DEVELOPING AN ENHANCED TRIAXIAL TESTING SYSTEM WITH CYCLIC PORE-PRESSURE CAPABILITIES

By

JEFFREY WADE FRANK

A THESIS PRESENTED TO THE GRADUATE SCHOOL OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING

UNIVERSITY OF FLORIDA

2004
ACKNOWLEDGMENTS

I would like to acknowledge my advisor, Dr. Bjorn Birgisson, for his supervision and genuine regard for research and the development of young engineers. His experience and excitement in the field of engineering inspired me to pursue a master’s degree under his guidance. I would also like to thank Dr. Frank Townsend and Dr. Reynaldo Roque, for the wealth of knowledge they shared with me and countless colleagues. All of these individuals are truly mentors in the purest sense of the word.

I extend my gratitude to George Lopp, whose tireless efforts and engineering expertise kept the laboratory and my research functioning. George first got me to think of pursuing a master’s degree when I worked for him at the Florida Department of Transportation. His friendship is truly boundless and for this, I thank him.

To everyone in the Materials Group at the University of Florida with whom I shared late hours, difficult work, and many enjoyable times, I would like to extend my sincere gratitude. Special thanks go to Dr. Yusuf Mehta, D.J. Swan, Mike Wagoner, Tom Grant, Oscar Garcia, Claude Villers, Tait Karlson, Adam Jiliardo, and Minh Le (for his contribution of work for complex modulus testing). I learned more from them than I could ever have hoped.

Finally, and most especially, I would like to thank the people who have given the most during this time in my life: my wife, Amy; and daughter, Sara. Their love, support, and understanding allowed me to finish this thesis.
# TABLE OF CONTENTS

ACKNOWLEDGMENTS .................................................................................................. ii

LIST OF TABLES ............................................................................................................ vii

LIST OF FIGURES ......................................................................................................... viii

ABSTRACT ....................................................................................................................... xi

CHAPTERS

1 INTRODUCTION ........................................................................................................1
  1.1 Problem Statement ...............................................................................................1
  1.2 Objective ..............................................................................................................2
  1.3 Scope ....................................................................................................................3

2 LITERATURE REVIEW .............................................................................................4
  2.1 Triaxial Systems Presently Used ...........................................................................4
  2.2 Compression Testing with a Triaxial Cell .............................................................6
  2.3 Tension Testing with a Triaxial Cell .....................................................................7

3 TESTING EQUIPMENT DESIGN ............................................................................20
  3.1 Introduction .........................................................................................................20
  3.2 Design Considerations .........................................................................................22
  3.3 Construction and Design ......................................................................................26
      3.3.1 Enhanced Triaxial Testing System Design ................................................26
          3.3.1.1 Design-parameter determination .....................................................27
          3.3.1.2 Piston-assembly design .................................................................30
          3.3.1.3 Top and base-plate design ..............................................................34
          3.3.1.4 Strut design ......................................................................................37
          3.3.1.5 End-platen design ............................................................................40
          3.3.1.6 Confining cylinder design ...............................................................43
          3.3.1.7 Confining ring design .....................................................................44
          3.3.1.8 Radial LVDT-holder design............................................................45
          3.3.1.9 Seal selection and placement ...........................................................46
          3.3.1.10 Instrumentation ports ....................................................................48

iii
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3.1.11</td>
<td>Component tolerance specification</td>
<td>49</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Fluid Distribution System</td>
<td>50</td>
</tr>
<tr>
<td>3.3.3</td>
<td>Water Conditioning Systems</td>
<td>53</td>
</tr>
<tr>
<td>3.4</td>
<td>Targeted Testing</td>
<td>54</td>
</tr>
<tr>
<td>4</td>
<td>TESTING METHODOLOGY</td>
<td>56</td>
</tr>
<tr>
<td>4.1</td>
<td>Test-Specimen Preparation</td>
<td>56</td>
</tr>
<tr>
<td>4.2</td>
<td>Saturation Procedures and B-Value Determination</td>
<td>57</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Introduction</td>
<td>57</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Saturation Procedure</td>
<td>57</td>
</tr>
<tr>
<td>4.2.2.1</td>
<td>Discussion</td>
<td>57</td>
</tr>
<tr>
<td>4.2.2.2</td>
<td>Procedure</td>
<td>58</td>
</tr>
<tr>
<td>4.2.2.3</td>
<td>Verification of saturation</td>
<td>61</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Determination of the B-Value</td>
<td>61</td>
</tr>
<tr>
<td>4.2.3.1</td>
<td>Theory of testing</td>
<td>61</td>
</tr>
<tr>
<td>4.2.3.2</td>
<td>Procedure</td>
<td>64</td>
</tr>
<tr>
<td>4.3</td>
<td>Hydraulic Conductivity</td>
<td>64</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Introduction</td>
<td>64</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Falling-Head Hydraulic Conductivity Test</td>
<td>68</td>
</tr>
<tr>
<td>4.3.2.1</td>
<td>Theory of testing</td>
<td>68</td>
</tr>
<tr>
<td>4.3.2.2</td>
<td>Test procedure</td>
<td>71</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Constant-Head Hydraulic Conductivity Test</td>
<td>73</td>
</tr>
<tr>
<td>4.3.3.1</td>
<td>Theory of testing</td>
<td>73</td>
</tr>
<tr>
<td>4.3.3.2</td>
<td>Procedure</td>
<td>76</td>
</tr>
<tr>
<td>4.4</td>
<td>Compression Testing</td>
<td>79</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Theory of Testing</td>
<td>79</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Specimen Preparation</td>
<td>80</td>
</tr>
<tr>
<td>4.4.3</td>
<td>Test Procedure</td>
<td>80</td>
</tr>
<tr>
<td>4.5</td>
<td>Resilient Modulus</td>
<td>81</td>
</tr>
<tr>
<td>4.5.1</td>
<td>Theory of Testing</td>
<td>81</td>
</tr>
<tr>
<td>4.5.2</td>
<td>Specimen Preparation</td>
<td>81</td>
</tr>
<tr>
<td>4.5.2.1</td>
<td>Instrumentation</td>
<td>81</td>
</tr>
<tr>
<td>4.5.2.2</td>
<td>Initial conditions</td>
<td>83</td>
</tr>
<tr>
<td>4.5.3</td>
<td>Test Procedure</td>
<td>83</td>
</tr>
<tr>
<td>4.6</td>
<td>Complex Modulus</td>
<td>85</td>
</tr>
<tr>
<td>4.6.1</td>
<td>Theory of Testing</td>
<td>85</td>
</tr>
<tr>
<td>4.6.2</td>
<td>Specimen Preparation</td>
<td>86</td>
</tr>
<tr>
<td>4.6.2.1</td>
<td>Instrumentation</td>
<td>86</td>
</tr>
<tr>
<td>4.6.2.2</td>
<td>Initial conditions</td>
<td>86</td>
</tr>
<tr>
<td>4.6.3</td>
<td>Test Procedure</td>
<td>87</td>
</tr>
<tr>
<td>4.7</td>
<td>Extension Testing</td>
<td>88</td>
</tr>
<tr>
<td>4.7.1</td>
<td>Theory of Testing</td>
<td>88</td>
</tr>
<tr>
<td>4.7.2</td>
<td>Specimen Preparation</td>
<td>89</td>
</tr>
<tr>
<td>4.7.2.1</td>
<td>Instrumentation</td>
<td>90</td>
</tr>
<tr>
<td>4.7.2.2</td>
<td>Initial conditions</td>
<td>90</td>
</tr>
<tr>
<td>4.7.3</td>
<td>Methods of Testing Procedure</td>
<td>91</td>
</tr>
</tbody>
</table>
4.7.3.1 Theoretical expectations for failure ................................................. 91
4.7.3.2 Observed testing difficulties ............................................................ 92
4.7.3.3 Variations of testing protocol .......................................................... 93

5 SPECIMEN HEATING AND COOLING PROCEDURES ............................... 100

5.1 Introduction .......................................................................................... 100
5.2 Specimen Set-up for Calibration .......................................................... 101
5.3 Method of Cooling and Heating Calibration ......................................... 104
  5.3.1 Cooling Calibration Results .............................................................. 105
  5.3.2 Heating Calibration Results ............................................................... 107
5.4 Summary .............................................................................................. 108

6 TESTING RESULTS ....................................................................................... 110

6.1 Determination of the $B$-value ............................................................... 110
6.2 Hydraulic Conductivity .......................................................................... 110
  6.2.1 Falling-Head .................................................................................... 110
  6.2.2 Constant-Head ................................................................................ 112
  6.2.3 Conclusions .................................................................................... 114
6.3 Compression .......................................................................................... 115
  6.3.1 Test Results .................................................................................... 115
  6.3.2 Conclusions .................................................................................... 119
6.4 Resilient Modulus .................................................................................. 120
  6.4.1 Test Results .................................................................................... 120
  6.4.2 Conclusions .................................................................................... 123
6.5 Complex Modulus .................................................................................. 127
  6.5.1 Results of Specimens Tested at 40°C ................................................. 128
  6.5.2 Results of Specimens Tested at 10°C ............................................... 129
  6.5.3 Conclusions .................................................................................... 129

7 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS ........................ 137

7.1 Summary .............................................................................................. 137
7.2 Conclusions .......................................................................................... 137
7.3 Recommendations ................................................................................ 138
  7.2.1 Recommendations for Testing Procedures ....................................... 138
  7.2.2 Recommendations for ETTS Construction and Design ..................... 140

APPENDIX

A TRIAXIAL CELL FABRICATION DRAWINGS ............................................. 143

B CONSTANT-HEAD HYDRAULIC CONDUCTIVITY EQUATION
   DERIVATION FOR USE WITH THE ENHANCED TRIAXIAL CELL ............. 158

C TESTING PROTOCOLS ............................................................................... 162
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1.  Nitrile O-ring Schedule</td>
<td>48</td>
</tr>
<tr>
<td>3-2.  Enhanced Triaxial Testing System Specifications</td>
<td>55</td>
</tr>
<tr>
<td>4-1.  Job Mix Formula for Coarse-Graded Granite Mix (C1)</td>
<td>56</td>
</tr>
<tr>
<td>4-2.  Resilient Modulus Testing Sequence</td>
<td>85</td>
</tr>
<tr>
<td>4-3.  Data Recording Interval Per Testing Frequency</td>
<td>88</td>
</tr>
<tr>
<td>6-1.  Data for the $B$-value</td>
<td>110</td>
</tr>
<tr>
<td>6-2.  Falling-Head Hydraulic Conductivity Results (cm/s)</td>
<td>112</td>
</tr>
<tr>
<td>6-3.  Constant-Head Hydraulic Conductivity Results (cm/s)</td>
<td>114</td>
</tr>
<tr>
<td>6-4.  Angle of Internal Friction Results</td>
<td>118</td>
</tr>
<tr>
<td>6-5.  Modified Failure Envelope Angle Values</td>
<td>118</td>
</tr>
<tr>
<td>6-6.  Undrained Resilient Modulus Test Results</td>
<td>120</td>
</tr>
<tr>
<td>6-7.  Drained Resilient Modulus Test Results</td>
<td>121</td>
</tr>
<tr>
<td>6-8.  Consecutive Drained Resilient Modulus Test Results (Specimen J14)</td>
<td>121</td>
</tr>
<tr>
<td>C-1.  Initial Conditions for Constant-Head Conductivity Testing per Gradient</td>
<td>165</td>
</tr>
<tr>
<td>D-1.  Percent Air Void Results</td>
<td>166</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1.   Typical Triaxial Cell</td>
<td>5</td>
</tr>
<tr>
<td>2-2.   Hollow Cylinder Tensile Test Frame</td>
<td>15</td>
</tr>
<tr>
<td>2-3.   Radial and Tangential Stresses in a Hollow Cylinder</td>
<td>16</td>
</tr>
<tr>
<td>2-4.   Bridgman’s Graphical Explanation of Indirect Tensile Stress</td>
<td>17</td>
</tr>
<tr>
<td>2-5.   Hoop Stress in a Pressurized Cylinder</td>
<td>17</td>
</tr>
<tr>
<td>2-6.   Longitudinal Stress in a Pressurized Cylinder</td>
<td>18</td>
</tr>
<tr>
<td>2-7.   Biaxial Stress Test Frame</td>
<td>18</td>
</tr>
<tr>
<td>3-1.   Enhanced Triaxial Testing System Component Schematic</td>
<td>27</td>
</tr>
<tr>
<td>3-2.   Triaxial Cell Thru Drawing-Front View</td>
<td>30</td>
</tr>
<tr>
<td>3-3.   Triaxial Cell Thru Drawing-Rotated 45° from Front View</td>
<td>31</td>
</tr>
<tr>
<td>3-4.   Piston Assembly Detail</td>
<td>34</td>
</tr>
<tr>
<td>3-5.   Top Plate to Confining Ring Connection Detail</td>
<td>38</td>
</tr>
<tr>
<td>3-6.   Top-Plate to Strut Connection Detail</td>
<td>40</td>
</tr>
<tr>
<td>4-1.   Calculated $B$-value with Increasing Confining Stress</td>
<td>94</td>
</tr>
<tr>
<td>4-2.   Membrane Position with Increasing Confining Pressure</td>
<td>94</td>
</tr>
<tr>
<td>4-3.   Elapsed Test Time vs. Pressure Transducer Reading</td>
<td>95</td>
</tr>
<tr>
<td>4-4.   Elapsed Test Time vs. Influent Line Pressure</td>
<td>95</td>
</tr>
<tr>
<td>4-5.   Elapsed Test Time vs. Hydraulic Conductivity Falling-Head Test</td>
<td>96</td>
</tr>
<tr>
<td>4-6.   Permeant Routing Diagram Falling-Head Test</td>
<td>96</td>
</tr>
<tr>
<td>4-7.   Permeant Routing Diagram Constant Headwater Rising Tailwater</td>
<td>97</td>
</tr>
</tbody>
</table>
6-20. 4 Hz Cyclic Loading at 10°C (Undrained) ...........................................................135
6-21. 16 Hz Cyclic Loading at 10°C (Undrained) ........................................................135
6-22. 16 Hz Cyclic Loading at 10°C (Drained) ............................................................136
6-23. Comparison of Dynamic Modulus at 10°C .........................................................136
A-1. Enhanced Triaxial Cell Fabrication Drawings – Title Sheet ......................................144
A-2. Cell Profile ............................................................................................................145
A-3. Base Plate .............................................................................................................146
A-4. Top Plate .............................................................................................................147
A-5. Confining Ring ....................................................................................................148
A-6. Piston Sleeve ......................................................................................................149
A-7. Strut ......................................................................................................................150
A-8. Piston ..................................................................................................................151
A-9. Piston Plate Cover ..............................................................................................152
A-10. Base Platen .......................................................................................................153
A-11. Riser ..................................................................................................................154
A-12. LVDT Holder ....................................................................................................155
A-13. Connection Detail .............................................................................................156
Abstract of Thesis Presented to the Graduate School of the University of Florida in Partial Fulfillment of the Requirements for the Degree of Master of Engineering

DEVELOPING AN ENHANCED TRIAXIAL TESTING SYSTEM WITH CYCLIC PORE-PRESSURE CAPABILITIES

By

Jeffrey Wade Frank

May 2004

Chair: Bjorn Birgisson
Major Department: Civil and Coastal Engineering

Triaxial testing has been used for many years by geotechnical engineers, to measure the response of soils to varying stress conditions. Similarly, hot-mix asphalt (HMA) has been tested using triaxial systems to determine the reaction of the material to both static and cyclic loads.

The material properties of HMA present special considerations as compared to testing of soils. For example, unlike soils, the response of the matrix of HMA to loading is temperature dependent. Therefore, at lower temperatures, the mixture will perform much differently than at higher temperatures. Another distinction is that, as compared with typical soils, HMA requires that higher confining stresses and backpressure be applied to achieve saturation. Also, HMA mixtures are often tested under cyclic-load conditions, such as resilient and complex modulus testing, to simulate vehicular traffic. Conversely, soils are more commonly tested with static-load application, to determine strength properties, consolidation and deformation characteristics.
To understand better the development of pore pressure under varied stress conditions, a system was developed that is capable of static and cyclic testing of drained and undrained HMA specimens at a controlled temperature and saturation level, with the added ability to monitor and record pore-pressure response. Testing protocols were developed that allow the measurement of the response of pore pressure in common laboratory tests (such as resilient modulus, complex modulus, and undrained compression). The system is capable of performing tests over a wide range of temperatures while maintaining a saturated condition. Methods to conduct both falling and constant-head hydraulic conductivity testing, without the need for special equipment, were also developed. Additionally, protocols for saturating a specimen and determining Skempton’s (1954) B Parameter, (more commonly, the B-value) were developed using a coarse-graded Superpave mixture. Testing was conducted at both low (10°C) and high (40°C) temperatures.

Pore pressure was shown to occur at low strain levels during static and cyclic loading of a saturated specimen. However, during cyclic loading at high frequencies, pore-pressure excitation was not clearly defined. Specimens tested at the low temperature were found to require higher magnitudes of cyclic loading to achieve a comparable pore pressure excitation as those required at high temperature. During cyclic loading, the pore pressure response exhibits a time lag behind the application of the load. We also found that pore-pressure could be induced by indirect methods (such as an increase in confining stress or an application of axial load) and that the excitation of pore pressure within the specimen is independent of the method of load application.
CHAPTER 1
INTRODUCTION

1.1 Problem Statement

Triaxial testing has been used for many years by geotechnical engineers, to monitor the response of soils to varying stress conditions. Similarly, Hot-Mix Asphalt (HMA) has been tested, using triaxial systems, to determine the reaction of the material to both static and cyclic loads.

The material properties of HMA present special considerations as compared to testing of soils. For example, unlike soils, the response of the matrix of HMA to loading is temperature dependent. Therefore, at lower temperatures, the mixture will perform much differently than at higher temperatures. Accurate assessment of HMA requires that a control system be used to achieve and maintain temperature throughout the duration of a test. Another distinction is that, as compared with typical soils, HMA requires that higher confining stresses and backpressure be applied to achieve saturation. This is attributed to the arduous path of interconnected voids that exists within the structure of the material. Also, HMA mixtures are often tested under cyclic load conditions (such as resilient and complex modulus testing) to simulate vehicular traffic. Conversely, soils are more commonly tested with static load application, to determine strength properties, consolidation and deformation characteristics.

