td>0.70</td>
</tr>
<tr>
<td>CaO (%)</td>
<td>0.40</td>
</tr>
<tr>
<td>MgO (%)</td>
<td>0.50</td>
</tr>
<tr>
<td>Na$_2$O (%)</td>
<td>1.40</td>
</tr>
</tbody>
</table>

The fine aggregate was SC215 from Blackburg, SC with the fineness modulus of 2.71 and saturated surface dry bulk specific gravity of 2.63. The surface absorption ratio is taken as 0.5%. The steel microfibers with the dimensions of 0.2 mm in diameter and 13 mm in length, specific gravity of 7.8 g/mm$^3$ and ultimate tensile strength of 2000 MPa were used to prepare the specimens. In order to produce high strength mortar, low water to cement ratio is preferred. 1% by weight of the cementitious material of high range water reducer (Melflux 4930F manufactured by BASF) was also added to the mixture.

5.2.3 Mortar mixing

A set of 100mm × 200mm (4 × 8 in.) concrete cylinders were cast according to ASTM C31 (Standard, 2015). Water to cementitious material (cement and silica fume) ratio was equal
to 0.2 for all specimens. 20 percent of type III cement was replaced by silica fume. Two ratios -0.5 and 1.25- of sand to cementitious materials were adopted and labeled as A and B, respectively. Specimens with different percentages of steel fibers from 0 to 2 with increment 0.5 by volume were prepared. The details of mix proportion are shown in Table 5-4.

Table 5-4  Proportions of raw materials for 1 m³ concrete (Unit: Kg)

<table>
<thead>
<tr>
<th>Fiber (%)</th>
<th>S/CM=0.5 (Labeled as A)</th>
<th>S/CM=1.25 (Labeled as B)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>Cement</td>
<td>1197.6</td>
<td>1192.2</td>
</tr>
<tr>
<td>Sand</td>
<td>718.5</td>
<td>715.4</td>
</tr>
<tr>
<td>Water</td>
<td>287.3</td>
<td>286.0</td>
</tr>
<tr>
<td>Silica fume</td>
<td>239.3</td>
<td>238.7</td>
</tr>
<tr>
<td>Water reducer</td>
<td>14.4</td>
<td>14.3</td>
</tr>
<tr>
<td>Fiber weight</td>
<td>0.0</td>
<td>40.7</td>
</tr>
</tbody>
</table>

First, oven-dry sand was added into the bowl, following by cement and silica fume, the materials were dry mixed for 2 minutes at low speed (100 RPM). Then, one-third of water was added to the dry mix and mixing continued for 30 seconds. All water was then added and mixing continued for 1 minute. Mixing speed was increased to intermediate speed (300 RPM), and the mixing continued for 2 additional minutes. Then, the steel fibers were
added into the mixture and the mixing continued for another 3 minutes at medium speed (300 RPM) before casting the concrete. It should be mentioned that no tamping or vibration was involved in the whole process. 24 hours after casting, the specimens were demolded and moved to maintenance room for curing. After 28 days, all specimens were moved to laboratory and dried for 24 hours at ambient temperature before cutting and testing. The specimens were transversely cut into eight pieces and the resulting thicknesses between 20 mm to 22 mm.

5.2.4 Photo acquisition and post-processing

The photos were taken by a full frame Canon EOS 6D camera with 50 mm f/1.8 STM lens. The captured images were in JPEG format with the resolution of 5472×3648 pixels. The camera was set to manual mode, and the aperture, shutter speed and ISO were set to f/8, 1/60 and 200, respectively. Taking a picture that shows all fibers of the surface of each piece was challenging due to different orientations and thus different reflections. Therefore, extra light source was used to minimize this issue. In order to take high quality photos and capture maximum number of fibers on the surface, the following photography setup was employed. One table lamp with scattered light was used as the light source. The camera was positioned on tripod with its lens headed towards the specimen. The distance from the top surface of specimen to the bottom of lens was fixed at 30mm. The lamp positioned on the other side of the specimen, with 8° angle between the centerline of camera lens and vertical line, as well as the centerline of lamp and vertical line.
5.2.5 Procedures of photo post-processing

With the aim to quantitatively analyze fiber content in the captured photos, the photos were processed by ImageJ (Rasband, 2008), which is a Java-based image processing program developed at the National Institutes of Health. The detailed procedures of processing are shown as following