Testing of HMA specimens by cyclic application of stress induces a strain resulting in a temporary reduction of the air voids of the structure. If the voids are partially or fully saturated, pore-pressure can develop against the asphalt film, leading to
moisture damage. If the pore-pressure increases to a high level, the asphalt film on the aggregate will rupture, allowing water to infiltrate between the film and the aggregate (Wagoner 2001).

To understand better the development of pore-pressure under varied stress conditions, an Enhanced Triaxial Testing System (ETTS) was developed that is capable of measuring this pressure during static and cyclic testing.

Our study attempted to develop equipment and test protocols that could measure the response of pore-pressure in common laboratory tests (such as resilient modulus, complex modulus, and compression). The system would also need to be able to perform tests over a wide range of temperatures, while maintaining a saturated condition. Additionally, the correlation between permeability and moisture damage necessitated the development of a method to conduct hydraulic conductivity testing without the need for additional auxiliary equipment.

1.2 Objective

Our objective was to develop a triaxial system capable of static and cyclic testing of drained and undrained HMA specimens, at a controlled temperature and saturation level, with the added ability to monitor and record pore-pressure response. In addition, protocols were developed to perform hydraulic conductivity testing in both constant-head and falling-head configurations, a principle property of HMA. The foremost concern of the development process was to create a system capable of providing the special testing requirements of HMA, while incorporating adequately sensitive monitoring and recording capability for pore-pressure changes.
1.3 Scope

Designing a system capable of addressing the special testing considerations of HMA specimens required research of existing triaxial systems. Particularly interesting were systems used for testing asphalt specimens.

After reviewing existing systems, an enhanced system had to be designed to address the limitations of these systems and incorporate an infrastructure capable of monitoring and recording pore-pressure response to cyclic loading. Methods to improve the delivery and control of permeant to the specimen were of special consideration.

On completion of design and construction of the system, a protocol was needed to saturate effectively an HMA specimen. To ensure a threshold of saturation, a protocol for taking Skempton’s (1954) B parameter (more commonly the $B$-value) also needed to be developed. Additionally, to allow the specimen to be tested at controlled high and low temperatures, a conditioning system needed to be developed, followed by protocol development for the conditioning times required to achieve target temperatures.

Finally, proof testing was needed to determine the sensitivity of the newly designed system for inducing and monitoring pore-pressure response to cyclic loading. Tests such as resilient and complex modulus were conducted using a well-known mix design, to determine collaterally if results with the ETTS are typical of those achieved with existing systems.
2.1 Triaxial Systems Presently Used

The triaxial testing system is used in many facets of engineering. From testing soils and clays to testing asphalt and concrete, the basis of the triaxial system is the same. A cylindrical specimen is installed into a triaxial cell and a confining stress is applied by air, water, or a combination of both (as in the case of air over water). This stress serves to replicate the confinement conditions that the particular specimen would be expected to maintain in application. An axial load, typically applied by either hydraulic control or screw-driven base plate, is induced to determine the response of the specimen to different loading rates and magnitudes.

Figure 2-1, shows a typical triaxial cell for testing asphalt specimens configured such that an axial load is applied via a top platen attached to a rod. This rod (in turn) is attached to a hydraulic load frame that is controlled by a computerized system. The interface with a computerized controller means that high-precision testing (such as complex and resilient modulus) can be accomplished with relative ease.

The demand for more accurate systems (that can perform ever-increasingly complicated testing) has prompted researchers to develop sophisticated systems. Over the years, testing on HMA has progressed to a point that requires specimens to be saturated and conditioned to a temperature before testing. These requirements mean additional components (such as chillers and heaters) need to be used in conjunction with the typical triaxial system, to assimilate better the field conditions of interest.
We searched for systems presently used to test HMA specimens and found the Environmental Conditioning System (ECS) being developed at the University of Texas, El Paso (Alam et al. 1998). This system was designed specifically to evaluate the moisture susceptibility of HMA specimens by resilient modulus testing. To saturate the specimen, the ECS uses a vacuum-based control panel that draws water through the specimen from a storage reservoir. Simultaneously, temperature-conditioned water was cycled around the specimen to get it to a proper temperature for testing. The
disadvantage of this configuration is that, by flowing ambient-temperature water through the specimen, adequate conductance was prevented between the permeant and the confining water. As a result, the actual temperature of the specimen was unknown during testing. The well-known sensitivity of HMA to temperature makes this approach questionable. Additionally, the conditioning system is inefficient, relying on a copper coil, which runs through a heated water bath. The pressurized water running through the coil relies on conductance through the copper to condition it. This configuration required up to 16 hours before the system was stabilized at temperature, precluding it from use as a production-capable system. Also, the system is limited to testing at temperatures above ambient.

The specificity of purpose limited ECS design to resilient modulus testing. Protocols for tests such as hydraulic conductivity, complex modulus, and compression have not yet been developed.

2.2 Compression Testing with a Triaxial Cell

One of the targeted tests for the ETTS was compression testing. Research conducted by Wissa and Blouin (1968) showed that effective stresses rather than total stresses controlled the strength behavior of HMA. Their research attempted to assess the effects of strain rate, temperature, and undrained conditions on HMA specimens.

We investigated the influence of strain rate on the derived friction angle. Tests were made at three strain rates (0.1, 1.0, and 10%). Although no significant change in friction angle was found over this range of strain rates, it was noted that cohesion increased rapidly with increasing strain rate. This lack of influence was explained by the linear relationship between specimen dilatancy and axial strain.
Temperature effects were investigated at low, 0.5°C, and high temperatures, 55°C. Wissa and Blouin (1968) found that lowering the temperature had no effect on the friction angle but increasing it caused a significant increase. Conversely, lowering the temperature resulted in a large increase in cohesion while raising the temperature caused it to drop slightly.

The undrained behavior of the specimen showed an increase to shear resistance with increasing strain. The shearing resistance increased as the specimen dilated and pore-pressure became negative. As with soils, this was attributed to the increase in average effective stress, which increased the shearing resistance of the specimen by increasing the normal effective stress on the failure plane.

### 2.3 Tension Testing with a Triaxial Cell

The Indirect Tensile test (IDT) is used to measure the loading required to create a failure in a specimen due to the onset of cracking. Indirect tensile testing applies a compressive load across the diametrial axis of a cylindrical specimen. The applied tensile stress is assumed nearly uniform but, in reality, is more intense at the center of the specimen than at the extreme edges. Modeling a material’s capability to resist tensile stresses by the introduction of a compressive force onto it may not result in an accurate summation of its resistance to fatigue cracking. Micro cracks, an inherent characteristic of brittle materials such as asphalt concrete, will close when a compressive force is applied and consequently are denied the opportunity to propagate during an indirect tensile test. As a result, the bonding strength of the material in tension is overly estimated. Achieving mechanical, direct tension to a specimen is extremely difficult. The difficulty is predominately with the development of stress concentrations that result in failures near where the tension device clamps to the specimen (Buttlar 1999).
An alternate method of device-specimen interface is to apply platens to the ends of the specimen. These applications while relieving the stress concentrations produced by clamping are a time-consuming and tedious task. A more efficient and simpler approach to developing a specimen in tension would be to induce a tension by pushing from the inside. A newly introduced test referred to as a Hollow Cylinder Tensile (HCT) test was developed that can be used to determine the tensile strength of a specimen at both low and intermediate temperatures (Buttlar 1999). As is shown in Figure 2-2, the specimens used for this test are cylindrical with the center core of the material removed throughout its length. An assembly is inserted into the hollowed specimen core that is capable of exerting pressure onto the inner walls of the cylinder via water. The inner face of the specimen is lined with a flexible membrane to prevent the pressurized fluid from penetrating voids in and around the specimen. Strain is produced causing a tensile or hoop stress to develop. The pressure used to induce tension is uniformly distributed about the internal face of the specimen thus stress concentrations at points of device-specimen interface are not considered. The mechanics of analysis are similar to those of a pressurized tank, the exception being that pressure is inflicted only on the internal wall of the specimen and not on the ends.

A schematic of the test specimen, as shown in Figure 2-3, reveals the simplicity of analysis. The applied stress acts outwardly from the inner wall of the specimen and can be considered initially in equilibrium with the external (atmospheric) pressure. If it is understood that the specimen will fail by mode of fracture when the applied cavity stress equals the tensile stress of the specimen, the ultimate tensile stress can be computed from the geometry of the specimen. The tensile stress at failure, or physically the tangential
hoop stress ($\sigma_t$), is a function of the thickness of the specimen wall and the inner radius. Some of the problems with this test have to do with the selection of the thickness of the wall dependent upon the maximum aggregate size in the mix design.

Published results indicate a concern for the “wall-thickness-to-particle ratio”. It was noted that thick walls are advantageous for increasing the wall thickness-to-maximum aggregate size ratio while thin walls favored a more uniform stress distribution therefore yielding a more accurate value of tensile strength. Another noted concern was with regards to the effects of non-homogeneity of gyratory-compacted specimens. Part of the specimen preparation concerns removal of the center core of the specimen. With this approach, the change of specimen density from extreme surface to center is not considered.

Bridgman first summarized the process that a specimen will fail in tension under biaxial stress in 1931. Bridgman (1931) proposed that applying water pressure axisymmetrically to the specimen is equivalent to a tensile test. As is shown in Figure 2-4, the mechanics of failure assume that the specimen fractures just as the applied tensile stress reaches the hydrostatic pressure value. Bridgman (1931) conducted his research with hollow-cored materials such as glass and steel and with these explored failure under differing stress conditions. A product of this research was the recognition that specimen failure initiated within the discontinuities of the specimen’s microstructure and propagated in response to increasing stress. Worthy of note are Bridgman’s (1931) observations that, when induced by an increasing internally applied pressure, brittle materials such as glass initiated failure from the interior while ductile materials such as steel began failure at the exterior surface and matured radially inwardly (Bridgman
Additionally, Bridgman (1938) noted that impervious, brittle materials, under applied biaxial stress, failed under a compressive force twice that of the tensile strength of the material. That is, the compressive force is applied along two axes instead of one. Therefore, the longitudinal stress is one half that of the hoop stress (Figures 2-5 and 2-6). Additionally, his research noted that when ductile materials were tested under biaxial stress a pinching off effect occurred. This pinching off of the specimen at its midpoint complicated the analysis and subsequent prediction of the tensile strength of the specimen due to the added force component directed parallel to the longitudinal axis.

In their research with concrete specimens, Boyd and Mindess (2001) used a test referred to as a pressure tensile strength test to increase the pore-pressure within a pre-saturated specimen. Unlike the HCT test, specimens were not modified prior to testing. Specimens were placed into an apparatus such that their ends were open to the atmosphere and the remaining portion was confined within a hermetically sealed cell (Figure 2-7). Gas (nitrogen) was then injected into the sealed cell and permitted to act onto the curved surface of the cylinder. The applied pressure to the cell was slowly increased until the specimen failed. Failure occurred on a plane perpendicular to the longitudinal axis of the specimen. The aforementioned increase of pore-pressure is mechanically equivalent to applying a tensile stress to the specimen yet is relieved of the problems that were discussed earlier with a mechanical, direct tension test. The pore-pressure increase, in contrast with the indirect tensile stress (compression) induced by the IDT cycle, allows crack propagation and yields a more realistic measurement of the strength of the specimen in tension. In Boyd and Mindess’ (2001) research, specimens were tested using the splitting tensile strength test, the compressive strength test, and the
new pressure tensile strength test. Boyd and Mindess (2001) concluded that the pressure
tensile strength test appeared to be more sensitive to modeling the effects of internal
damage such as micro cracking than either of the more commonly used methods of
strength determination.

By using a test frame similar to that illustrated in Figure 2-7 the tensile strength of
asphalt concrete might be quantified. The testing of asphalt under biaxial stress is, at this
point, assumed comparable to the previous testing on concrete. Both mediums are
porous, non homogeneous, and contain micro cracks. As was previously mentioned,
Boyd and Mindess (2001) used pressurized nitrogen gas to fail his specimens. The
advantage to using gas for this application is that the specimen fails rapidly and, unlike
with water, the test frame requires significantly less preparation. One noted disadvantage
with gas is that the failure is sudden and has the potential to be extremely violent. This
sudden liberation of the internal stresses effectively evolves the initially static specimen
into a powerful projectile. When concrete was tested, a Poisson effect was not
determined. The use of an LVDT is difficult to incorporate into the test frame due to the
potential for damage when fracture occurs. The use of water as a stress-inducing
medium, as with the HCT test, allows LVDTs to be incorporated on either end of the
specimen without the potential for damage. Water, assumed incompressible at low
pressure, will gently fail the specimen thus reducing the length of stroke the specimen
will travel at failure. The use of water as a tool towards failure of the specimen will
produce the same failure as that experienced when air is used to induce a pressure.
However, the required tensile stress required to achieve failure is significantly higher
when water is used as compared to air (Clayton 1979). A concrete cylinder subjected to
water pressure on its curved surface will have a stress at time of fracture of nearly twice that required during a direct tensile test. If the same specimen were to be subjected to air pressure, the stress at failure would be nearly identical to that of a direct tensile test. Water pressure is not as effective as is air at increasing the internal pressure within the specimen while the exterior pressure is being decreased due to the specimen’s elongation during tension. This imbalance when water is used means that the applied pressure must be increased slowly as to allow these forces to equate on both the interior and exterior surfaces of the specimen. In comparison with the pressure tank analysis shown earlier (Figures 2-5 and 2-6), porous materials will react to applied stress differently. As is shown in Figure 2-8, the hoop stress is mechanically nullified due to the presence of voids within the specimen. As external pressure is increased, the pore water pressure within the specimen equates and acts in all directions about the voids. This equal and opposite force configuration effectively yields a hoop stress of zero. This conclusion is of course highly dependent upon the rate at which the pressure is increased; too rapid an application of pressure will deny the opportunity for pore water pressure equilibrium and a condition similar to that of a pressurized tank will occur.

Another fundamental point is that the mechanical analysis assumes that the specimen is fully saturated and is constructed of interconnected voids. The conflict with this statement is that if a fully saturated condition is not achieved, the specimen will contain encapsulated pockets of air about its cross section. A multi-phase condition will present problems with accurate assessment of the materials tensile strength and with repeatability of testing.
Longitudinal stress is mechanically similar to that of the pressurized tank (Figure 2-6). Unlike with hoop stress, the pore water pressure is not opposed as the biaxial stress increases and therefore will elongate the specimen until ultimate stress is reached.

The stress at failure that Boyd and Mindess (2001) encountered with their concrete specimens was so high that the inclusion of a frictional component by the rubber seals at either end of the specimen was not included in his analysis (Figure 2-7). Unfortunately, the length of stroke prior to failure of the concrete specimens was not observed due to the difficulty of LVDT mounting as mentioned previously. The frictional contributions of the rubber o-rings at either end of the test frame were indicated by Bridgman (1938), although at the time of his research, quantitative effects were not summarized. The rubber seals (o-rings) can be assumed to contribute a restricting force against the elongation of the test specimen. This restricting force will assist the specimen against failure therefore requiring a higher biaxial stress to be applied prior to failure. If biaxial pressure is applied to the specimen slowly, the effect of o-ring induced friction with respect to the elongation of the specimen will be minimized.

A concern with testing relates to the possibility that the specimen may want to neck when a confining force is applied to it. Not commonly discussed in reference to brittle materials but rather when testing ductile materials in an atmosphere of confined pressure, necking can dramatically complicate the analysis of a specimen under compressive forces. When the specimen compresses inward more rapidly than it elongates, the split section of the specimen takes on a shape similar to that of an hourglass. Once this deformation occurs, the specimen now has a force component that is directed parallel to the longitudinal axis. This additional force assists in failing the specimen in tension
(Bridgman 1938). The stress experienced by the specimen must then be analyzed as the sum of two stress systems: a uniform hydrostatic pressure equal to the pinching-off pressure over the entire exterior surface of the specimen, plus an ordinary tension on the ends also equal to the pinching-off pressure. In Bridgman’s (1938) work with rupture, he stated that the pinching-off pressure could be concluded as being “numerically equal to the tensile strength, suitably defined, which would be shown by the specimen if it were subject to a uniform confining pressure all over equal to the pinching-off pressure”. This conclusion holds valid whether the specimen necks down or not.

Research done by Visser (1998) on dry and saturated sandstone specimens, examined the fracture propagation at the macro level when induced by a radial stress in excess of the axial stress. In dry extensile testing, Visser (1998) maintained a radial stress of 870 psi (6 Mpa) and decreased the axial stress until fracture occurred perpendicular to the longitudinal axis. In order to control the location of the fracture, a circular notch 5/32 inch (4 mm) wide by 3/16 inch (5 mm) deep was made about the circumference of the specimen at mid height. The exterior surface of the specimen was then coated with resin and polished thereby creating an impermeable and smooth coating. Testing of saturated specimens contained a similar notch. However, only the ends of the specimen were coated and polished.

Visser (1998) found that fracture of the specimen could be accomplished in a manner illustrated by Bridgman (1931) in Figure 2-4. Since the testing occurred under fixed boundaries, free fracture propagation was limited. Fracture of the specimen initiated on one side followed by a rotation due to the crack opening. Subsequently, a bending moment develops. Rotation is limited due to the fixed boundaries. As a result,
further propagation is prohibited and a second crack begins to develop and propagate from the opposite side of the specimen.

Figure 2-2. Hollow Cylinder Tensile Test Frame
\[
\sigma_t = \left[\frac{a^2 p}{(b^2 - a^2)}\right]\left[1 + \left(\frac{b^2}{r^2}\right)\right]
\]
\[
\sigma_r = \left[\frac{a^2 p}{(b^2 - a^2)}\right]\left[1 - \left(\frac{b^2}{r^2}\right)\right]
\]

where

\( p = \text{Internally Applied Pressure (psi)} \)

\( \sigma_t = \text{Tangential (hoop) Stress (psi)} \)

\( \sigma_r = \text{Radial Stress (psi)} \)

\( a = \text{Inner Radius (in)} \)

\( b = \text{Outer Radius (in)} \)

Figure 2-3. Radial and Tangential Stresses in a Hollow Cylinder
Figure 2-4. Bridgman’s Graphical Explanation of Indirect Tensile Stress

At equilibrium $\sum F_x = 0$;
$\sum F_x = P(2r \, dy) - 2(\sigma (t \, dy)) = 0$
$P(2r \, dy) = 2(\sigma (t \, dy))$
$(Pr \, dy) = (\sigma t \, dy)$
$\sigma_{hoop} = Pr/t$

Figure 2-5. Hoop Stress in a Pressurized Cylinder
At equilibrium $\sum F_y = 0$;

$\sum F_y = \sigma(2\pi t) - (P\pi r^2) = 0$

$P(\pi r^2) = \sigma(2\pi t)$

$Pr = 2\sigma t$

$\sigma_{\text{longitudinal}} = \frac{Pr}{2t}$

Figure 2-6. Longitudinal Stress in a Pressurized Cylinder

Figure 2-7. Biaxial Stress Test Frame
Figure 2-8. Hoop Stress in a Porous Medium

hp = hydrostatic pressure
pwp = pore water pressure
3.1 Introduction

The ETTS is a modified triaxial testing system designed specifically for the testing of asphalt specimens. The concept of the Enhanced Triaxial Testing System was prompted by the need to analyze better the effects of water-induced damage to an asphalt structure. Testing of a specimen in the triaxial environment allows for precise application of stress in three different directions. If a specimen is thought of as a cube, these directions can be represented in the familiar x-y-z coordinate system. The laboratory created specimens are cylindrically shaped, thereby reducing the coordinate system to an axial vector (y) and a sum of biaxial vectors (x). These vectors, acting normal to the surface of the specimen, can be increased or decreased in a multitude of combinations allowing control of axial and confining stresses onto the specimen.

For years, the triaxial cell has been used by the geotechnical engineering community to assimilate insitu stresses on the specimen of interest and then, through deviation of the confining and axial stresses, quantify the material’s reaction to an anticipated load. The advantage of soil testing in a controlled environment is of significant value and allows the engineer greater control than could be acquired in the field. At present, there are several systems in different stages of development that attempt to simulate field conditions while, at the same time, producing a testing sequence that is simpler and more accurate than systems presently used. The ETTS is unique amongst
other systems used today in that the system is designed to be versatile and comprehensive with respect to specimen testing.

As with soil, asphalt concrete specimens have long been tested in a triaxial cell. Tests such as hydraulic conductivity (permeability), resilient modulus, complex modulus, shear strength, and creep are common in asphalt test labs using a triaxial device. A distinct limitation to the triaxial cells constructed today as compared with the Enhanced Triaxial Testing System is the design of the force application piston and how it transfers stress onto the specimen. Traditionally, these platens are no more than a disk of rigid material that acts as a medium between the force from a shaft and the specimen itself. The limitation occurs when stress is applied to the circumferential surface as occurs when confining stress is applied. As the confining stress increases, so too does the axial stress onto the specimen. This relationship limits the stress paths the researcher can apply onto the specimen. The initial design of the ETTS addressed this problem by designing a top platen (piston) encased within a sleeve. This piston-sleeve design relieves the researcher of the limitation of stress paths by allowing the axial and confining stresses to be independent of one another, thereby allowing for greater control and flexibility with applied stresses. In addition, the system is designed to allow for in-place conditioning with the support of an external water temperature conditioner as well as the ability to perform both constant and falling-head permeability testing without removing the specimen from the test cell. These added benefits allow for a sequence of testing to be performed without the risk of damage to the specimen during transportation from one test setup to another. Also, the additional integral capabilities of the ETTS diminish the need for auxiliary equipment required to perform testing of conditioned specimens.
3.2 Design Considerations

Prior to the commencement of the system design, a full understanding of the end purpose of the system needed to be defined. The system needed to be capable of performing tests in compression and tension. As a result, the structural frame of the cell needed to be designed to allow for the corresponding forces. The tests would all be performed in effective stress state conditions, thereby creating the need to develop a saturation procedure. And lastly, the system needed to be capable of getting a specimen to a stabilized temperature rapidly and maintain that temperature throughout the duration of the test.

Saturation of specimens, particularly those composed of soil, in triaxial cells is typically achieved by pulling permeant through the specimen’s structure using vacuum techniques. For the design of the ETTS, allowance was made so that the system would be capable of applying a vacuum as well as forcing the permeant through the specimen from the influent end.

The variation in test data as a result of inconsistent specimen temperature during testing is well known and of foremost concern for a test requiring a high degree of precision. HMA is extremely temperature susceptible (Roberts et al. 1996). Repeatability of tests such as resilient modulus ($M_r$) determination is very unlikely if specimen groups are tested at varying temperatures. For this reason, the creation of a system that would be capable of achieving target temperature rapidly and continue to maintain that temperature throughout testing was a criterion for design.

The achievement of heating and cooling of water used in existing triaxial testing systems used at the University of Florida and in many systems are through indirect methods. Heating is achieved via conduction from thermo probes onto the base plate.
The base plate would, in turn, heat the confining water. Thermo probes are commercially available and operate much like the surface heating coil on an electric stove. As electricity is passed through the probe, resistance is developed that transforms the electrical energy to heat. Typically, two probes, approximately \( \frac{3}{8} \) inches in diameter and 8 inches long, fit into the base plate of the cell via smooth borings that run parallel to one another. The main disadvantage of this design is that the cell acts as a heat sink, requiring that it be heated prior to the confining water. The specimen is then reliant upon the conduction of heat from the confining water in order to arrive at the test temperature. The combined mass of steel and water requires a large amount of time and energy to arrive at the test temperature. Additionally, cooling of the confining water is achieved via indirect methods. Chilled water is circulated through a copper coil that travels around the exterior surface of the confining cylinder. To minimize the absorption of thermal energy from the atmosphere, the cell was wrapped with a plastic-encased sheet of fiberglass insulation. Although the insulation impedes the absorption of unwanted thermal energy, it is not completely effective and the achievement of low temperatures is not possible due to the inefficiency of the system. As with the method of heating, this configuration must condition the temperature of the cell prior to the confining water, thereby creating a lengthy conditioning period.

It was recognized early in this process that a direct method of water conditioning would need to be developed that would be capable of readying a specimen in a reasonable amount of time as to make the system useful in production testing. The rapid achievement of test temperature was largely based on three factors:

- The selection of properly sized cooling and heating devices
• Reduction of the length of transmission lines in order to minimize thermal losses or gains

• The minimization of the volume of confining water space within the cell thereby minimizing the amount of energy required by the temperature conditioner to be either removed or added to the water

The overall appearance of the cell is very typical of other existing triaxial cells.

The structural core consists of two round plates separated by posts or what are referred to in this paper as struts. The structural core is encased with a cylinder and the entire package is sealed which creates an enclosed cavity capable of being pressurized. The variable of the cell’s design is the proportionality of these components. The dimensions of the test specimen dictated much of the subsequent design of cell components. The diameter of specimens used with this cell was decided as 4 inches (100 mm). This system was developed as a prototype and it was deemed prudent to ensure it could operate properly before designing a cell capable of testing larger specimens (6 inches; 150 mm). Additionally, as the diameter of the specimen increases, the overall size of the cell increases in a near proportional manner. Therefore, in an attempt to balance overall size and cost to manufacture, the smaller specimen size was chosen.

The system was designed as a self-contained testing device. In order to achieve a saturated specimen, backpressure saturation techniques would be required. The integration of a vacuum device capable of relieving at least one atmosphere of pressure to assist with the liberation of air trapped in the specimen was required.

Although a prototype, the system was intended for use in production testing. The process for specimen installation was examined as the cell design progressed. Owing to the complexity of the installation of instrumentation used to monitor the specimen, AutoCAD generated schematics were used to ensure that these instruments could be
The tests also required that a latex membrane be placed over the specimen and overlapped over the end platens. This step is critical for ensuring the isolation of the saturated specimen from the confining water. Therefore, consideration was given to the allowances required to enable the operator to successfully position this membrane in a limited space in order that the overall size of the cell be minimized as greatly as possible. For this, several mockups were made to determine which combination of configuration and spacing provided the optimum balance of size and function.

As discussed, in research for an Environmental Conditioning System (ECS) developed at the University of Texas, El Paso, one of the problems experienced was the lack of rigidity with the system as a whole. This lack of rigidity could contribute to erroneous data as a result of linear displacement of the specimen during dynamic testing since the system will deform slightly when induced by high-pressure loads. To avoid such a problem with this system, connectivity of components of the cell was examined prior to the construction. Where components interfaced with an o-ring incorporated to act as a seal, allowance was made to ensure that the groove in which the o-ring was seated provided proper volume to contain the compressed seal. This would allow the mating components to achieve surface-to-surface contact thereby producing a rigid connection. The center vertical core of the cell is configured to allow for all forces from the piston to be directed normal to the base plate without rotation or movement from an inclusive component. The base platen and piston use both end bearing and thread bearing from a threaded rod and piston shaft respectively. This compliment of connectivity creates an extremely stable union of components.
Finally, a great effort was made to produce a system that not only would be simple to manufacture and operate, but would also be as cost effective as requirements would allow. Utilizing available raw metal shapes and specifying proper tolerances of machining constructed a relatively inexpensive cell. Components that required a high degree of machining effort, such as the top and base platen, were specified only after being investigated for alternative design and necessity for the desired function of the cell.

### 3.3 Construction and Design

The ETTS is composed of six sub-systems:

1. Modified triaxial cell
2. High-pressure water distribution system
3. Data acquisition system (Material Testing Systems (MTS) Model 810)
4. Hydraulic load frame (MTS 22 kip)
5. Low temperature water conditioner
6. High temperature water conditioner

Part of the objective of this research was the design and manufacture of the former two (1 and 2) sub-systems and subsequent integration with the latter four (3 through 6) support sub-systems. A schematic of the system components is shown in Figure 3-1.

#### 3.3.1 Enhanced Triaxial Testing System Design

The design for the modified triaxial cell was approached in the following order:

1. Determination of parameters of targeted testing that dictated design elements of the cell (e.g., size of specimens to be tested, instrumentation to be integrated with the cell, and system pressure)
2. Piston assembly design
3. Top and base plate design
4. Strut design and bearing capacity calculation
5. End platen design
6. Confining cylinder selection
7. Confining ring design
8. Seal selection and placement
9. Component tolerance specification
10. Radial LVDT holder design

![Enhanced Triaxial Testing System Component Schematic](image)

**Figure 3-1. Enhanced Triaxial Testing System Component Schematic**

### 3.3.1.1 Design-parameter determination

The design specimen height was arrived at as a compromise between recommended aspect ratios for the two primary tests of the system, hydraulic conductivity (permeability) and resilient modulus. During the literature review of permeability testing, an aspect ratio recommendation was found to be from 0.5 to 1.0 (Carpenter and Stephenson 1986). This translates into a specimen height of 2-4 inches (50-100 mm). The recommended aspect ratio of a specimen for resilient modulus testing is 1.50, which translated into a specimen 6 inches (150 mm) high. A compromised design specimen height of 5.5 inches (137.5 mm) was decided upon in order to facilitate both of these tests into one device.
The cell was also designed for the development of a new test in which large confining pressures would be placed onto the specimen to induce a failure in tension. This meant that the cell would be expected to contain larger pressures than those in typical triaxial cells. Based upon the mechanics of the anticipated failure, the cell was designed to contain 400 psi of fluid pressure.

At this point in the design process, as with all new equipment development, reasonable engineering judgment needed to be applied for certain parameters. One of these parameters is the length of piston stroke required for the desired test. As will be discussed later, the design of the top platen assembly required that the maximum stroke length be minimized to maintain sealing integrity. Based on review of previous compression to failure testing, the maximum stroke length was concluded to be 0.75 inches.

Another issue of design was how large the cell needed to be made in order to minimize structural stresses and facilitate specimen installation. A thorough effort was made to limit the overall size of the cell without making it so compact as to interfere with specimen installation and subsequent data acquisition instrumentation such as linear variable displacement transducers (LVDTs). This effort was made out of structural concerns with regards to the sizing of the supporting struts (vertical support members) compared to the end area of the cell. As the interior diameter of the cell increased, so too did the diameter of the four supporting struts required to restrain the resulting force on the top and bottom plates of the cell. The four struts that maintain the position of the base and top plates are analogous to the columns of a building. However, unlike columns, the struts must maintain forces in tension since the interior of the cell is
pressurized. Therefore, as the end area of the cell (top and base plates) increases, so too does the resulting tension forces acting on the struts. An optimization of end area versus strut diameter was performed to produce an interior cell cavity that was adequately sized to install instrumentation, yet compact enough for reasonable structural component sizing. The cell is intended for 4 inch (100 mm) diameter specimens with an aspect ratio of 1.25-1.50. Side views of the cell components are shown in Figures 3-2 and 3-3. All components are fabricated of 303 stainless steel with the exception of the piston, end platens, and the confining cylinder, which were made from 6061-T6 aluminum. Stainless steel was chosen for four reasons: 1) availability, 2) high strength to unit area ratio, 3) ease of machining, and 4) corrosion resistance. Aluminum was the logical choice for components such as the confining cylinder where weight was an issue, and the end platens and piston where intricate design details precluded the use of hardened steel.

Throughout the design process, corrosion control of components was a factor of material selection. Owing to the aggressive environment that these components operate in, the potential for reaction between dissimilar metals was an issue for design. Aluminum and stainless steel are considered compatible, as shown in galvanic series charts, when one material is finished with at least one coat of anodizing primer (Juvinall 1983). Where aluminum was used, these components were anodized to retard the corrosion process. Anodizing of aluminum alloys produces a stable aluminum oxide film that provides substantial corrosion resistance (Juvinall 1983). Additionally, separation between aluminum and stainless steel components was provided via buna-N o-rings, which further assisted with the dampening of electrical current flow through the
dissimilar metal interface. With the major design parameters defined, efforts were
directed to the design of the individual components.

3.3.1.2 Piston-assembly design

The piston-assembly was a logical place to begin the design process in that it
dictated many of the subsequent component designs. It was imperative that the sizing
and function of the piston-assembly be determined prior to the design and manufacture

Figure 3-2. Triaxial Cell Thru Drawing-Front View
of the remaining cell components. As was previously mentioned, the most prominent
distinction between the ETTS and traditionally manufactured cells is the piston-sleeve
assembly. The challenge of design was to create an assembly that would yield low
frictional contributions while simultaneously providing a leak-proof barrier between the
interface of the cell and the atmosphere. The initial piston-sleeve assembly design
consisted of a Frelon® bearing for a sleeve and a custom fabricated stainless steel cylinder
for a piston. A Frelon® bearing is a commonly used bearing constructed of a hollow,
aluminum cylinder that is lined with a sheet of the low-friction material Frelon®. The
opinion at the time was that the Frelon® bearing would act as a low friction surface for the cylinder to cycle on while, at the same time, preventing water from emigrating from the triaxial cell interior, past the Frelon® bearing, and to the exterior of the cell. The foremost advantage to this design was the immediate availability of the bearing from several suppliers with bore diameters of 4 inch and 6 inch common. After procuring a bearing for a determination of suitability, several weaknesses were discovered. First, the sheet of Frelon® that lines the bore is glued to the inside of the aluminum cylinder and results in a poor quality seam where the two ends of the sheet union. After consideration, it was decided that this seam would not be capable of restraining the increasing water pressure from within the cell during a typical testing sequence. Secondly, the roundness from true of the interior of the bearing (bore) varied in excess of .003 inches in diameter that would make the complimentary mating of a piston difficult. After consulting with several area machinists, it was concluded that even if a matching piston could be manufactured, the precision required between the piston and the Frelon® bearing to accomplish the aforementioned goals is too high and not practical nor cost effective for the project.

The next consideration for a piston assembly was more tolerant of geometric imperfections and proved easier and less costly to fabricate. The piston assembly is composed of two main components, a piston sleeve and a piston. The piston sleeve is affixed to the top plate of the cell and acts as a fixed member for the piston to travel within. In Figure 3-4, the piston sleeve was constructed using stainless steel. This material was selected for its ability to be machined to very high tolerances and polished for low frictional contributions of seals in contact with the interior surface. Additionally,
this component required welding as part of its manufacture thereby dismissing aluminum as a viable candidate. In Figure 3-5, the piston contains a flanged ring allowing for the passage of bolts to secure it to the top plate. This flanged ring was welded to the tubular portion of the piston, which made fabrication costs lower than if the piston were to be machined from a solid piece of material. The utilization of available geometric shapes and sizes from material suppliers not only expedited the construction process, but also aided with the creation of a cost-effective cell.

Conversely, the piston is machined from a billet of aluminum to provide the strength necessary for compression-based tests. The piston contains two inscribed grooves about its circumference designed to receive flexible seals. Although one seal would have been adequate for this application, duplicity was chosen to further steady the piston inside of the sleeve and act as a backup if the primary seal were to fail. Due to the critical role these seals play in the successful operation of the cell, the grooves were designed to compliment the component specifications of the seals. These seals are made of wear-resistant Nitrile lip seals and resemble a flared “U”. They are installed into the grooves of the piston cupped in the downward direction, which forces any increase in water pressure to act within and outwardly through the seal. This change of pressure increases the squeeze of the seal onto the interior surface of the piston sleeve. These seals are appropriate for this application in that as they wear at the contact surface, the downward cup design compensates by allowing the seal to open to a greater degree, thereby assuring a tight seal against the piston sleeve. This attribute provides a much longer service life than could be expected from other seals having a more symmetrically
shaped profile. Seals with a symmetrical profile such as o-rings, are less forgiving of an uneven wear pattern and are not appropriate to dynamic applications.

Figure 3-4. Piston Assembly Detail

This configuration has performed extremely well in proof testing and throughout several production tests, having successfully prevented any bypass of water from the cell’s interior. For the purpose of design, the seals are considered to be consumable components of the test system and will eventually require replacement. After many sequences of testing, the seals have performed up to the design goal and indicate no visible signs of wear.

3.3.1.3 Top and base-plate design

The thickness of the base and top plate is a function of the bearing capacity required from the struts onto the plate and was calculated with a factor of safety of 2 at
the maximum safe operating pressure of 800 psi. It was anticipated that the cell would operate in the range of 0-400 psi for the types of tests the system was being designed for.

The base plate performs three basic functions. First, it acts as a staging platform for other components of the system. Secondly, it contains the watertight entrances for instrumentation cables entering the cell, and thirdly, it includes the conduits for pressurized water entry both through and around the specimen.

There are four ports (thru holes) that were specified for use with plug-in type fittings available from Geotechnical Consulting & Testing Systems (GCTS), Tempe, Arizona. These fittings consist of hollow cored, threaded male and female pieces that, when tightened together, compress a confined o-ring, thereby sealing the interface. The cables for instrumentation used for the system can be chased through these assemblies, allowing for easy installation of any combination of instruments into the cell. These cables exit the cell’s interior and are neatly chased via grooves in the bottom of the plate to the data acquisition system.