1) Open original JPEG file, Figure 5-5a,

2) Smooth the image to minimize the noise, using smooth filter in ImageJ,

3) Apply exponential operation to increase the contrast between the matrix and fibers, Figure 5-5b,

4) Convert the image to binary, Figure 5-5,

5) Use elliptical selection tool, to select the desired circular area on the photo, red circle in Figure 5-5d,

6) Measure the area percentage (the area occupied by the fibers), Figure 5-5e,
Figure 5-5  Procedures of image processing and sample results
5.3 Chloride detection in concrete slab

To test the capability of the designed EIT system for being used in large areas, with the aim to detect the chloride-contaminated area in concrete, a 900mm × 900mm concrete slab with the thickness of 100mm was cast. Eight No. 4 parallel steel rebar were embedded from each direction, 100mm from each other and 50mm from each end of the slab. During casting, a portion of mixture was contaminated with 300g of sodium chloride and the chloride-contaminated concrete was spread at upper right side of the slab (point F-6 in Figure 5-6). The slab was cured for 48 hours. Detailed mixture proportion and slump of the concrete used to cast the slab are given in Table 5-5.

In order to perform laboratory experiments, the top surface of slab was marked by 8×8 grid and data were captured at each cross point, as shown in Figure 5-6. The rebars that were parallel to vertical directions were labelled with numbers, 1 to 8 from left to right, whereas the rebars that were parallel to horizontal direction were labelled with letters A to H from top to bottom. Copper wires were soldered to the end of the rebar for electrical connections.
Table 5-5  Proportions of raw materials for 1 m³ concrete (Unit: Kg)

<table>
<thead>
<tr>
<th>Item</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I cement</td>
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</tr>
<tr>
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<tr>
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<tr>
<td>Granite #4</td>
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</tr>
<tr>
<td>Sand</td>
<td>409.9</td>
</tr>
<tr>
<td>Water reducer</td>
<td>1.1</td>
</tr>
<tr>
<td>Slump</td>
<td>76.2 mm</td>
</tr>
</tbody>
</table>


Figure 5-6  Photo of concrete slab with rebar labelled
5.3.1 Half-cell potential measurement

Corrosion half-cell potential on slab surface was also measured by copper-copper sulfate electrode (CSE). Before conductive the test, the top surface of the specimen was sprayed with tap water and a wet sponge was positioned on each spot to enhance the interface contact between the CSE and the surface of the slab.

5.3.2 Resistivity measurement

A four-probe Wenner resistivity meter was used on top surface of the slab to measure the resistivity of concrete. To minimize the error and possible influence of the direction of the embedded rebar, the resistance tests were conducted 4 times at each joints; i.e. 0° (parallel to rebar in horizontal), 45°, 90° (parallel to rebar in vertical) and 135°. Then, the average of four measurements was taken as the resistivity at each point.

5.4 EIT testing

The first step was to cover the tips of spring pins with the electric conductive gel to enhance electrical connections. When the measurement unit was placed on the top surface of the specimens, additional steel weight was applied to improve the contact as shown in Figure 5-7. Next step was to set the parameters for current injection, such as current amplitude and voltage limit through the front panel of current source. The following steps were setting the file path for measured data and starting the LabVIEW program. Similarly, as experiments on specimens with conductive coating, the conductive gel was applied to the
tip of each electrode, to enhance electrical contact. The measurement unit was then placed on top of the unpainted surface on the specimen and the measurements were carried out.

![Image of measurement unit](image)

*Figure 5-7 Performing test on specimens with top surface coated by conductive paint*

For the steel fiber reinforced concrete specimens, 16 electrodes measurement unit was used and the amplitude of injected current was set to 0.1 mA. It should be mentioned that the mortar slices were in dry condition. Conductive gel was also used to improve the electrical contact.