The protocols for testing require that the system be capable of circulating water both through and around the specimen. The ability to transport water through the specimen is essential for achieving saturation and also is essential for permeability testing. In order to apply fluid pressure around the specimen and condition it to the testing temperature, it was required to have an entrance for fluid coming from the water distribution panel. With these requirements in mind, the base plate has two 1/8 inch diameter conduits that run through the center of the base plate terminating at the specimen location and the cell cavity location.
The thickness of material chosen for the base plate was dependent upon the required bearing surface area of the threaded struts that fastened into the plate. An optimization was conducted to size the struts versus the thickness of the plate (see strut design for further discussion).

The primary function of the top plate is to act as a platform for the piston assembly. The plate is fastened to the four struts via socket head screws that pass through the plate. At this point in the design process, a block shear type of failure about the socket head screw had not been investigated. This analysis was conducted in the following component phase therefore, at this point, the thickness of the plate was assumed to be 1 inch. The piston assembly is fastened to the lower face of the top plate with four (4) stainless steel button head cap screws. A 1 inch inside diameter flange-mounted self-aligning bearing is fastened to the upper face of the plate to guide the travel of the rod attached to the piston. The incorporation of a self-aligning bearing eliminates the potential for damage to the piston sleeve from a misaligned piston. Both the piston assembly and the self-aligning bearing are capable of being adjusted about the vertical axis of the cell to ensure proper alignment of the end platens on either end of the specimen.

The top plate contains two 0.500 inch diameter holes that allow the exiting of fluid from within the cell. One hole is located such that it falls over the piston. This hole allows for the placement of copper tubing for the transport of water from the top of the specimen. The second hole is positioned outside of the piston assembly profile providing an outlet for temperature-conditioned water or an inlet for pressurized air.
3.3.1.4 Strut design

By this time in the design process, the diameter of the struts was already determined during the optimization process within the base plate design stage. The connectivity of the struts to the plates was determined based upon methodology of construction. As can be derived from the connection detail shown in Figure 3.5, the success of an adequate seal at all o-ring points is dependent upon the uniform compression of these seals along the length of the o-ring. To ensure uniformity, the separation between the top and bottom plates must be tolerable within a fraction of the o-ring’s diameter. If, for example, the distance of separation were too far out of tolerance, one portion of the o-ring would contact before the opposing side, creating an inadequate seal. Designing a strut that would be capable of adjustment was therefore necessary to ensure uniformity of seal compression.

All four struts are typical and are a combination of exterior (male) threading on the end that interfaces with the base plate, and interior (female) threading on the end interfacing with the top plate. This combination allows for the struts to be adjusted for equidistant separation prior to the top plate being installed. Subsequently, the top plate is secured using the high-strength socket head bolts (Figure 3-6).

The design of the threaded ends of the struts had to be specified. Since the struts were to be designed as tension members, the end bearing capacity of the struts were not considered and the design approach turned to the bearing ability of the threads. Bolts (as is the assimilation of the male strut end) can fail in tension four different ways: 1) thread stripping of the bolt if it is a weaker material than the nut, 2) thread stripping of the nut if it is a weaker material than the bolt, 3) stripping of the bolt and nut if both are of similar
Figure 3-5. Top Plate to Confining Ring Connection Detail

Based upon the geometry of the cell, an applied factor of safety of 2, and the pressures it is designed to contain, the resulting tension force anticipated for each strut was calculated as 15.7 kips. The bolt tensile force required to yield the entire threaded cross section is defined as

\[ F = A_t S_y \approx \frac{\pi}{4} (0.9d)^2 S_y \]  \hspace{1cm} (3.1)

where

\[ F = \text{Bolt tensile load required to yield the entire thread-stripping failure surface of the strut (kips)} \]

\[ A_t = \text{Total surface area of threads resisting tensile force (in}^2) \]

\[ S_y = \text{Yield strength of strut (0.2\% offset) (ksi)} \]

\[ d = \text{Major diameter of the strut (in)} \]
The bolt tensile load required to yield the entire thread-stripping failure surface of the base plate is defined as

\[ F = \pi d (0.75t)(0.58S_y) \]  \hspace{1cm} (3.2)

where 
- \( F \) = Bolt tensile load required to yield the entire thread-stripping failure surface of the base plate (kips)
- \( d \) = Major diameter of the strut (in)
- \( t \) = Depth of engagement into the base plate (in)
- \( S_y \) = Yield strength of strut (0.2% offset) (ksi)

Equating the former two expressions for \( F \) yields balanced tensile and thread-stripping strengths when the depth of engagement is approximately

\[ t = 0.47d \]  \hspace{1cm} (3.3)

The process for calculating the design of the strut to base plate connection was as follows:

1. Calculate depth of engagement using Equation 3.3
2. Arbitrarily choose a thread designation and, by using the depth of engagement \( t \) solved for in step 1, determine the corresponding bolt tensile load required to yield the entire thread-stripping failure surface of the base plate, \( F \), as defined in Equation 3.1
3. Continue with iterations of differing thread designations until \( F \), as defined in Equation 3.2 approximates the design resistance force of 15.7 kips as defined for design

The design of the strut to top plate connection utilized the same methodology as the previous connection with the primary exception being that it has inside threads and utilizes a socket head bolt (See Figure 3-6). The socket head bolts are Society of Automotive Engineers (SAE) Grade 5, with yield strength, \( S_y \), of 92 ksi. For all sense and purpose, this level of strength far exceeds the requirement of this application. However, the cost of these bolts was reasonably low and the added level of strength is of
value when considering this added strength effectively removes a failure mode from probability. The additional failure modes that needed to be checked were:

- Shearing at the reduced-area cross section
- Shearing of the bolt
- Block failure (pullout) of the top plate about the socket head: bolt interface

With the design of these connections accomplished, the structural core of the system was complete. The following components would be designed to compliment this structure.

### 3.3.1.5 End-platen design

The approach for the design of the end-platens began with a review of needs for this component from each test. Depending upon the test, these platens needed to perform
different tasks. For example, tests such as resilient modulus and drained and undrained compression, required that the platens resist induced compressive stresses. Additionally, any contributory end effects resulting from friction between the platens and the specimen’s ends needed minimization as much as design would allow. Other tests such as constant and falling-head hydraulic conductivity (permeability) placed a greater emphasis on the ability of the platens to conduct and distribute water with a minimal amount of interference. It is the opinion of this researcher that existing designs do not efficiently allow the transport of fluid through the specimen but rather force the fluid through specific and limited paths, thereby introducing error into the test. This becomes evident when an inventory of losses due to constrictions, expansions, and bends along the fluid’s path is made. After consideration of the requirements it was concluded that different platens would be required for different tests.

Unlike more commonly used end platens, which distribute water via one hole and conducting grooves or dimples, those in the ETTS contain many orifices across its surface. This allowed water to be transported through the test specimen uniformly and without concern for isolated piping or excessive pressure gradient development. Additionally, these platens are fabricated with concentric grooves to better distribute the water across the face of the specimen. This configuration is also advantageous in the initial specimen saturation phase since it allows for a front of fluid to pass through the specimen, which more effectively liberates entrapped air bubbles. The presence of conducting channels across the entire profile of the platens diminishes the likelihood of entrapped air bubbles between the platens and the specimen.
The complexity of the profile coupled with the relatively small conducting orifices specified dismissed stainless steel as a material candidate. Aluminum was chosen due to its relative ease of machining and ability to harden to a level required for use by anodizing the part. Both the top and the bottom platen have identical profiles. This similarity ensures conservation of volume in and out of the specimen and decreases production costs since only one profile had to be identified for machining.

The top platen is basically a plate that caps the end of the piston. It is fastened via a screw into the piston which when tightened, compresses an o-ring placed between the two mating parts that prevents water from being conducted through the mated seam. The base platen is attached to the base plate via a threaded stud that also assists with the proper, concentric alignment of the platen about the cell. A concentric, half-round groove is machined into the mating face of the platen for installation of an o-ring serving the same purpose, as does the aforementioned o-ring. Machined into the circumference of the platen are two half-round grooves that are used to seat the o-rings that hold the latex membrane to it. Additionally, a 1.0 inch high hollow riser was manufactured that can be placed between the base plate and platen. The option of using a riser allows a specimen height range of 5-6 inches (127.0-152.4 mm).

For compression-based testing it was necessary to protect the faces of the platens from marring and increased damage. Additionally, the concentric grooving in the face of the platens introduced an unfavorable end constraint of the specimen. To lessen these end effects, several sets of low friction, high-strength Duron® platens were fabricated to fit between the aluminum platens and the specimen. These Duron® platens are mechanically fastened to the aluminum end platens to prevent any shifting during testing.
Additionally, they contain concentrically positioned holes that compliment the location of the grooves contained in the aluminum platens, thereby still allowing a method to saturate a specimen and determine its hydraulic conductivity prior to compressive testing.

### 3.3.1.6 Confining cylinder design

Due to the large diameter of the cell, the availability of cylindrically shaped material was limited. Early in the design process, it was understood that the larger the cell’s diameter became, the less number of incremental diameters of confining cylinder would be available. With this in mind, the selection of a suitable material/diameter combination was researched. Since the cell would be operating at much higher pressures than typical triaxial cells, plastics, such as the commonly used material Lucite® with a maximum allowable wall pressure of 150 psi, would not be adequate.

The finished length of the confining cylinder, considering cumulative compression of o-rings, was calculated as 14.60 inches with a required diameter of approximately 9.5 inches or larger to accommodate the struts, specimen, and instrumentation within the cylinder. Since this component would require constant removal and reinstallation for testing, the overall weight was a concern for two reasons: 1) physical requirements for any future operators (i.e., strength) were not reasonable to assume, and 2) as the weight of the cylinder increases and becomes more unwieldy, so too does the potential for damage attributed to mishandled or colliding parts. Therefore, relatively dense materials such as stainless steel were excluded from consideration. Aluminum alloys were researched for adequacy and availability. Aluminum 6061-T6 weighs approximately 0.10 lb/in³, which is roughly one-third the weight of a stainless steel material. A 10 inch nominal diameter, schedule 40 pipe was located which has yield strength of 40 ksi. The anticipated maximum hoop stress was calculated from Beer and Johnston (1992) as
\[
\sigma_{\text{hoop}} = \left( \text{factor of safety} \right) \left( \frac{Pr}{t} \right)
\]  

(3.4)

where \( P \) = Maximum operating pressure (psi)
\( r \) = Inside radius of cylinder (in)
\( t \) = Cylinder wall thickness (in)

With a factor of safety of 2, the hoop stress was calculated as 10.98 ksi, far below the allowable stress of the material. Although thinner walled material was available, it would not have been adequate since this narrower dimension would have created difficulties mating with the o-ring seals at the ends of the cylinder. It is of value to note that pipe of this dimension and material type is difficult to locate. This type and size pipe is used in specialized applications such as electric generation plants and is manufactured in lengths exceeding 10 feet. The procurement of a 15 inch long piece of these segments entailed a special cutting fee. The cylinder, while being structurally adequate, does raise a concern with similarly designed cells that may be constructed in the future. Owing to the fabrication method and subsequent storage of the material at the manufacturer, the material is slightly out of round when purchased. This distortion makes the mating of the cylinder to the o-rings contained in the lower and upper portions of the cell more difficult than if the cylinder were truly round. If additional cells are manufactured in the future, thicker walled cylinders are recommended followed by a center-less ground method of machining to create a cylinder that is truly round.

3.3.1.7 Confining ring design

The confining ring is one of the most critical of all the components. The ring compresses the seals in contact with the confining cylinder and the seal inset into the exterior face of the top plate that prevents the migration of pressurized fluid from the interior of the cell. The ring is attached to the top plate via four 1 inch long socket head
bolts. These bolts resist the force applied to the ring through a gap between the confining cylinder and the top plate. The force against the ring is relatively small compared to forces exerted onto other components. For this reason, the nominal thickness of the ring is 0.50 inches. The socket head bolts employ flat washers between them and the surface of the confining ring to increase the contact area with the ring. The ring was analyzed for block shear about the bolts as well as stripping type failures of the bolt to top plate connection.

The confining ring has a recessed, concentrically located channel machined into the face that contacts the confining cylinder. This channel helps to align the top of the confining cylinder within the ring thereby locking the two components together. Two semi-circular grooves are placed into the channel for the placement of o-rings where the confining ring interfaces with the confining cylinder. Four thru-holes are positioned into the ring, which compliment the locations of the bolt heads from the top plate to strut connections. An additional thru-hole is provided which fits over a quick disconnect fitting installed into the top plate allowing fluid to be cycled through the cell’s interior.

3.3.1.8 Radial LVDT-holder design

The use of LVDTs is necessary for the computation of the variation of the cross sectional area of the specimen during failure testing in compression. These LVDTs are positioned such that they are normal to the cylindrical surface of the specimen in 90° increments. A holder was designed that allows for the installation of four LVDTs in this configuration. Machined from aluminum and anodized for corrosion resistance, the holder contains four thru-holes that allow the holder to be integrated with the struts of the cell. Slightly oversized, these thru-holes enable the holder to travel to any position along the length of the struts. Once positioned, the holder is affixed to the struts via eight
nylon-tipped, stainless steel setscrews. The nylon tip prevents marring of the strut and is intended for applications where the setscrew is continuously reengaged. The LVDTs are placed into the holder via thru holes and restrained with stainless steel set screws. This simple configuration allows for rapid positioning of the devices at any position along the length of the specimen.

3.3.1.9 Seal selection and placement

With the exception of the u-cup seals used for the piston, all other seals were accomplished with buna-N o-rings supplied by Parker Seals, Inc. Buna-N (Nitrile) is a commonly used o-ring material that is available in a wide range of diameters and cross sectional thickness. This material is resistant to petroleum-based fluids and maintains its shape and pliability after a high number of compression cycles. The combination of these factors was necessary for the anticipated use of these o-rings. The design of all components relying on these seals was performed simultaneously with the o-ring selection process. This coordination ensured that specially sized o-rings would not have to be manufactured.

Figures 3-5 and 3-6 show that the o-rings are placed such that as the cell is assembled, the proper alignment of the o-rings with the corresponding component can be achieved easily. The cross sectional diameter of the o-rings was chosen such that an equivalent degree of compression of all the o-rings is accomplished following the tightening of the cap head bolts about the confining ring. The consideration of group-dependent compression of the o-rings is critical to ensure that each individual seal is properly compressed to maintain the confinement pressure.

The grooves that accept the o-rings are predominately square in profile and of adequate cross sectional area to allow for the total inclusion of the o-ring upon
compression. As was previously discussed in the design considerations section, this provision allows for proper sealing while simultaneously facilitating rigidity at the interface developed from the surface-to-surface contact. Where the aluminum base platen interfaces with the base plate, a semi-circular groove profile was specified. This shape allows for the inclusion of only half of the cross section with the remaining half being reserved for compressed deformation in the area between the two components. This configuration is intentional to prevent galvanic corrosion between these two components. Where contact occurs between aluminum alloy and stainless steel, corrosion will be accelerated (Juvinall 1983). Aluminum is more anodic than steel and therefore will have the greater tendency to ionize and develop a greater negative charge (electrode potential). The aluminum component acts as an anode and the steel a cathode, thereby allowing for the development of an electrical current flowing from the aluminum to the steel. This continuous discharge of aluminum ions will eventually corrode that part. Another type of corrosion, electrochemical corrosion, can occur if these parts are placed in an electrolytic solution such as fresh water or water with a high salt content. An electrolytic solution acts as an ion carrier with positively charged aluminum ions going into solution leaving an excess of negatively charged electrons on the component (electrode). This action will continue until a condition of equilibrium is reached (Halliday et al. 1992). Since these components function in an environment where water is repeatedly drained from and refilled into the cell, equilibrium would not occur and continued corrosion could be expected.

The combined use of an insulator (Nitrile o-ring) and de-ionized water as a confining fluid helps to lesson the potential for corrosion of these components.
Additionally, the aluminum base platen and riser was anodized to fill in the porous surface of the material, making it more resistant to the effects of corrosion and hardening it to protect the surface from abrasion. Compared to the cost of machining the intricate platen, the relatively small cost to anodize the part is prudent for maintaining its integrity.

Table 3-1. Nitrile O-ring Schedule

<table>
<thead>
<tr>
<th>Component</th>
<th>Parker Part Number</th>
<th>Number Req’d</th>
<th>Application Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base-Plate</td>
<td>10-341</td>
<td>1</td>
<td>Interface between confining cylinder and base plate</td>
</tr>
<tr>
<td></td>
<td>2-008</td>
<td>4</td>
<td>Sealant for cables exiting thru base plate</td>
</tr>
<tr>
<td>Top-Plate</td>
<td>2-272</td>
<td>1</td>
<td>Interface between top plate and confining ring</td>
</tr>
<tr>
<td></td>
<td>2-160</td>
<td>1</td>
<td>Interface between top plate and Frelon bearing</td>
</tr>
<tr>
<td>Strut</td>
<td>2-118</td>
<td>4</td>
<td>Interface between top of strut and top plate</td>
</tr>
<tr>
<td>Confining Ring</td>
<td>2-275</td>
<td>1</td>
<td>Interface between confining ring and confining cylinder</td>
</tr>
<tr>
<td>Piston Plate</td>
<td>2-044</td>
<td>2</td>
<td>Restraining rings for membrane to piston plate</td>
</tr>
<tr>
<td>Piston Plate Cover</td>
<td>2-044</td>
<td>1</td>
<td>Interface between piston plate cover and piston plate</td>
</tr>
<tr>
<td>Base Platen #1</td>
<td>2-044</td>
<td>2</td>
<td>Restraining rings for membrane to piston platen</td>
</tr>
<tr>
<td></td>
<td>2-042</td>
<td>1</td>
<td>Interface between base platen and base plate</td>
</tr>
<tr>
<td>Base Platen #2</td>
<td>2-044</td>
<td>2</td>
<td>Restraining rings for membrane to piston platen</td>
</tr>
<tr>
<td></td>
<td>2-042</td>
<td>1</td>
<td>Interface between base platen and base plate</td>
</tr>
</tbody>
</table>

3.3.1.10 Instrumentation ports

With these components designed, attention then turned towards the requirements for instrumentation incorporated with the cell. As a minimum, it was decided that a total of five sealed ports were needed to analyze the specimen during testing. Of these ports, two are designated for axial LVDTs, two for radial LVDTs, and one for temperature monitoring by way of a thermistor probe. With the exception of the thermistor probe which is connected to an outlet conduit at the top of the cell, the remaining instruments exit the cell through the base plate and are chased neatly to the back of the cell. In order to ensure there are no leaks when the LVDT cables penetrate through the base plate,
special two-piece fittings were procured. These fittings were designed such that as the two parts are screwed together an o-ring compresses against the cable that is passed through the two parts, thereby effectively sealing the penetration. Additionally, the two-part assembly contains an outer o-ring that seals against a bore made through the base plate. This configuration makes instrument installation of the cell rapid and flexible with regards to configuration.