The EIT was carried out on the top surface of the concrete slab with a 16 electrode measurement unit, as shown in Figure 5-8. The EIT was conducted at every cross point. Thus, the 64 measurements was carried out each time. The amplitude of injected current adopted was set to 10μA.
Figure 5-8  Experiment setup for EIT test on top surface of concrete slab
CHAPTER SIX

RESULTS AND DISCUSSIONS

6.1 Surface damage detection

Figure 6-1 shows the actual photos of the specimens with longitudinal anomalies as well as their reconstructed images. The images were reconstructed by both linear GN and nonlinear TV methods. The locations of the simulated damages were successfully identified. Furthermore, the severity of damage (not coated area on each specimen) could be estimated by the color of anomalies in the images. The double perpendicular damages were also identified with both algorithms. It can also be observed that images reconstructed by TV method conserved more useful information at the discontinuities than images reconstructed by GN method, and this indicated its capacity on reconstructing the damage shapes. Although the location and the shape of the damages could be determined using both algorithms, the damage size was difficult to be estimated.
Figure 6-1 Photo and reconstructed images for specimens with longitudinal anomalies
For circular anomalies, the photos of specimens and corresponding reconstructed images were shown in Figure 6-2, the images reconstructed from both algorithms captured all the anomalies even the smallest one. GN method showed better capacity in reconstructing the shapes of damages while TV method inaccurately identified the circular damages as square anomalies.
Figure 6-2  Photo and reconstructed images for specimens with circular anomalies
Figure 6-3 shows the photo of specimens with zigzag anomalies and their corresponding images reconstructed by EIT. For smaller size with leg length of 20 mm, both algorithms were capable to identify the existence of anomalies, as well as approximate location of the damage. However, neither algorithm could recover the shape of anomalies. Larger anomaly with leg length of 40 mm was also recognized but not as good as the smaller one with several fake identifications, the possible reason was that the relatively large stripes significantly disturbed the electrical fields.

Figure 6-3  Photo and reconstructed images for specimens with zigzag anomalies
Although both GN and TV methods were able to identify the damages, GN method presented much better capacity in damage indications with less fake identifications. However, in the case of complex shapes such as the zigzag ones, EIT showed limitation and was not capable to identify these anomalies.

Figure 6-4 shows the reconstructed images of the polyester transparent sheet with artificial damages. Both TV and GN methods were employed. All damages on this sheet could be identified. The two images in the middle of sheet represented the intact areas and only showed noise. As can be seen, the images reconstructed from TV method revealed more improper elements compared to that reconstructed with GN method whereas GN method presented much better damage indications with less fake identifications and all four simulated damages were detected. The circular damage on top right were also successfully identified with accurate location. While, the wide stripe damage on bottom right was identified as large circle, which is not accurate. The possible source of error might be the limitation of EIT in identifying relatively large anomalies.
Figure 6-4  Painted plastic sheet and corresponding images reconstructed by (b) TV (c) GN
6.2 Subsurface damage detection in two dimension

Figure 6-5 shows the photo of the reference specimen (Group I) without damage and its reconstructed image. As it was expected, the reconstructed image showed uniform conductivity distribution in most of the specimen surface area except the boundaries of the specimen. This observation was attributed to the boundary effect in electrical field due to contact resistance.

![Figure 6-5 Reference specimen and (b) its reconstructed image](image-url)
Figure 6-6 shows the reconstructed images of group II specimens. Similar to Figure 6-5, the conductivities at boundary were slightly lower than those in the center of each specimen. As can be seen, the distance of the damage to the surface of the specimen had impacts on the detectability of the damage. As shown in Figure 6-6a, the damage 10 mm below the surface was easily detected. By increasing the distance of the damages area to the surface of the specimen, the color representing the damage became lighter and unclear. Another issue was that the identified damage widths in the reconstructed images were not comparable with the actual width (i.e. 0.1mm); however, the locations of the damages were reasonably identified.
Figure 6-6 Photos and corresponding reconstructed images of specimens with damages created using embedded plastic sheet with (a) 10mm (b) 20 mm and (c) 30 mm, below the top surface
Figure 6-7 shows the specimens and their reconstructed images with 3 mm damage, created using saw blade (Group III). The locations of the damages in all cases were identified on the reconstructed images. As can be seen, by increasing the depth of the damage, the length of the damage shown in the images decreased. The shape of the damages curved on the reconstructed images. Additionally, the indications became weak, as the damage went deeper.
Figure 6-7  Photos and corresponding reconstructed images of specimens with single saw cut damage 10mm (a and b), 20 mm (c), below the top surface
The images of two damages in one specimen could also be captured as shown in Figure 6-8. Similar phenomenon was observed. The deeper damages lead to lighter color. Also, the boundary effects can be seen in these images. The tests of this group showed the capability of the EIT in detecting multiple damages simultaneously.