3.3.1.11 Component tolerance specification

As with any machine design, the specification of dimensional tolerance was required as part of the design process. Since two different materials, aluminum alloy, and stainless steel, were used in the cell thermal expansion effects needed to be considered.

The only moveable component in the cell is the piston. As a result, this component and the tolerance of the sleeve it oscillates within, warranted special consideration. Calculation of dimensional tolerance was accomplished using tables published by the American National Standard Index (ANSI). The piston sleeve assembly was considered as a running clearance fit, which is typical for applications requiring lubricant between the piston and sleeve (Earle 1994). Although no lubricant was intended to be used, the gap created between the two components ensured that there would not be any abrasion due to contact. Any contact could cause unrecoverable damage to the surface of the piston and diminishing the effectiveness of the u-cup lip seals. The calculated tolerances were then checked versus the anticipated expansion of the piston and sleeve to ensure that a gap would still exist at high testing temperatures. For calculation, the high test temperature was taken as 140°F. Coefficients of thermal expansion were taken as 12x10^{-6} in/{°}F for aluminum alloy and 8x10^{-6} in/{°}F for stainless steel (Juvinall 1983). As can be seen from these values, the higher coefficient of thermal expansion for the
aluminum alloy piston validated the design considerations. If the gap between the piston and the sleeve were too small, the piston could become engaged with the sleeve at high operating temperatures. Since the piston was to be anodized, the diameter and tolerance were defined as post-coating.

All thru hole locations were specified using rectangular coordinates. Over-sizing of holes, in locations where bolts would be used, was specified with common drill diameters. This relieved the fabricator from the needless effort of obtaining an over-prescribed tolerance. This over-sizing made all the mechanical connection points flexible with regards to orientation of the mating parts. This flexibility allowed for mild adjustments, which created optimal sealing conditions for the structural components.

The length of the confining cylinder was defined to the hundredth of an inch. Although a more stringent overall length could have been specified, doing so would have placed an undue burden on the fabricator and resulted in higher than necessary cost. The ability for the struts to be lowered or raised meant that the clear distance of the top and bottom plate controlled with the struts could correct any error in the overall length of the confining cylinder.

Square-profiled grooves for o-rings were specified a tolerance as recommended by the manufacturer. These tolerances represent the manufactured tolerance of the o-rings, which, due to their elastic property, can adjust to minor dimensional intolerance.

### 3.3.2 Fluid Distribution System

The fluid distribution system is critical for effective stress state tests. The system is composed of four basic components: 1) a hydraulically driven volume changer, 2) a 50 mL capacity graduated burette/annulus, 3) a manually controlled fluid routing board, and 4) a vacuum/pressurized air control panel.
The water delivery and pressurization system is separate and free standing from the cell. All fittings and conduits are high-pressure capacity with the minimum pressure fitting having a capacity of 1200 psi. This surplus of capacity over and beyond the maximum test pressure is owed to the availability of fittings from common suppliers. Valves are manufactured from carbon steel and are gate valve typed.

In determining the layout of the distribution lines, an effort was made to limit the length of each respective line. In long conduits, a phenomenon referred to as a dynamic front can occur where pressure exerted at one end of the conduit is delayed from developing at the opposite end of the line. This is attributed to a retardance of the pressure transmittance due to sidewall friction. The valves were positioned such that they limit the length of conduit between the area of interest and the pressure transducer monitoring that line.

The system is pressure-driven via a servo-controlled, hydraulically actuated volume changer. This volume changer acts similarly to a syringe in that it draws and plunges water from a bore-type reservoir. Through a network of unidirectional valves, the volume changer is capable of refilling with de-aired water from an inline storage reservoir without allowing a decrease in pressure in the network beyond it. From the volume changer, pressurized water can be distributed through one or any combination of three conduits: bottom of specimen, top of specimen, or cell interior (confining space around the specimen). Each of these three lines is monitored with a pressure transducer that communicates to the volume changer through a system controller, thereby allowing for the control of exerted pressures within and around the specimen. This closed loop control allows for precise measurement and rapid monitoring of pressure. Additionally,
the volume changer is monitored by an LVDT, which reports the displacement of the piston within it. As with the pressure transducers, this LVDT acts in a closed loop with the system controller allowing for rapid monitoring and command of positioning. By calibrating the volume of water discharged from the volume changer per linear displacement, the quantity of fluid forced through the specimen can be determined. This is a critical design element in that this quantity allows for the verification of saturation of the specimen.

In order to protect the cell against damage due to an accidental over-pressure, a blow-off valve was installed in the distribution system that is gauged to open if line pressure exceeds 400 psi. This valve is located in the distribution line that supplies water around the specimen. This position was logical since the test with the greatest anticipated pressure is the indirect tension (extension) test wherein the pressure around the specimen is increased until failure occurs. Since the volume changer is rated at 1200 psi, far exceeding the capability of the cell, it was believed prudent to allow for the safe release of unwanted pressure if a system malfunction occurred. Measures such as this are essential in designing a safe system considering that the relative incompressibility of water can yield compounding values of pressure with very little displacement of the volume changer.

The basis for designing this system is for the testing of specimens in effective stress conditions. Therefore, it is necessary to ensure that the specimen is saturated and that the fluid used for saturation is free from dissolved air. The water used for all testing is first de-aired using a 2-liter capacity vortex de-ainer. This fluid is then stored in a large volume until testing. For the initial filling of the cell to begin a testing sequence, the
large volume is drawn on directly via a filling line that utilizes elevation head to expedite filling. For the distribution of fluid through the specimen, the water is first conveyed to a smaller storage tank where, through a network of check valves, the fluid can be introduced into the volume changer or burette.

Backpressure saturation is possible from a water volume storage tank and vacuum line integrated to the water distribution system. This allows for a specimen to be installed into the cell and saturated and conditioned in-place prior to testing.

For flow measurements through the specimen, the system is outfitted with a calibrated 50 mL burette that is designed specifically for use when performing permeability testing.

### 3.3.3 Water Conditioning Systems

For temperature control, the water delivery system can be connected to either a heater or chiller unit. The heater and chiller are each capable of pumping water through the water delivery system and into and out of the cell cavity prior to returning in a closed-loop path. Conditioning in this manner utilizes the principle of conduction as the mode of energy transference.

The combination of the heating and chiller units allows the test specimen to be controlled within the range of 2-75°C. Unlike other systems which use indirect conditioning methods (e.g., a closed conduit running through a temperature bath), this configuration has proven very responsive and capable of conditioning a specimen from room temperature to the aforementioned range limits in less than 90 min. A discussion on conditioning confirmation with this system is presented later.
3.4 Targeted Testing

The compilation of systems was designed to provide a more efficient manner in which to perform a multitude of tests in one workstation. The ETTS is designed to test asphalt specimens in both effective and total stress conditions. Presently, protocols have been developed which allow the system to perform the following:

- In-place saturation and conditioning
- Constant-head permeability determination
- Falling-head permeability determination
- Compression testing
- Resilient modulus testing
- Complex modulus testing

Future development will allow the system to perform other tests such as

- Creep testing
- Tension testing

The successful development of these protocols will allow the user to perform a multitude of tests without relocating or damaging the specimen. The improvements incorporated into this new system also makes the excitation of pore water pressure more easily controlled, thereby allowing for a better assessment of specimen response to these pressures.
Table 3-2. Enhanced Triaxial Testing System Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall dimensions</td>
<td>18.95 inches high x 12.50 inches in diameter</td>
</tr>
<tr>
<td>Maximum operating pressure</td>
<td>400 psi</td>
</tr>
<tr>
<td>Maximum design pressure</td>
<td>800 psi</td>
</tr>
<tr>
<td>Maximum piston travel length</td>
<td>0.75 inches</td>
</tr>
<tr>
<td>Specimen diameter</td>
<td>4 inches (100 mm)</td>
</tr>
<tr>
<td>Specimen aspect ratio</td>
<td>1.25-1.50</td>
</tr>
<tr>
<td>Accessory ports</td>
<td>4 through base plate, 1 through top plate</td>
</tr>
<tr>
<td>LVDT orientation capability</td>
<td>2 axial, 4 radial</td>
</tr>
<tr>
<td>Volume of water to fill cell</td>
<td>3.6 gal (825 in³)</td>
</tr>
<tr>
<td>Structural frame material</td>
<td>Stainless steel 303</td>
</tr>
<tr>
<td>Confining cylinder material</td>
<td>Aluminum 6061-T6</td>
</tr>
<tr>
<td>Piston and end platen material</td>
<td>Aluminum 6061-T6</td>
</tr>
<tr>
<td>Soft seal material</td>
<td>Buna-N o-rings</td>
</tr>
<tr>
<td>Piston seal material</td>
<td>2 Nitrile U-cup lip seals</td>
</tr>
<tr>
<td>Water conditioning range</td>
<td>2-75°C</td>
</tr>
</tbody>
</table>
CHAPTER 4
TESTING METHODOLOGY

4.1 Test-Specimen Preparation

Specimens made for testing used a well-known mix design. A coarse granite mix (C1) traffic level 5, commonly used by the Florida Department of Transportation (FDOT), was used with a target air void content of 7.5% ± 0.5%. Prior to gyratory compaction, all specimens were long-term oven aged at 140°F for 16 hours followed by a 2 hour aging at 275°F. Specimens were gyrated to $N_{\text{design}} = 109$ and then stored at ambient temperature for a minimum of 72 hours prior to cutting. The ends of the specimens were then cut using a manually operated wet saw. This additional step was done in order to create perpendicular faces to the longitudinal axis of the specimen. This ensured that the entire end surface of the specimen was in contact with the end platens. Bulk specific gravities were then taken to determine percent air voids. Table 4-1 presents the job mix formula used for the specimen batching.

Table 4-1. Job Mix Formula for Coarse-Graded Granite Mix (C1)

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>#7 Stone</th>
<th># 89 Stone</th>
<th>W-10 Screens</th>
<th>Filler</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;3/4&quot;</td>
<td>0.0</td>
<td>311.7</td>
<td>1260.9</td>
<td>2734.3</td>
</tr>
<tr>
<td>&quot;1/2&quot;</td>
<td>73.9</td>
<td>311.7</td>
<td>1260.9</td>
<td>2734.3</td>
</tr>
<tr>
<td>&quot;3/8&quot;</td>
<td>311.7</td>
<td>311.7</td>
<td>1260.9</td>
<td>2734.3</td>
</tr>
<tr>
<td>#4</td>
<td>311.7</td>
<td>1260.9</td>
<td>1260.9</td>
<td>2734.3</td>
</tr>
<tr>
<td>#8</td>
<td>311.7</td>
<td>1260.9</td>
<td>1991.9</td>
<td>2734.3</td>
</tr>
<tr>
<td>#16</td>
<td>311.7</td>
<td>1260.9</td>
<td>2286.3</td>
<td>2734.3</td>
</tr>
<tr>
<td># 30</td>
<td>311.7</td>
<td>1260.9</td>
<td>2453.8</td>
<td>2734.3</td>
</tr>
<tr>
<td>#50</td>
<td>311.7</td>
<td>1260.9</td>
<td>2567.8</td>
<td>2734.3</td>
</tr>
<tr>
<td>100</td>
<td>311.7</td>
<td>1260.9</td>
<td>2679.3</td>
<td>2734.3</td>
</tr>
<tr>
<td>200</td>
<td>311.7</td>
<td>1260.9</td>
<td>2734.3</td>
<td>2734.3</td>
</tr>
<tr>
<td>&lt;200</td>
<td>311.7</td>
<td>1260.9</td>
<td>2734.3</td>
<td>2831.1</td>
</tr>
</tbody>
</table>
4.2 Saturation Procedures and $B$-Value Determination

4.2.1 Introduction

Specimens tested in an effective stress condition were required to be saturated prior to testing. This was required for two fundamental reasons: 1) any air entrapped in the void network of the specimen would compress upon stress application thereby dampening the response of the specimen to applied stresses and 2) an acceptable repeatability of testing results required that specimens have similar initial state conditions. Therefore, a method had to be established to ensure a threshold of saturation in the most expeditious and repeatable way.

4.2.2 Saturation Procedure

4.2.2.1 Discussion

The specimens used for testing contained air voids of 7.5 ± 0.5%. In a paper discussing the factors affecting permeability of Superpave designed pavements, Mallick (2003) reported that “Recent work by the FDOT has indicated that coarse-graded Superpave mixes can be excessively permeable to water at air void levels around 6%”. It was further reported that as the nominal maximum aggregate size of a mixture increases so too does the potential for interconnected voids. It is these voids, which allow permeant to network through the specimen thereby permitting saturation in a triaxial cell. Therefore, at the beginning of this research it was believed that specimens could be effectively saturated in the laboratory if a protocol could be developed that would maximize the transport capacity of these interconnected voids. However, it is known that, as the thickness of the asphalt increases, the potential for permeability will likely decrease (Cooley et al. 2001). This relationship of thickness versus permeability potential was of foremost concern during the development of a saturation protocol.
4.2.2.2 Procedure

Saturation of the specimen was achieved combination of three techniques: vacuum saturation, flushing, and the application of backpressure by a. Early in the design of a saturation protocol, the specimen was installed into the cell dry and saturation procedures were initiated. This approach was soon abandoned due to the amount of time required for saturation – typically, 3-4 hours. An abbreviated form of the AASHTO T-283 conditioning method was employed to assist with the saturation of the specimen prior to installing it into the cell. The dry specimen was submerged into a water-filled vacuum chamber and a pressure of –26 in Hg was applied for 5 min. At the end of this time, the developed vacuum was released and the specimen was allowed to rest for 1 min. As a vacuum is applied to the specimen, entrapped air within the specimen is allowed to exit since the pressure outside of the specimen is less than that inside of it. As the entrapped air is pulled from the specimen a negative pressure (vacuum) develops within the corridors of air. When the negative pressure within the specimen is equal to that of the chamber, the liberation of air ceases and further saturation is not possible. The rest period allows the water surrounding the specimen to enter the specimen and mix with the remaining entrapped air. By cycling this procedure, the concentration of air lessens as an increasing volume of water occupies the network of voids. This process of vacuum saturation and rest period was repeated until no air was observed leaving the specimen. For a typical specimen, this process would be conducted 4 or 5 cycles.

Following the vacuum saturation, the specimen was placed into a sink, wrapped with a latex membrane, and outfitted with the o-rings that would be used to secure the membrane to the end platens of the triaxial cell. Prior to the placement of the o-rings, the ends of the membrane were rolled back onto the specimen thereby leaving the ends
uncovered. By rolling the membrane back onto itself, the likelihood that the sharp ends of the specimen would puncture the membrane were reduced. Now ready for installation into the cell, the specimen was transported in a water-filled bucket. The efforts made to keep the specimen submerged were warranted since the coarse mix specimen would drain rapidly if allowed.

Prior to installing the specimen into the cell, the system was flushed of any air. Water was forced through the distribution panel and up to the point where it reached the bottom platen. This step allowed any air within this link to be pushed out thereby precluding the air from having to travel through the specimen once it was installed and negating the efforts made to saturate it.

After the specimen was installed into the cell, a flushing cycle was conducted. The flushing cycle consisted of water being forced through the bottom of the specimen and exiting from the top. With the confining cylinder left off to allow viewing of the membrane encased specimen, a gradient of approximately 5, the equivalent of 1 psi, was applied to the burette creating an adequate flow of water to assist in forcing any remaining pockets of entrapped air out of the specimen. Being able to view the specimen allowed for the detection of any leaks in the membrane, which would compromise the effectiveness of any subsequent testing. Since there was not a confining stress applied to the specimen at this point, the membrane was allowed to balloon around it allowing any air between the membrane and the specimen’s circumferential surface to exit rapidly through the top platen. This decreased the amount of time needed to flush air from the specimen since this portion of air did not have to travel through the specimen but rather
around it. Typically, 500 to 600 mL of water was forced through the specimen before air was not observed exiting the specimen.

The next phase of saturation was to remove dissolved air from the permeant. A vacuum saturation procedure was then conducted with a pressure of –26 in Hg applied to the top of the specimen. Since the valve leading to the bottom of the specimen was closed, a vacuum was allowed to develop within the specimen. When the vacuum reached –26 in Hg, the fluid conduit leading into the top of the specimen was closed and the bottom conduit opened thereby allowing water from a storage reservoir to be drawn through the specimen’s void network. This process was continued until air was not observed in the burette at the effluent end of the specimen.

At this point, the confining cylinder of the cell was not installed and the membrane-encased specimen was exposed. In order to install the cylinder and fill the cell with water for confinement pressure application, the influent valve was closed and the effluent line disconnected at a point in the line between the distribution panel and the cell. After installing the confining cylinder and securing the confining ring, the effluent line was reconnected and the cell filled with water via the inlet located in the base of the cell. With the cell pressure-tight, the influent valve closed, and the effluent valve open, a confining stress of 5 psi was applied to the specimen. This confining stress forced the ballooned membrane in contact with the specimen. Any water that was between the membrane and the specimen was forced through the effluent line and into the burette. To ensure that all of the air that was introduced into the effluent line upon disconnection was discharged from that line, an additional flushing cycle was conducted.
The final phase of saturation used a backpressure technique. With both the influent and the effluent valves open, pressure was increased until the confining pressure and pore-pressure readings at both ends of the specimen were approximately 60 psi and 55 psi respectively. The confining and pore-pressures were incrementally increased such that a maximum effective stress of 5 psi was maintained. The backpressure was applied for 30 min prior to the taking of a $B$-value.

**4.2.2.3 Verification of saturation**

To verify the saturation process, the volume of water delivered into the specimen was compared to the volume exiting it. The volume of water entering the specimen was calculated by recording the linear displacement of the volume changer and converting that displacement into a volume. The corresponding volume of water exiting the specimen was read directly in the burette on the distribution panel. The displacement of the volume changer was kept small during this verification process. This was done because the relatively low conductivity of the specimen meant that dissipation of high pressure at the influent end, as would occur with a large displacement of the volume changer, would occur slowly. This slow pressure dissipation rate could lead to premature taking of the burette reading which would appear low as compared to the volume of water pushed into the specimen. To alleviate this possibility, burette readings were not taken until the pressure transducer readings at the top and bottom of the specimen were approximately equal.

**4.2.3 Determination of the $B$-Value**

**4.2.3.1 Theory of testing**

Prior to any testing of saturated specimens, it was necessary to correlate the pore-pressure coefficient $B$ with percent saturation. The traditional method of obtaining the
coefficient, commonly referred to as the $B$-value, on soil specimens is to increase the
confining stress on it and measure, via a pressure transducer, the resulting increase in
pore water pressure. This relation is thereby expressed as

$$ B = \frac{\Delta u}{\Delta \sigma} $$

(4.1)

where $\Delta u =$ Change in pore water pressure  
$\Delta \sigma =$ Change in confining stress

This relation suggests two fundamental assumptions:

- The voids within the specimen are connected such that the pore water pressure is
  conducted through the skeleton.
- The specimen’s skeleton is elastic such that the induced confining pressure is
  transferred to the water-filled voids and not carried exclusively by the skeleton.

In research done to assess the potential factors affecting HMA permeability, coarse
graded asphalt mixtures were shown to contain larger individual air voids and thus an
increased potential for interconnected voids (Cooley et al. 2001). This supported the
premise that a specimen could be successfully saturated by the conduction of water
through it from end to end.

The skeleton of an asphalt specimen at room temperature is extremely stiff. An
asphalt specimen is analogous to heavily over-consolidated clay exhibiting both adhesive
and cohesive properties. It is therefore logical to question what percentage of confining
stress will be carried by the skeleton and accordingly transferred to the water-filled voids.
A concern with the process of establishing a $B$-value with asphalt specimens is that as
more confining stress is applied, the resulting $B$-value increases to a point and then
decreases. This decrease is attributed to the stiffness of the specimen, which increases as
the specimen undergoes compression. From resilient modulus testing, stresses as high as
40 psi were required to induce a vertical strain of $250 \times 10^{-6}$ in/in when tested at 40°C. At a relatively low confining stress, a negligible amount of compression occurs.

During development of the protocol, a trend was observed in the resulting $B$-value as the effective stress was increased. As the effective stress was increased, the $B$-value would increase, stabilize, and then decrease sharply. This trend is believed to be a function of the geometry of the specimen’s circumferential surface as well as the relative stiffness of the skeleton. Conceptual illustrations of this trend are shown in Figures 4.1 and 4.2, as the effective stress is increased, the corresponding $B$-value goes through three distinct phases. At the start of Phase 1, the effective stress is approximately 3 psi; the membrane is in contact with the high points on the circumferential surface of the specimen and suspended over the surface indentations cushioned on water. As the effective stress is increased, the membrane is forced into the indentations, in the process absorbing some of the stress in its deformation; this results in an increasing $B$-value. At the start of Phase 2, the membrane is stretched into the indentations and compression of the water within the specimen has occurred. As the effective stress is further increased, the membrane is forced further into the voids of the specimen until a limit is reached. Within this phase, the optimal $B$-value is reached. The thickness (0.012 inch) of the membrane prevents it from further penetration into the voids of the specimen with an increase in confining pressure. At this point, Phase 3 begins wherein the increasing confining pressure yields a correspondingly small increase in pore-pressure. This relationship results in a decreasing $B$-value.

With the process understood, the approach to a $B$-value was achieved by increasing the confining pressure in small increments to reveal the optimal $B$-value range. With
typical initial effective stress conditions employed for each specimen, and similar surface
geometry, the optimum $B$-value was achieved within approximately the same quantity of
confining stress increase.

4.2.3.2 Procedure

At the commencement of the taking of the $B$-value, the specimen had been
backpressure saturated for 30 min. The confining pressure and pore-pressure were pre-
established at approximately 60 psi and 55 psi respectively. To begin the $B$-value test,
the influent and effluent valves were closed effectively locking in the approximately 55
psi of pore water pressure. Using an air over water configuration, the confining pressure
was increased in approximate increments of 0.25 psi. As discussed in the previous
section, there was a point where an increase in confining pressure would not yield an
increase in pore-pressure. By increasing the confining pressure in small increments, the
optimal $B$-value range was detected. Typically, the optimal $B$-value was obtained with an
increase of about 2 psi of confining pressure. Further increase of the confining pressure
would show a marginal increase in the pore-pressure.

All pressure readings were taken from a virtual instrument display of the three
installed pressure transducers. The air pressure used over water to increase the confining
pressure onto the specimen was controlled by a needle valve. This configuration was
extremely responsive at high pressures.

4.3 Hydraulic Conductivity

4.3.1 Introduction

A fundamental test for asphalt specimens is hydraulic conductivity determination.
The hydraulic conductivity of asphalt concrete pavement has been shown, in research, to
have a direct relation to durability (Cooley et al. 2002). Permeable pavements allow air
and water to enter into the void structure. The introduction of air will facilitate oxidation of the binder contributing to excessive age hardening. Additionally, water infiltration can contribute to failure of the material. Consideration was made during the initial design of the triaxial cell and distribution panel for hydraulic conductivity testing utilizing both constant and falling-head methodologies. The research attempted to eliminate known errors of testing while developing test protocols that are simple to perform and yield repeatable results. Three specific factors that were addressed during the development of these protocols are: 1) development of a method to ensure that the specimen is saturated prior to testing, 2) establishment of a method to ensure flow through the specimen is in steady-state condition, and 3) development of a method to ensure that continuity is established. These factors are known to have an effect on the “accuracy and reliability” of the conductivity measurements (Kanitpong et al. 2001).

Hydraulic conductivity testing was performed on saturated specimens with a $B$-value $\geq 0.92$. Prior to testing, specimens were wrapped in a latex membrane and the cell filled with de-aired water to act as a medium for confining stress application. As part of the protocol leading up to the taking of a $B$-value, the fluid transmission lines were evacuated of any air that was present through flushing and vacuuming techniques. Therefore, upon the commencement of testing, the system was free from any air bubbles that would hinder the flow of water through the specimen.

A key aspect of hydraulic conductivity testing is to ensure that equilibrium has been established before the test is terminated. ASTM D5084 (Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible-Wall Permeameter) uses two criteria: 1) steady hydraulic conductivity (steady state), and
2) steady flow (continuity). Steady hydraulic conductivity requires that the measurements exhibit no temporal trend, and that the last four measurements fall within 25\% of their mean. Steady flow, which is tantamount to requiring continuity, is ensured using similar criteria wherein the ratio of incremental inflow to incremental outflow shall not exhibit any temporal trend and have the last four measurements fall within 25\% of their mean.

Steady hydraulic conductivity condition was the criterion for inclusion of input data following the test procedure for both the falling and constant-head methods. The steady flow criterion was indirectly examined by reviewing pressure transducer output data at the end of each test. These data were found, through initial targeted experimentation, to fluctuate sporadically as the gradient across the specimen was altered. The ability for the system to monitor fluctuations in these pressures ensured that erroneous test data would be detectable. In the case of a constant-head test, initial screening of collected data would reveal any sudden increase or decrease in pressure that would warrant suspect of invalidity of the test. Figure 4-3 shows all three monitored pressures remained approximately constant without notable fluctuation; this trend is typical of all the subsequent tests. For the falling-head test, where a decrease in influent pressure was inherent, a temporal change in the rate of decrease of the influent pressure was used as a basis for invalidity of the test. Figure 4-4 shows a typical test produces a decreasing rate of influent pressure with respect to time. This is intuitively correct since it has been established that an increase in head has a corresponding increase in hydraulic conductivity. Therefore it would be expected to see the influent pressure become asymptotical to the abscissa with time as the influent pressure approaches zero. Precise
control of end conditions of the specimen and the confining stress as well the assurance of specimen saturation prior to testing, makes the possibility of unsteady flow unlikely.

According to Kanitpong (2001) the steady flow criterion is useful in detecting leaks in the testing system. The influence that any possible leaks in the system would have on the output data was examined prior to any hydraulic conductivity testing. Through intentional manipulation of the distribution panel and the membrane, which confined the specimen, it was determined that the sensitivity of the pressure transducers was adequate to detect any pressure fluctuation which would compromise the validity of the test. A pinhole-sized breach of the membrane, for example, was detectable when the specimen influent and effluent pressures suddenly equaled the higher confining pressure. For the permeant distribution panel, initial proof testing confirmed a pressure-tight system at a static pressure of 400 psi. For these reasons, the system was considered free from inline loss of pressure during testing.

In traditional, triaxial cells, hydraulic conductivity testing of soil specimens has been found to exhibit an increase of effective stress about the effluent end of the specimen (Carpenter and Stephenson 1986). End platens used in these cells are typically comprised of porous stones and filters that can clog due to migrating particles (Fang 1991). This clogging at the outflow end artificially retards the flow of fluid through the specimen in effect acting as a specimen with smaller cross sectional area. Subsequently, this effect yields a lower value for hydraulic conductivity than actual. In asphalt specimens, migration of particles is not dominant due to the adhesive property of the constituents. Additionally, the end platens used in this system are designed such that the entire cross sectional area of the specimen is allowed to transmit water through its ends
uninterrupted. This design is in contrast with typically designed end platens that contain a single hole centered on the face of the platen. A single point of influent/effluent transmission means that the permeant must flow parallel to the end faces of the specimen to conduct it from/to the distribution panel. This boundary influence was concluded to decrease the effective area of flow thereby resulting in an underestimation of hydraulic conductivity (Carpenter and Stephenson 1986). The enhanced end platens used with this system relieves the possibility of constrictions at the influent/effluent ends and supports the requirement for the use of Darcy’s equation that the flow front of permeant lie in a plane perpendicular to the direction of flow.

4.3.2 Falling-Head Hydraulic Conductivity Test

4.3.2.1 Theory of testing

The falling-head hydraulic conductivity test was configured such that falling headwater and constant tailwater conditions were imposed. The common method of testing is to allow the flow of a decreasing column of water to permeate through the specimen and, by recording the time of flow and the starting and ending water level elevations above a defined datum, determine the corresponding hydraulic conductivity.

By assuming continuity of flow and a unidirectional flow path, hydraulic conductivity \( k \), is defined by Daniel (1989) as

\[
k = 2.303 \frac{aL}{At} \log_{10} \frac{h_o}{h_I}
\]

where
- \( a \) = Cross-sectional area of burette (cm\(^2\))
- \( L \) = Length of specimen (cm)
- \( A \) = Cross-sectional area of specimen (cm\(^2\))
- \( t \) = Duration of test (sec)
- \( h_o \) = Head loss across the specimen at time \( t_o \) (cm)
- \( h_I \) = Head loss across the specimen at time \( t_I \) (cm)
In laboratory testing it is difficult to precisely time the duration of the test since the accuracy of test results is dependent upon the observation and response of the operator. The permeant, typically water, is assumed to be flowing continuously through the specimen even though a relatively small volume of fluid has passed through it at the start of the test period. Additionally, in a traditional falling-head test without automated data acquisition, the hydraulic conductivity is calculated using starting and end conditions parameters as input values. Therefore, the researcher is unable to ascertain any possible fluctuations in hydraulic conductivity during the test.

In order to utilize the existing test system, an innovative method had to be created to conduct falling-head hydraulic conductivity testing. Using the test methodology of the Florida method as a model, a modified falling-head hydraulic conductivity test was developed. The FDOT employs a method, commonly referred to as the Florida method, of falling-head permeability testing wherein a specimen is encased about its circumference by a latex membrane that is inflated with air. The confinement imposed by the inflated membrane effectively seals the circumferential face from migrating water. On the top of the specimen is placed a burette filled with water. The water is allowed to flow through the specimen and exit, from the bottom face of the specimen, to the atmosphere. At the start of the test, this gravity-driven arrangement’s column of water is between 36 to 48 inches in height, the equivalent of 1.3 to 1.7 psi of static elevation head. By recording the time it takes for the column of water to drop to a predetermined level in the burette, the permeability of the specimen can be calculated by utilizing Equation 4.2.

As can be seen from Equation 4.2, the height of the column of water is simply a pressure exerted onto the top of the specimen that decreases accordingly as the water
flows through the specimen. The testing system does not require the height of the column to be monitored since the pressure felt by the specimen on its ends were gauged by pressure transducers and automatically recorded throughout the duration of the test. This advantage over traditional arrangements not only provides more accurate data but also allows for the calculation of hydraulic conductivity at each time step. The ability to calculate hydraulic conductivity throughout the test is critical for assuring that the flow of water through the specimen is steady thereby complying with Darcy’s requirements for use of Equation 4.2.

Upon application of a hydraulic gradient across the specimen, there will exist some erroneous values for the representative flow. These values represent the non-linearity of the applied gradient as a result of sudden, differing end conditions. During this initial phase, flow paths within the specimen are still developing and the network of fluid within it is still not in equilibrium. As the test progresses, the gradient becomes more linear across the length of the specimen thereby yielding a steady-state flow condition. Figure 4-5 shows that approximately the first 10 to 15 sec of the test indicates unsteady flow through the specimen. This duration of time corresponds to the 3.0 to 2.0 psi of top pressure interval, which is not included in the final data set. Steady conductivity is apparent from this point until the top pressure is approximately 0 psi corresponding with a time of approximately 40 sec. Past this time, the pressure readings can be seen to fluctuate up and down sporadically. This sporadic behavior is owed to signal noise present in the transducer line. It is of value to note that the tailwater condition provides no resistance to flow since the fluid exits to the open atmosphere and is therefore not considered in the calculation.
4.3.2.2 Test procedure

After installation of the specimen and following saturation procedures, the effluent valve (bottom of specimen) was closed thereby restraining fluid and pressure within the specimen. The conduit connecting the distribution panel to the valve leading to the bottom of the specimen was then detached. This allowed the permeant to exit the specimen without resistance from the conduit. With the influent valve open (top of specimen), an air over water confining stress of 5 psi was then applied to the specimen to prevent any migration of water between the membrane and the circumferential area of the specimen. At this point in the test process, any water trapped between the membrane and the specimen was allowed to flow through the specimen and into the burette. Additional water was then added to the burette so that it contained approximately 45 mL of permeant. With the burette full of water, a pressure of 3 psi was applied to the column via the air control panel. The influent valve, located between the control panel and the burette, was then closed thereby locking in the 3 psi of air pressure acting onto the column of water. At this time, the specimen was considered ready for testing. A schematic of permeant routing is shown in Figure 4-6.

To begin the test, the effluent valve, located at the bottom of the specimen, was opened and the water allowed flowing through the specimen. As the flow progressed, the height of the column of water and the pressure driving the fluid decreased. Data acquisition was manually initiated and remained active until the conclusion of the test. A pressure of 2 psi corresponds approximately to the starting conditions of the Florida method and it was from this point that data was considered significant for comparison of results. The difference of 1 psi of pressure that is not considered for the test was used to establish steady state conditions prior to the data acquisition start of the test. It is within
this unconsidered portion of the test that erroneous values of hydraulic conductivity occur due to the non-steady state of flow. Data was acquired every 0.25 sec of the top, bottom, and confining pressures. Pressure transducers are located proximal to either end of the specimen thereby precluding the need to record beginning and ending water column elevations and calculating the equivalent head above a specified datum. The transducers provide the actual pressures required to accurately determine end conditions of the specimen.

The test was terminated when the top pressure read approximately 0 psi. At this point, the pressure within the burette was in equilibrium with the resisting forces of the specimen and water delivery lines (wall friction and losses at fittings). At this time, data acquisition was manually stopped and the effluent valve closed thus terminating the flow of water through the specimen.

For each tested specimen, three consecutive tests were run. Initial test conditions were again achieved by closing the effluent valve, opening the influent valve, refilling the burette with water, and reestablishing pressure on the influent side of the specimen. Care was taken not to allow any air within the burette to be introduced into the distribution lines leading to the specimen. If this were to occur, the specimen was required to be re-saturated and a $B$-value taken to ensure an adequate saturation level. Total time for reestablishing initial test conditions and completing a test was typically less than five min. Besides being a very rapid test to conduct, it also is extremely precise due to the use of pressure transducers coupled with a data acquisition system.
4.3.3 Constant-Head Hydraulic Conductivity Test

4.3.3.1 Theory of testing

By definition, the constant-head permeability test is accomplished with a constant gradient applied across the specimen for the duration of the test. This test is well suited for the triaxial cell type of system since confining as well as driving and resistive pressures can be controlled accurately. Creating a gradient across the length of the specimen produces conductance of fluid through the specimen. As published by Darcy in 1856, the discharge velocity \( (n) \) of water through saturated soils is equal to the product of the materials hydraulic conductivity \( (k) \) and the gradient applied across the specimen \( (i) \). Theoretically, this presents a linear relationship whereby an increase in the gradient yields an increase in the velocity of fluid through the specimen.

The question is therefore presented as what gradient should be used for determination of permeability. Practically, the hydraulic gradient should be as close as is possible to that expected in use (i.e., the roadway). For pavements, the gradient should be approximately 1 since gravity is the primary driving force for water conductance through the strata (Kanitpong et al. 2001). Presently, there are no guidelines for the recommended gradients for constant-head permeability testing in HMA specimens. The ASTM standards do provide a maximum for testing of soils but these gradients are conservatively low to compensate for the compression of the soil’s structure when influenced by pressurized flow through and against the cross section of the specimen. Since the structure of a HMA specimen is stiffer and more resilient to the compressive forces produced by fluid flowing through the specimen, it is reasonable to conclude that a higher gradient can be used with HMA specimens than can with soil specimens.
The gradient applied across the specimen can affect the hydraulic conductivity. In research conducted by Kanitpong (2001) hydraulic conductivity was shown to increase slightly as the gradient across the specimen increased and then decrease with further increase of the gradient. Research by Carpenter and Stephenson (1986) attributed the decrease in hydraulic conductivity with increasing gradient to the high effective stress applied to the outflow end of the specimen. As a result, the optimum hydraulic conductivity for the specimen can be found by conducting testing with an array of increasing gradients until a decrease in conductivity is noted.