Figure 6-8 Photos and corresponding reconstructed images of specimens with double saw cut damage 10mm (a), 20 mm (b), below the top surface
Figure 6-9 shows the specimen with the circular damage created by PVC pipe and its reconstructed image (Group IV). As can be seen, both the location and dimension of the damage were accurately identified. Unlike the longitudinal damages, the size of the damage on the reconstructed image was comparable with the actual circular damage.

*Figure 6-9  Specimen with circular damage and its reconstructed images*
6.3 Assessment of steel fiber distribution in UHPC

The objective of this test was to show the capability of the EIT technique in detecting the spatial distribution of steel fiber in UHPC.

6.3.1 Flowability test

Flowability is a crucial parameter that poses significant influence on fiber settlement. Considering the fact that the density of steel fiber is much more than the concrete, tamping or vibration was not performed during mixing process to avoid man-made segregation. Instead, high range water reducer was used to make the mix to be self-consolidating. To measure the flowability, a standard cone with the diameter of 100 mm was placed at the middle a square PVC plate with length 60mm. The fresh concrete was poured into the cone, and after leveling the surface, the cone was removed. After 30 seconds, the diameters at 0°, 45°, 90°and 135° were measured and recorded. Figure 6-10 showed the flowability of two mixes used in this study. As can be seen, for Mix A (dot in plot), the flow of mix decreased as the fiber percentage increased. When 0.5% fiber was added, the decrease of flow was about 20%. The flow of the mix containing 1% fiber was close to the mix containing 0.5%. A sharp drop (~25%) was observed when the fiber percentage increased from 1% to 1.5%. The flow of mix with 2% fiber is close to the mix with 1.5% fibers. The flow of mix B (circle in plot) slightly decreased as more fibers added into the mix.
6.3.2 Compressive strength test

Figure 6-11 presented the 7 days compressive strength of mix A with different fiber percentages. As can be seen, the compressive strength increased as more fibers added into the mixture. For the mix without reinforcing fibers, the compressive strength is more than 50 MPa. The compressive strength of mix containing 2% fibers is twice than that in the mix without fibers, which indicates the significant contributions of fibers to the compressive strength. The 28 days compressive strengths of Mix A are presented in Figure 6-12. Similar to 7 days, the compressive strength increased as more fibers contained in the mixture. Figure 6-13 and Figure 6-14 show the 7 days and 28 days compressive strengths of Mix B, respectively.
Figure 6-11  Compressive strength of Mix A at 7 days

Figure 6-12  Compressive strength of Mix A at 28 days
Figure 6-13  Compressive strength of Mix B at 7 days

Figure 6-14  Compressive strength of Mix B at 28 days
6.3.3 Image analysis

In order to assess the spatial distribution of fibers, image analysis were carried out with the aid of imageJ. Percentage of the surface area occupied by the fibers, area percent, at each layer were extracted for analysis. As described earlier, the fiber reinforced mortar cylinder was cut into 8 pieces with the thickness of approximately 22mm. Fiber area percentages were extracted for each slices and the average of this percentage versus fiber percentage were shown in Figure 6-15. As can be seen, the fiber area percentage value increased linearly with the increase in fibers content in the specimens. Also, the slopes of this increase for Mix A is higher than that of Mix B and the slopes were used as the coefficient to normalize the results shown in following figures.
Figure 6-15  *Area ratio versus actual fiber content for both mix A and mix B*

Figure 6-16 shows the fiber area percent versus the layers (slices) for each fiber content in mix A. Layer 1 represented the slice form the top of each specimen and layer 8, represented the bottom slice of each specimen. As can be seen, generally the trends for both mixes with 0.5% fibers were almost parallel to the horizontal axis, indicating the fibers were uniformly distributed from top to bottom and there was no significant fiber settlement. For mix A, 1%, 1.5% and 2% fiber contents behaved similarly, i.e. the fiber distribution was increased from layer 1 to layer 8. Mixtures with 1.5% reinforcing fibers showed the largest slope which indicated most settlement of fibers compared to the other fiber contents.
Figure 6-16 Normalized area ratio versus layer from top (layer 1) to bottom (layer 8) for Mix A
Figure 6-17 shows the fiber area percent versus the layers (slice) for each fiber content in mix B. For specimen containing 0.5% and 1% fibers, the curves were almost parallel to the horizontal axis, indicating the fibers were close to uniform distribution. However, the negative slope for mixtures containing 1.5% and 2% fibers indicated that more fibers existed in layers at top than at the bottom. This observation was attributed to the low flowability in mix B compared to that in mix A that prevented the mixtures being mixed thoroughly.