Initial development of the constant-head hydraulic conductivity test considered a constant headwater rising tailwater configuration. As is shown in Figure 4-7, a volume changer would be used to induce a gradient across a specimen and into a graduated burette. The volume changer is simply a hydraulically controlled plunger inside of a tube. The combination of these components forms a piston that is capable of delivering fluid to the system in precise increments. Much like a medical syringe, the volume changer would be controlled via a pressure transducer located on the influent line that would be in closed loop with a computerized control system. Pressure on the effluent end of the specimen would be controlled via an air pressure regulator outside of the system. The control system would ensure that a near constant gradient was applied across the specimen. Additionally, the volume changer would be outfitted with a LVDT that would record the linear displacement of the plunger, which in turn could be converted to a displaced volume. The derived equation for constant-head hydraulic conductivity using this configuration is derived in Appendix B and presented as

\[
k = \frac{-aL}{At} \ln \left[ \frac{(P_2 - P_1) + (Z_2 - Z_1) + h_b}{(P_2 - P_1) + (Z_2 - Z_1)} \right]
\]

(4.3)
This configuration has several distinct advantages including: promotion of a steady-state of flow, increased control of the quantification of influent, automated data acquisition, and ease of repeatability of initial conditions. With data acquisition equipment in a looped circuit with a controller, the test can be made completely automated thereby removing the chance of any human error. At the time the testing protocol was being developed, deficiencies with the capabilities of the system control device precluded this arrangement. At the time of this research, resolutions of these deficiencies were being conducted such that this configuration could be used in future testing.

The alternate method, and the one used in the presented research, also used a constant headwater rising tailwater condition, but air over water was used in lieu of the volume changer to pressure the influent water. It was recognized that further simplification of Equation 4.3 could be made since pressure transducers were located proximal to each end of the specimen. Pressure transducers, located at both the influent and effluent ends of the specimen meant that time dependent readings of the rising water in the burette were not required. As part of the data reduction following the test, influent and effluent pressures were converted to head of water and the difference of these two readings used in the following equation to arrive at a value for hydraulic conductivity at each time step.

Hydraulic conductivity \( (k) \) using the constant-head method was calculated using the equation presented by Das (1998) as

\[
k = \frac{QL}{Aht}
\]

(4.4)

where \( Q \) = Volume of fluid through the specimen (cm\(^3\)/s)
\[ L = \text{Length of specimen (cm)} \]
\[ A = \text{Cross sectional area of specimen (cm}^2\text{)} \]
\[ h = \text{Head applied across the length of the specimen (cm)} \]
\[ t = \text{Duration of test (sec)} \]

4.2.3.2 Test procedure

Pressure, both driving and resisting, was provided by air controlled through a system of needle valves. The control panel is capable of providing air pressure to the cell (confining stress) as well as to the top and bottom of the specimen. Pressure used for confining stress is introduced directly to the cell via access through the top plate. Pressure to the top of the specimen is routed from the top of a graduated burette where it interacts with a column of effluent water from the specimen. The bottom of the specimen receives fluid via a storage reservoir of de-aired water. A schematic of permeant routing for this test is shown in Figure 4-8. Although the control panel contains pressure dial gauges for each line, initial condition and data acquisition routines relied upon pressure transducers for all readings throughout the test. Therefore, any change of pressure during the test is accurately recorded in the data acquisition output. This time step acquisition allows for the calculation of hydraulic conductivity throughout the test period which would reveal any errors that may have occurred during the test, such as a sudden reduction/increase in pressure, that otherwise would not be detectable.

In order to ascertain the influence that differing gradients have upon hydraulic conductivity in HMA specimens, gradients of between 5 and 55 were used in increments of 5 and the corresponding hydraulic conductivity calculated accordingly. For a typical length specimen, this represents a pressure difference across the specimen of between 1 and 11 psi respectively. For the purpose of this paper, the condition at the end of the specimen with the lower pressure is referred to as the “resisting” pressure while the end
with the higher pressure is referred to as the “driving” pressure. The resisting pressure exerted on the top of the specimen (effluent) was constant for each test as 1 psi. The driving pressure exerted to the bottom of the specimen (influent) ranged from 2 to 12 psi. Confining stresses for each gradient were chosen to be high enough to prevent sidewall leakage but not so high as to hinder the flow of fluid through the specimen. These stresses ranged from 5 to 7.5 psi above the average pressures exerted onto the specimen. Table C-1 in Appendix C lists the applied stresses at each gradient.

Each specimen was tested over the aforementioned gradient range starting with the lowest. The prescribed confining stress was applied first since it was found that more control could be achieved with regards to the adjustment of the top and bottom pressures if the confining stress was already stabilized. The graduated burette was initially filled with enough water to ensure that the supply line leading to it was fully charged with fluid (typically 5 mL above the lower inlet). The top and bottom pressures were then adjusted to the prescribed values while allowing fluid to transport through the specimen. It was found that an attempt to close the valves to the specimen, achieve the desired pressures, and then open the valves for testing caused a continuity problem which would not stabilize before the burette was filled to capacity with permeant received from the specimen. Therefore, it was judged best to approach the target gradient with the influent and effluent lines open to achieve continuity before any data acquisition.

Data acquisition was initiated and terminated by manual control when the rising column of water reached predetermined levels in the graduated burette. As the gradient was increased for successive tests, the amount of fluid allowed to flow through the specimen prior to test termination was increased. This was done primarily to compensate
for the increased rate of flow through the specimen that results from a higher gradient and
normalize the duration of the test. Prior to the acquisition of data, fluid was allowed to
flow through the specimen in order to approach a condition of steady flow. The data
acquisition system took readings of: confining, top, and bottom pressures every 0.25 sec
as well as the total time of the test. Since the burette was calibrated prior to any testing,
the flow rate could be calculated and applied to the acquired data to arrive at the
accumulated volume of fluid passed through the specimen at each time step. Calculating
the difference between the top and bottom pressures and dividing by 27.68 in H$$^2$$O/psi
calculated the change in head across the specimen at each time step. With these data
along with the height and cross-sectional area of the specimen, the hydraulic conductivity
at each time step could be calculated.

As with the falling-head test, the first step of data reduction with the constant-head
test was to calculate the hydraulic conductivity at each time step. The hydraulic
conductivity was calculated at each time step using Equation 4.4. The accumulated
volume of fluid through the specimen and the accumulated time of testing were used as
input data respectively. The hydraulic conductivity was plotted versus time to detect any
temporal trends or sporadic behavior throughout the test period. Since the influent and
effluent pressures were maintained constant throughout the test, the possibility of such
occurrences is not prevalent in testing. However, such occurrences should be researched
since they would reveal data acquisition errors or distribution system discontinuities,
which would otherwise go undetected. Additionally, the steady hydraulic conductivity
termination criterion was applied to determine if the hydraulic conductivity reading at
each time step was within 25% of the mean of the previous four readings. Similarly to
the falling-head test, if a reading was found to fall out of the 25% allowance, all readings
taken past that time step were excluded from the data set. The average of the included
data was taken as the representative hydraulic conductivity of the specimen. These
procedures were repeated for each successive gradient in order to determine the
maximum conductivity.

By maintaining fluid in the transmission lines as well as in the column of the
burette, saturated conditions were maintained in the specimen. Therefore, the specimen
could be retested within a very short period of time, typically less than 5 min per test.
The specimen was readied for an additional test by refilling the burette with de-aired
water and establishing a new gradient.

4.4 Compression Testing

4.4.1 Theory of Testing

The Consolidated Undrained (CU) test is performed with the influent and effluent
lines to the specimen closed. With a confining stress applied to the specimen, the
deviator stress is increased until shear failure occurs. Since drainage is not allowed
during the test, pore water pressure will increase. In dense specimens such as clay, the
pore water pressure will increase with strain to a limit and then decrease and become
negative (Lambe 1969). The decrease is owed to the specimen dilating resulting in an
increase of specimen volume.

By conducting several tests with varying initial confining pressures, shear strength
parameters can be determined. This is done by generating Mohr’s circles and, either by
equations or graphical representation, deriving the angle of shear resistance, \( \Phi \).
4.4.2 Specimen Preparation

Prior to installing into the cell, the specimens were measured to determine average height and cross-sectional area. These values would be used to calculate strain and initial cross-sectional area respectively. Specimens were then saturated and a $B$-Value taken in accordance with the procedures outlined in Section 4.2. Following the saturation procedure, a pre-determined confining stress was applied and the influent an effluent valves leading to the specimen were closed.

A set of three specimens was used to establish shear strength at three different confining stresses. Confining stresses of 15, 25, and 35 psi were chosen to provide adequate variance for shear strength parameter determination. The specimens were stabilized to $40^\circ\text{C} \pm 0.1^\circ\text{C}$ in accordance with the protocol described in Chapter 5.

4.4.3 Test Procedure

At the start of the test, the influent and effluent lines were closed and the confining stress approximately equal to the target stress. The valve to the confining water was closed thereby locking in the pressure and an axial load was applied at constant rate. During the test, a data acquisition system recorded: axial displacement, axial load, top, bottom, and confining pressure at 1 sec intervals. Axial displacement continued until either a perceived decrease in stress carrying capacity occurred or a maximum 0.75 inches displacement of the piston occurred. The maximum displacement is a function of the cell and a displacement past this limit would expose the piston seals beyond the confines of the piston sleeve allowing confining pressure to be lost.

The specimen was loaded at a constant rate of 0.0025 in/s. For a typical length specimen of 5.5 inches, this rate of loading used produced approximately 2.75% strain.
4.5 Resilient Modulus

4.5.1 Theory of Testing

Resilient modulus, or what is sometimes referred to as repeated load indirect tensile test, is the most common method of measuring stiffness modulus with HMA specimens (Roberts 1996). The procedures for conducting the test are described in ASTM D4123 Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures. In the test, a cyclic load is applied for 0.1 secs followed by a rest (no load) period of 0.9 secs. The rest period allows the specimen to recover from the elastic deformation that occurred during the loading. This loading/unloading sequence produces a waveform from which the elastic deformation can be calculated.

The testing completed for this project was targeted to develop a method to monitor the resilient modulus of a specimen as a result of cyclic excitation of pore-pressure. Pore-pressure was excited in three different ways: by axial loading, confining pressure, and pore water pressure.

4.5.2 Specimen Preparation

Prior to testing, specimens were saturated and a $B$-value taken to ensure a level of adequacy. Specimens were tested at both 10°C and 40°C. Each specimen was first tested at 10°C and then at 40°C. The consecutive testing meant that the saturation procedure only needed to be completed once therefore expediting the combined test time. This procedure is the reason for the development of a time dependent cooling to heating protocol as is discussed in Chapter 5.

4.5.2.1 Instrumentation

Prior to sealing the cell, an LVDT holder was installed in which was attached two axial LVDTs. The holder is composed of two split rings that are affixed to the specimen
at four flat areas on the interior surface. These flat areas are grooved thereby allowing the rings to grasp onto the membrane and limit the amount of movement. Between the two rings are four removable gage struts, which ensure that the gage length is consistent with each test. The axial LVDTs were placed opposite from one another and secured to the top ring via thumbscrews.

Within the bottom ring, aligned opposite of the LVDTs installed in the top ring, are stainless steel dowels, which ride in thru holes and are affixed to the bottom ring via thumbscrews. In order to ensure that the LVDT piston was approximately at the mid range point, the piston was adjusted by moving the dowels up and down until the digital reading of the controller showed an approximate reading of zero. At this point, the thumbscrews were tightened to hold dowels steady.

The gage struts were then removed and the entire assembly inspected to ensure correctness. Of special concern were the points at which the flat areas of the top and bottom rings made contact with the latex membrane encasing the specimen. At these points it was found that, depending on the surface geometry of the specimen, a penetration of the membrane could occur that would void the test. To protect the membrane, small patches of membrane were added to the areas where contact would be made. The combined thickness of the encasing membrane and the patches created hearty contact points, which could better resist the stress of the flats. Additionally, prior to installation of the top and bottom rings, a vacuum was placed on the specimen. As a result, any compromise of the membrane could be detected by the presence of air at the point of penetration.
4.5.2.2 Initial conditions

Since the resilient modulus test was conducted at two different temperatures separate initial conditions were required to be established. Additionally, stress was induced in the form of axial, confining, and pore water pressure. Testing was done in the undrained state applying pressure in these forms and additional testing was done in the drained state with just the application of an axial load.

For all testing at 10°C, a seating load of 137.5 lbf, or approximately 11 psi, was applied. Due to the higher temperature, testing at 40°C received a seating load of only 75 lbf, or approximately 6 psi. Prior to application of the seating load, confining pressure and pore-pressure were approximately 10 psi and 5 psi respectively. Since the test was reliant upon effective stress application, a significant initial pore-pressure was applied to avoid any dampening of the pressure that may occur if the pore water pressure were closer to zero at the start of test.

4.5.3 Test Procedure

The specimens were first loaded axially and the resulting pore-pressure increase monitored. Then, cyclic pulsing of the confining pressure as well as the pressure distributed to the specimen mimicked the amplitude of the displacement. This was done to demonstrate that pore water pressure could be used to indirectly create a cyclic elongation of the specimen.

For the undrained testing at 10°C, an axial load of 1100 lbf was applied over 6 cycles. The first cycle was used to stabilize the test and was not considered in the data reduction. During the test, readings were taken every 0.005 sec of the axial displacement of the test frame, axial force of the load frame, displacement of the two axial LVDTs, and the top, bottom, and cell pressure. The data was then summarily reduced to determine the
pore water pressure excitation an average of both the top and bottom pressure transducers. From this, the volume changer was used to excite an approximately equal pore-pressure by application of confining stress and direct pore-pressure from the base of the specimen. In order to determine the amount of displacement required by the volume changer to excite the pore-pressure, a static exercise was conducted wherein the displacement was manually controlled until the required pressure was read on the system control screen. This value of displacement was then inserted into the program created for the resilient modulus test and run for the confining pressure application sequence. A similar exercise was performed for the pressure applied directly into the specimen.

A difficulty, which occurred as a result of determining the displacement by a static-based method was that the resulting pressure achieved during the dynamic application, as with the resilient modulus test, was far different than expected. Typically, the resulting pressures were lower during the dynamic application. This lower value is believed caused in part by the length of conduit the water must travel through to arrive at the application point. This length creates a dynamic front situation where the instantaneous achievement of a uni-pressure system is hindered by the restriction of numerous fitting and bends in the distribution system. To correct this situation, the displacement value required in the initial static application was slightly increased to make-up for any losses seen in the dynamic application. Throughout the course of many tests, an operator can become proficient at adjusting the displacement to achieve the desired pore-pressure excitation. For the undrained testing at 40°C, a similar sequence was conducted as with the previous testing at 10°C.
Additional testing was conducted in the drained state. This testing was done at 40°C at 5 min intervals up until 20 min and then every 10 min for a total period of 60 min. Identical readings were taken as with the undrained tests. As with the undrained testing at 40°C, a 500 lbf load was applied for 0.1 sec followed by a rest period of 0.9 sec. The number of applied cycles was typical of the other tests as 6 with the first cycled not considered. The summation of testing sequences is shown in Table 4-2.

Table 4-2. Resilient Modulus Testing Sequence

<table>
<thead>
<tr>
<th>Test #</th>
<th>Test Type</th>
<th>Temp. (°C)</th>
<th>Time (Min.)</th>
<th>Seating Load (lbf)</th>
<th>Dynamic Load (lbf)</th>
<th>Load Application Via</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CU</td>
<td>10</td>
<td>--</td>
<td>137.5</td>
<td>1100</td>
<td>Axial Load</td>
</tr>
<tr>
<td>2</td>
<td>CU</td>
<td>10</td>
<td>--</td>
<td>137.5</td>
<td>1100</td>
<td>Confining Pressure</td>
</tr>
<tr>
<td>3</td>
<td>CU</td>
<td>40</td>
<td>--</td>
<td>75.0</td>
<td>500</td>
<td>Axial Load</td>
</tr>
<tr>
<td>4</td>
<td>CU</td>
<td>40</td>
<td>--</td>
<td>75.0</td>
<td>500</td>
<td>Pore-pressure</td>
</tr>
<tr>
<td>5</td>
<td>CU</td>
<td>40</td>
<td>--</td>
<td>75.0</td>
<td>500</td>
<td>Confining Pressure</td>
</tr>
<tr>
<td>6</td>
<td>CU</td>
<td>40</td>
<td>--</td>
<td>75.0</td>
<td>500</td>
<td>Pore-pressure</td>
</tr>
<tr>
<td>7</td>
<td>CD</td>
<td>40</td>
<td>0</td>
<td>75.0</td>
<td>500</td>
<td>Axial Load</td>
</tr>
<tr>
<td>8</td>
<td>CD</td>
<td>40</td>
<td>5</td>
<td>75.0</td>
<td>500</td>
<td>Axial Load</td>
</tr>
<tr>
<td>9</td>
<td>CD</td>
<td>40</td>
<td>10</td>
<td>75.0</td>
<td>500</td>
<td>Axial Load</td>
</tr>
<tr>
<td>10</td>
<td>CD</td>
<td>40</td>
<td>15</td>
<td>75.0</td>
<td>500</td>
<td>Axial Load</td>
</tr>
<tr>
<td>11</td>
<td>CD</td>
<td>40</td>
<td>20</td>
<td>75.0</td>
<td>500</td>
<td>Axial Load</td>
</tr>
<tr>
<td>12</td>
<td>CD</td>
<td>40</td>
<td>30</td>
<td>75.0</td>
<td>500</td>
<td>Axial Load</td>
</tr>
<tr>
<td>13</td>
<td>CD</td>
<td>40</td>
<td>40</td>
<td>75.0</td>
<td>500</td>
<td>Axial Load</td>
</tr>
<tr>
<td>14</td>
<td>CD</td>
<td>40</td>
<td>50</td>
<td>75.0</td>
<td>500</td>
<td>Axial Load</td>
</tr>
<tr>
<td>15</td>
<td>CD</td>
<td>40</td>
<td>60</td>
<td>75.0</td>
<td>500</td>
<td>Axial Load</td>
</tr>
</tbody>
</table>

4.6 Complex Modulus

4.6.1 Theory of Testing

Complex modulus, or what is also referred to as dynamic modulus, is determined by applying a sinusoidal vertical load at different frequencies and calculating the vertical strain. The procedures for testing are outlined in ASTM D3497 Standard Test Method for Dynamic Modulus of Bituminous Mixtures. The American Society for Testing and Materials recommends that a specimen aspect ratio of 2 to 1 be used to limit the end
effects of the platens. The triaxial cell is limited to a specimen height of approximately 5.5 inches or an aspect ratio of 1.25 to 1. However, an aspect ratio as low as 1 to 1 has been used in combination with low friction end platen material (Roberts 1996). As a result, the specimens tested were done so with Teflon® end platens installed at both ends. The specimens tested were observed in undrained and drained conditions respectively. This was done to observe the influence pore-pressure has upon vertical deformation and to monitor pore-pressure effects during loading.