![Figure 6-17: Fiber area percent versus layer from top (layer 1) to bottom (layer 8) for Mix B](image)

*Figure 6-17  Fiber area percent versus layer from top (layer 1) to bottom (layer 8) for Mix B*
6.3.4 Electrical impedance tomography measurement

EIT measurement was also carried out to investigate the capability of EIT in assessing the fiber distribution in UHPC. The study was carried out based on the assumption that the addition of fibers changes the conductivity distribution of the object. The objective was to inversely determine the fiber inclusion basing on the reconstructed conductivity map. As illustrated in Section 3.2, EIT image reconstruction was consisted by forward calculation and inverse calculation. FEM was commonly used in forward calculation and provide the reference for the following inverse calculation. In this study, one additional step was proposed to improve the accuracy of the reconstructed images. Two slices were taken from the middle of specimens without reinforcing steel fibers and the corresponding EIT images were reconstructed. Those conductivity maps were then used as reference. The index of conductivity map was scaled by the color bar right to the images, the closer to the top (in red), the higher the conductivity compared to the reference. In addition to qualitative analysis, mean conductivity difference was calculated and used for preforming quantitative analysis. The mean conductivity difference is the difference between the average conductivity of the specimen under test and the average conductivity of the reference specimens.

Figure 6-18 shows reconstructed images for all layers from one specimens of Mix A containing 0.5% fibers. All slices showed higher conductivity than the reference, indicating presence of the fibers. However, as can be seen, by moving towards the bottom of the
specimen, the conductivity increased, meaning that steel fibers segregated and settled at the bottom part of the specimen. Figure 6-19 shows the quantitative results which are in similar behavior.

Figure 6-18  Reconstructed image for specimen Mix A with 0.5% steel fiber

Figure 6-19  Mean conductivity difference for Mix A with 0.5% steel fiber

108
Figure 6-20 and 6-21 showed the reconstructed images for all layers from one of the specimens with Mix A containing 1% fibers and the mean conductivity difference, respectively. The two layers at the bottom displayed much higher conductivity than upper layers. Nonetheless, the high conductivity as well as the mean conductivity difference of 7th and 8th layers indicated partial fibers segregation.

Figure 6-20  Reconstructed image for specimen Mix A with 1% steel fiber
Figure 6-21  Mean conductivity difference for Mix A with 1% steel fiber
Figure 6-22 and 6-23 show the reconstructed images for all layers from one of the specimens with Mix A containing 1.5% fibers and the mean conductivity difference, respectively. As can be seen, the 5th and 6th layers showed higher conductivity than other layers, indicating more fibers than other layers, whereas the two layers at bottom had less fiber than other layers. It can be hypothesized that as more fibers added into the mixture, the flowability decreased. As a result, more fibers entangled together and they were not able to settle down.

*Figure 6-22  Reconstructed images for specimen Mix A with 1.5% steel fiber*
Figure 6-23  Mean conductivity difference for Mix A with 1.5% steel fiber
The reconstructed images for layers from specimens with Mix A and 2% reinforcing fibers are shown in Figure 6-24. All layers had higher conductivity than the reference specimen. The top three layers showed lower conductivity compared to other layers. The Mean conductivity difference in Figure 6-25 also indicated the same pattern as the images.

Figure 6-24  Reconstructed images for specimen Mix A with 2% fiber
Figure 6-25  Mean conductivity difference for Mix A with 2% steel fiber
Figure 6-26 presented the qualitative images for specimen with Mix B and 0.5% fibers. All layers showed higher conductivity than the reference specimen. The two layers at the bottom exhibit higher conductivity than the other layers. This also was shown by the mean conductivity difference in Figure 6-27.

Figure 6-26  Reconstructed images for specimen Mix B with 0.5% fiber
Figure 6-27  Mean conductivity difference for Mix B with 0.5% steel fiber
Figure 6-28 showed the conductivity map for layers from Mix B with 1% steel fibers. Similar as last set, all layers displayed higher conductivity than the reference specimen. Images from the 5th and 6th layers showed higher conductivity than the other layers, indicating more fibers in those layers compared to the other layers. This trend can also be found in the mean conductivity difference in Figure 6-29.

*Figure 6-28  Reconstructed images for specimen Mix B with 1% fiber*
Figure 6-29  Mean conductivity difference for Mix B with 1% steel fiber
The conductivity maps for 1.5% fibers inclusion in mix B are presented in Figure 6-30. All layers showed similar conductivity except layers 1 and 8 (the top and bottom layers, respectively) Layer 1 showed lower conductivity, indicating less fibers and layer 8 showed higher conductivity, indicating more fibers compared to other layers. The mean conductivity difference, Figure 6-31, also indicates similar pattern.

*Figure 6-30  Reconstructed images for specimen Mix B with 1.5% fiber*
Figure 6-31 Mean conductivity difference for Mix B with 1.5% steel fiber
The conductivity maps for 2% fibers inclusion in mix B are presented in Figure 6-32. The light color for layer 1 (top layer) indicated less fibers embedded in this layer. The color maps of other 7 layers were similar. From Figure 6-32 and 6-33, it can be concluded that fibers were almost uniformly distributed along the height of the specimen except the top layer.

*Figure 6-32  Reconstructed images for specimen Mix B with 2% steel fiber*
In general, the results indicated that Mix B showed more segregation of steel fibers compared to Mix A and the distribution of fibers in Mix A was more uniform. These results are in agreement with the results from image analysis.
6.4 Chloride diffusion in concrete slab

6.4.1 Half-cell potential and resistivity measurements

Half-Cell potential tests were carried out to evaluate chloride contaminated concrete slab. In this study, potential contour was used to display the test results. The first test was performed one month after casting and the results are shown in Figure 6-34a. The results of the following tests, shown in Figure 6-34c to f, which indicated expansion in the chloride contaminated area.
Figure 6-34 Potential contour maps from half-cell potential test (Unit: mV) on the concrete slab
The concrete resistivity was also measured at the same day as half-cell potential tests using by the Wenner method. As shown in Figure 6-35, the chloride contaminated area can also be clearly identified. In the first month after casting (Figure 6-35a), the resistivity at chloride contaminated area was about 5 kΩ while this value in the intact zone was about 15 kΩ/cm². One month later, the resistivity at both zones increased to 8 kΩ/cm² and 23 kΩ/cm², respectively. It was interesting to find that the resistivity went up at the end of third month (Figure 6-35c) and dropped dramatically the following month (Figure 6-35d). The results captured at six months, corresponding to Figure 6-35e, were slightly higher than those obtained in third months. Figure 6-35f showed that the resistivity kept increasing in the past two months.
Figure 6-35 Resistivity contour plots from Wenner measurements (Unit: kΩ/cm²)
6.4.2 Electrical impedance tomography

Four months after the concrete slab was cast, EIT tests were performed to investigate its potential application in chloride detection in large slab. The results were presented in three forms: (1) contour plot of the mean resistivity shown in Figure 6-36, (2) conductivity reconstructed images shown in Figure 6-37, and (3) contour plot of mean conductivity in Figure 6-38.

For resistivity contour map, 16 resistances between every adjacent electrode pairs were measured and the average was taken. As can be seen in Figure 6-36, the plot identified the chloride contaminated area well. Furthermore, the location and shape of chloride contamination zone was close to that captured by the Wenner resistivity test. It should be noted that the unit of resistance captured by the EIT system was ohm. Figure 6-37 presented the conductivity reconstructed image at every cross points. The location of the chloride contaminated area is shown by a red dashed ellipse. The main issue of this plot was that the contrast was not clear enough and no useful conclusion can be reached. The contour plot of mean conductivity, calculated from the reconstructed images, was shown in Figure 6-38. Similar shape of chloride contaminated area was identified with bright yellow color. These results showed the potential of implementing EIT in detecting chloride detection in large specimens. It can be hypothesized that the large amount of data collection in the EIT compared to the conventional resistivity method can minimize the error and enhance the quality of the image.
Figure 6-36 Contour plot of mean resistivity (Unit: Ω)
Figure 6-37 Mapping from EIT reconstructed images (dark blue means low conductivity)
Figure 6-38  Contour plot of the mean conductivity
CHAPTER SEVEN

SUMMARY

7.1 Automated measurement system

The automated measurement unit is portable and can be used on different objects without the need of being attached permanently. The system allows continuous measurement, which is meaningful for monitoring changes of the electrical properties of the object, such as moisture movement, chloride diffusion, cement hydration, etc. The system described in this study was successfully used to construct 2D images from specimens with surfaces painted with conductive paint and unpainted specimens.

7.2 Surface damage detection

With the aid of conductive paint, the location and shape of damages with different shapes were identified. Results indicated that the TV methods could better conserve the sharp changes in the object of interest compared to the GN method. It was also shown that both algorithms were capable to identify the locations of damages. The study on large surface was also carried out and the proposed technique could identify the simulated damages. GN method is more attractive to detect large surface since less error involved in reconstructed images compared to that in TV method.
7.3 Subsurface damage detection

In this study, the feasibility of implementing EIT in identifying the subsurface damage in concrete was demonstrated. Damages with different sizes and geometries were artificially created in mortar specimens. The reconstructed images obtained from EIT clearly showed the locations and approximate geometries (longitudinal versus circular) of the damages. While the size of the longitudinal damages could not be estimated using the reconstructed image, and the size of the damages on the reconstructed image from the circular image was comparable with the actual damage. Results indicated that this modality has limitations on identifying deep damages. However, in this study a constant current was used in all measurements. Increasing the amplitude of injected current might improve the resolution of the images. In addition, the boundary effects could be removed if the larger specimens were used. Results also indicated the efficiency and reliability of the automated measurement system with the portable measurement unit used in this study. It should be emphasized that, all specimens were cast with normal water-to-cement ratio and treated as regular mortar cylinders. Increasing water-to-cement ratio, adding conductive materials in mixture, using conductive paint on the surface and saturating specimens are some of the approaches that previous investigators used to improve the precision of the images. While these methods can enhance the quality of images, they are not suitable for use in the field. Though, the results presented in this study were preliminary results, they showed the potential of the EIT as a promising nondestructive tool to determine subsurface damages in a real concrete structure.
7.4 Fiber detection in UHPC

The fiber spatial distribution was investigated from two perspectives: slice surface and bulk conductivity. Image analysis technique was utilized to analyze the fiber density from top surface. The results validated that the proposed image analysis technique was capable to depict the distribution of steel fibers at different levels. The limitation of image analysis method was that only the fibers that were visible on top surface could be analyzed. It was concluded that this method could approximately access the trend of fiber distribution.

The conductivity image as well as the mean conductivity value for each layer was obtained using the data from EIT test. The reconstructed conductivity image for each slice showed the fiber inclusions. The mean conductivity values- quantitatively measured the fiber percent at each level and it corresponded well with EIT images. The results indicated the EIT is an effective tool for assessing fiber spatial distribution and mean conductivity is a reliable indicator.

7.5 Chloride contaminated area detection

Conventional half-cell potential test and four probe resistivity technique were carried out to investigate the area that contaminated by chloride. EIT tests were also performed and compared to results from these methods techniques. Contour maps were plotted using the data from all methods. The location of the chloride-contaminated area was successfully determined by all techniques. However, the map of mean conductivity at every cross point, obtained from the EIT test, showed clearer indication of the chloride contaminated area.
compared to the maps obtained from the results of both half-cell potential and resistivity measurements.
CHAPTER EIGHT

FUTURE WORK AND RECOMMENDATIONS

EIT technique was proved to be a promising NDE tool for being used in cementitious material structures. However, the efforts of improving the accuracy and image resolution are needed. Future work can be summarized as following:

- Considering the hypothesis that higher current density improves the accuracy and inherent low conductivity of cementitious materials, using powerful current source is recommended for future studies.

- One of the main challenges of EIT is the ill-posed feature of inverse problem. Considering the complexity and heterogeneity of the cementitious materials, investigating other advanced regularization algorithms is imperative.

- The studies in this work were mainly focused on electrodes in circular arrangement. However, other types of electrodes arrangements, such as square, rectangular and arbitrary arrangement needs to be investigated to meet the needs of complicate geometry of cementitious structures.

- The implementation of EIT in damage detections in other materials used in civil infrastructures, such as carbon fiber reinforced polymer laminates, carbon fiber sheet delamination for concrete repair and corrosion detection in steel structures need further investigation.
- The preliminary results of the feasibility of using EIT on large slab were presented in this work. However, only small circular measurement setup was used in this work. Other approaches such as using larger measurement setup and using the rebars as the electrical media are suggested for future investigation.

- In this study, the current was applied on the adjacent electrodes. Other options such as opposite current injection might improve the quality of the images.

- Only direct current was used in this investigation. Using alternative current might improve the quality of the images although the analysis of the alternative current field is more challenging and further efforts are needed.
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151