4.6.2 Specimen Preparation

Prior to installing the specimen, the Teflon® end platens were mechanically affixed to the aluminum end platens to limit any end effects due to restraint of the specimen during loading. By mechanically connecting these components, the possibility for any movement of the platens during loading was precluded. As with the resilient modulus test protocol, the specimens were saturated prior to testing and a $B$-value taken. Specimens were tested at 10°C and 40°C.

4.6.2.1 Instrumentation

Vertical deformation values were recorded by two axial LVDTs. The LVDTs were mounted to the specimen via the holder described in section 4.5.2.1. Horizontal deformation was gauged with radial LVDTs mounted in the radial LVDT holder and positioned mid height of the specimen.

4.6.2.2 Initial conditions

For undrained testing, at both 10°C and 40°C, an effective stress of approximately 1 psi was introduced to the specimen. For the lower temperature the confining stress was approximately 10 psi and at the higher temperature approximately 2 psi was placed onto the specimen. The effective stress was chosen to be substantial enough to indicate a
pore-pressure response to cyclic loading but low enough in order to limit the magnitude of axial load needed to induce strain onto the specimen.

Testing in the drained condition followed those done in the undrained condition. Prior to testing, the valves leading to the top and bottom of the specimen was opened and the pore-pressure allowed dissipating over a period of 5 min. Complex modulus testing was then conducted following the steps presented in the following section.

4.6.3 Test Procedure

Specimens were tested with loading frequencies of: 16 Hz, 10 Hz, 4 Hz, and 1 Hz. The series of loading was applied to the specimen in order decreasing frequencies to minimize damage. Between tests, a rest period of 10 minutes allowed the specimen to recover from any elastic deformation, which may have occurred during loading. Prior to the application of the Haversine waveform, a contact load was applied. This contact load was required to ensure that complete interaction was achieved at the end platen/specimen interface thereby avoiding any erroneous deformation data collected from a sudden application of stress. In order to limit the initial impact to the specimen, the contact load was applied at an increasing stress over a 60 sec period. The contact load applied was approximately 10% of the Haversine load.

The Haversine load varied from 112.4 lbf (500 N) to 1798.5 lbf (8000 N) depending upon the testing frequency and temperature. Calculation of the load was based upon the achievement of strain in the range of $50 \times 10^{-6}$ to $150 \times 10^{-6}$ in/in (Witczak et al. 2002).

For testing at 10°C, a contact load of 179.8 lbf (800 N) was applied to the specimen. In order to determine the magnitude of loading required to achieve axial strain in the range previously discussed, trial loads of between 1124.0 lbf (5000 N) and 1798.5
lb (8000 N) were applied to the specimen at a frequency of 16 Hz. From these loadings, the strain was calculated and an optimum load chosen. This load was applied at 16 Hz, 10 Hz, 4 Hz, and 1 Hz for 200 cycles each.

Testing at 40°C used a contact load of 45.0 lb (200 N). Optimum load was determined over a range of 449.6 lb (2000 N) to 674.4 lb (3000 N) in the same manner as with the test at lower temperature.

For both test temperatures, recordings were taken at intervals depending upon the test frequency. As is shown in Table 4-3, the recording interval increased as the testing frequency decreased. Recordings were taken of axial force, axial and radial displacement, and top, bottom, and cell pressure at each time step.

Table 4-3. Data Recording Interval Per Testing Frequency

<table>
<thead>
<tr>
<th>Testing Frequency (Hz)</th>
<th>Data Recording Interval (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>0.00125</td>
</tr>
<tr>
<td>10</td>
<td>0.002</td>
</tr>
<tr>
<td>4</td>
<td>0.005</td>
</tr>
<tr>
<td>1</td>
<td>0.02</td>
</tr>
</tbody>
</table>

4.7 Extension Testing

4.7.1 Theory of Testing

In research completed by Visser (1998), the mechanics of extensile failure were illustrated by investigating the relationship of axial stress, $\sigma_1$, to the biaxial stress (confining stress), $\sigma_2 = \sigma_3$. As shown in Figure 4-9, two different extensile failure paths were used in Visser’s research of saturated porous materials. For both load paths, the specimens were first loaded with hydrostatic stress. Load path 1 maintains a constant radial stress while the axial compressive stress is slowly lessened allowing controlled extension of the specimen. This is similar to the test procedure described in Section 2.3.
Conversely, load path 2 maintains a constant axial compressive stress while increasing the radial stress. Again, this load path controls the mechanism of failure.

Special cases of extensile failure are indicated as 1a and 2a. In the case of 1a, no radial stress is applied and fracture of the specimen is solely dependent upon uniaxial tension. This method could be accomplished by gluing end platens to a specimen and the failing it through tension. Case 2a is similar to the biaxial stress test frame described in Section 2.3 where radial stress is increased until failure occurs.

For this research, load path 2 was utilized to determine if asphalt specimen could be failed with indirect tension.

4.7.2 Specimen Preparation

Prior to the installation of the specimen, the Teflon® end platen caps used in conjunction with other tests were removed from the end platens. Since the end platens were not expected to endure compressive stresses, the potential for damage to the surface at the interface with the specimen, was not a concern. Additionally, the removal of the Teflon® caps allowed for an additional 1 inch of extension stroke length for the piston to move before conflicting with the latex membrane encasing the specimen.

As with all test specimens, those used for extension testing were cut on each end using a wet saw. By cutting both ends, any irregularities that existed as a result of the compaction effort were removed leaving a flat smooth surface. This surface allowed for a uniform contact between the end platens and the specimen. Additionally, the sawing ensured that the surfaces were perpendicular with the longitudinal axis of the specimen allowing for installation between the two end platens without rotation that would allowing for the influence of confining pressure on the specimen’s end.
Consistent with the methods previously discussed, the specimens were saturated and a subsequent $B$-value taken prior to the commencement of testing. An acceptable $B$-value was considered as $\geq 0.95$. The latex membrane, which encased the specimen, was folded back onto itself at the center of the specimen’s length creating an overlap of approximately 1 inch. This overlap was created to allow for extension of the specimen without pulling the membrane from the end platens. Conditioned water was then circulated around the specimen until its core temperature was $10^\circ C \pm 0.1^\circ C$.

4.7.2.1 Instrumentation

During the test sequence, axial displacement was monitored by an LVDT mounted on the Material Testing Systems (MTS) test frame. Since it was unknown how the specimen would fail, axial LVDTs were not used within the cell as was typical with all other discussed tests. Readings were taken of the top, bottom, and cell pressure. Confining stress was induced by the volume changer displaced at a constant rate, which varied throughout the development of a viable protocol. In order to calculate the volume of fluid introduced into the cell, an LVDT reading was taken of the volume changer displacement. This displacement could be converted to a volume using calibration data established as part of the system assembly process. Readings were taken at a minimum of every 1 sec or a maximum of every 0.05 sec depending upon the displacement rate of the volume changer. The displacement rate varied throughout the iterations of testing protocol development ranging from 0.2 in/s to 0.5 in/s.

4.7.2.2 Initial conditions

After the saturation procedure was completed, and an acceptable $B$-value obtained, a confining pressure was applied via the volume changer. The influent and effluent
valves leading to the specimen were closed thereby allowing any pore water pressure to accumulate.

To ensure a positive contact with the specimen’s end, an axial load was applied equal to the pore-pressure reading at the top of the specimen multiplied times the area of the top platen; this was done to create a balance of pressure between the confining and axial pressures. It was anticipated that, as the confining pressure was increased, the specimen would extend thereby displacing the axial piston. Since the axial load is fixed, it axial displacement would continue as pore-pressure accumulated within the specimen. If confining pressure could be applied at a relatively high rate, it was believed that pore-pressure would increase faster that the controller could maintain axial force onto the specimen thereby allowing fracture to occur.

4.7.3 Methods of Testing Procedure

The specimen was induced with an increasing confining pressure via the volume changer. The displacement rate of the volume changer was controlled by a looped signal between the system controller and an LVDT located on the volume changer. The computer program for the test specified that the axial load set in the initial conditions be maintained throughout the duration of the test. This parameter was controlled via a looped signal between the system controller and a load cell placed on the axial shaft of the load frame.

4.7.3.1 Theoretical expectations for failure

The higher permeability of the asphalt specimen as compared with the sandstone used in extensile testing completed by Visser (1998) suggested that pore-pressure would be a more efficient mechanism in asphalt. It was anticipated that failure would occur when the cohesive strength of the binder was exceeded by the pore-pressure developed
within the interconnected voids of the specimen. The mechanics of failure for this test relies on the specimen being allowed to elongate axially until the strain exceeds that allowed by the bitumen binder. It is at this point that failure would be defined. The approximate range in which a tensile failure would occur was presumed to be 100 psi to 250 psi.

4.7.3.2 Observed testing difficulties

The principle difficulty with the test concerned the loss of contact of the piston from the specimen end. Once this disconnect occurred, the membrane would collapse inward allowing for the creation of an upward force onto the end platen of the piston. The cause for disconnect is uncertain but is believed to be caused, in part, by confining pressure acting on the piston plate. The pressure may have been allowed to act onto the top platen through indentations about the specimen’s end.

Figures 4-10 and 4-11 show plots of measured parameters versus time. As is shown in Figure 4-11, the axial displacement of the piston occurs almost immediately following the start of the test. This immediate displacement of the piston at relatively low pore-pressure (bottom pressure) supports the conclusion that confining water may have acted onto the face of the platen via indentations of the membrane into the top of the specimen. After approximately 400 sec, the rate of displacement increases, decrease, and the increase again wherein the rate is approximately constant until the termination of the test. Referring to Figure 4-10, it is shown that the pore water pressure increases rapidly during the first 200 sec of the test. At the end of this interval, the pore water pressure actually surpasses that of the confining pressure and then parallels it approaching convergence.
4.7.3.3 Variations of testing protocol

In an attempt to prevent the piston from displacing until a surplus of pore water pressure could develop, several tests were conducted with higher axial loads and confining pressures. It was presumed that a higher initial stress state would help to achieve failure more readily than tests at lower initial stress state conditions by establishing a higher pore water pressure at the commencement of the test. Tests performed with the higher initial stress state exhibited a similar trend as those shown in Figures 4-10 and 4-11.

In order to alleviate premature displacement of the top platen due to a collapse of the membrane at the top of the specimen, an additional ring of membrane was placed on the top and bottom circumference of the specimen. This addition had little effect on the performance of the test.

In other attempts to develop pore-pressure without an immediate displacement of the piston, the displacement rate of the volume changer was increased. The goal was to increase the confining stress very rapidly and develop pore-pressure before the computer controlled load frame could respond by displacing the piston upward. Again however, removal of the top platen from the specimen occurred without failing the specimen.

Based on the parametric test procedures, it was concluded that the computer-controlled test frame was too responsive to allow pore-pressure development to a significant level that would cause a fracture of the specimen. As pore-pressure developed upon the initial increase in confining stress, the piston began displacement, which allowed confining water to act on the membrane between the top of the specimen and the top platen.
Figure 4-1. Calculated $B$-value with Increasing Confining Stress

Figure 4-2. Membrane Position with Increasing Confining Pressure
Figure 4-3. Elapsed Test Time vs. Pressure Transducer Reading

Figure 4-4. Elapsed Test Time vs. Influent Line Pressure
Figure 4-5. Elapsed Test Time vs. Hydraulic Conductivity Falling-Head Test

Figure 4-6. Permeant Routing Diagram Falling-Head Test
Figure 4-7. Permeant Routing Diagram Constant Headwater Rising Tailwater

Figure 4-8. Permeant Routing Diagram Constant-Head Test
Figure 4-9. Extensile Failure Load Paths

Figure 4-10. Time vs. Pressure for the Extension Test
Figure 4-11. Time vs. Vertical Strain for the Extension Test
5.1 Introduction

At the time the specimen is first placed into the system, it is stabilized at room temperature. The specimen is surrounded about its circumferential perimeter by confining water. This water not only acts as a medium for pressure application but also for temperature conditioning of the specimen. As the temperature-conditioned water surrounding the membrane-encased specimen is cycled through the system, thermal energy is either drawn from the specimen, as occurs during cooling, or added to it, as occurs during heating. During the cooling process, heat is conducted from the specimen to the colder confining water; the opposite is true for the heating process. As this process continues, concentric layers of the cylindrically shaped specimen reach thermal equilibrium starting from the outer layer and migrating towards the central core (Çengal 1997).

The transfer of energy from more energetic particles to less energetic adjacent particles through interactions is the thermodynamic process of conduction.

The equation for the rate of heat conduction is defined as

\[ Q_{\text{cond}} = kA \frac{\Delta T}{\Delta x} \]  

(5.1)

where

\begin{align*}
Q_{\text{cond}} &= \text{Rate of heat conduction, (W)} \\
k &= \text{Thermal conductivity of the layer, (W/(m}\cdot\text{K})) \\
A &= \text{Area normal to the direction of heat transfer, (m}^2) \\
\Delta T &= \text{Temperature difference across the layer, (K)} \\
\Delta x &= \text{Thickness of layer, (m)}
\end{align*}
The layer referenced in the variable definition, \( \Delta x \), is the latex membrane that encapsulates the specimen. Thermal conductivity of the latex membrane is approximately 0.13 W/m·K with a thickness, \( \Delta x \), of \( 3.048 \times 10^{-4} \) m (0.012 in). A circumferential surface area of approximately \( 0.045 \) m\(^2\) simplifies equation 5.1 to

\[
Q_{\text{cond}} = 19.19 \Delta T \text{ (W)}
\]

As can be seen from equation 5.2, the larger the difference in temperature across the layer, the greater the rate of heat conduction. Additionally, it can be inferred that, as the temperature on either side of the layer approaches equilibrium, the rate of heat conduction decreases. Therefore, to achieve a specimen target temperature rapidly, the temperature difference between the specimen and the circulating water must be as large as possible to maximize the rate of heat conduction without surpassing the target temperature.

### 5.2 Specimen Set-up for Calibration

As previously discussed, the final portion of the specimen to reach equilibrium is the central core. Therefore, it is this region of the specimen that controls the length of conditioning time prior to the establishment of thermal equilibrium. Since the testing protocol for specimen temperature conditioning relies upon conductance for specimen heating or cooling, it was necessary to plot the change in temperature of the confining water and the core of the specimen versus time.

Although both the heater and chiller units used with the system digitally report the water temperature within their fluid reservoirs, thermal losses or gains that occur along the fluid distribution panel can vary from the reported temperature by several degrees. A series of trials were conducted for both cooling and heating to determine the most time
conservative sequence to rapidly achieve the target temperature. Since the rate of heat conduction is directly proportional to the temperature difference across the layer (latex membrane), initially set temperatures were significantly lower (in the case of cooling) or higher (in the case of heating) than the target temperature to expedite thermal equilibrium. The large combined mass of the triaxial cell, water, and components of the distribution panel required a large rate of energy exchange be implemented in order to achieve the target temperature.

Two type-K thermocouple probes connected to digital gages were used to report the temperature of the confining water and the specimen’s core throughout a series of heating and cooling sequences. The thermocouples used were bare-tip and were connected to digital gages that had a recording tolerance of ±0.1°C. Prior to implementation, the thermocouples were calibrated using a certified laboratory grade mercury thermometer. From these calibrations, offsets were determined across the anticipated range of temperatures. These offsets were applied to the raw recorded data to derive a time versus temperature relationship.

The calibration of the specimen in conditions as close as is possible to those anticipated during testing is extremely important to fully account for variables of energy transference. These variables are present due to thermal sources and sinks (metal cell components) as well as insulators (latex membrane). Thermocouple 1, used to monitor the confining water temperature, was installed through one of the accessory ports located at the base of the triaxial cell. In order to avoid false readings that may have occurred by contact between the probe and metal components of the cell, the probe’s end was suspended within the volume of the cell with cotton thread. Thermocouple 2, which was
required to be inside of the specimen, was more difficult to install. To simulate testing conditions, the specimen was required to be wrapped in the latex membrane thereby preventing routing of the thermocouple into the cell like that of the formerly discussed probe. Routing of the thermocouple wire through the cell’s piston was eventually decided as the only viable option to achieve placement of the probe even though it required dismantling of active components of the system. The specimen used for calibration was prepared by first cutting the ends to facilitate contact between the specimen and the end platens. To allow for the installation of the probe into the specimen, a 0.25 inch diameter hole was drilled into the specimen, parallel with the longitudinal axis, starting centered on the specimen’s end and terminating at a depth equal to \( \frac{1}{2} \) the specimen’s length. The thermocouple was then inserted through the cell’s piston and into the void in the specimen. In order to affix the thermocouple in its position and prevent energy transfer from the air-filled void to the end of the piston, the specimen’s end was sealed with silicone. The specimen was then set aside for 24 hours to allow the silicone to cure. Following the 24-hour cure time, the specimen was positioned between the end platens, wrapped with latex membrane, and secured to the end platens with o-rings.

As previously discussed, the installation of the thermocouple into the specimen required partial dismantling of the piston assembly. The removal of components used to conduct water through the specimen prevented a saturation sequence as is typical with test specimens. Therefore it was decided to calibrate the heating and cooling times of the specimen in a dry condition. Water is a more efficient conductor of thermal energy than
is air, 0.613 W/(m·K) and 0.026 W/(m·K) respectively; therefore, testing with a dry specimen yields conservative calibration times for thermal equilibrium.

5.3 Method of Cooling and Heating Calibration

At the commencement of the cooling conditioning process, both the specimen and the conditioning water were approximately 25°C which was the typical ambient temperature of the room in which testing occurred. A multitude of chiller set temperature combinations were run to determine the most expedient sequence for equilibrium with a target end temperature of 10°C ± 0.1°C for the specimen. Owing to the efficiency of the chiller unit, care was taken not to allow the chiller to run lower than the target temperature for too long. Once the specimen temperature, in the cooling process, is achieved, any increase in temperature can only occur due to thermal conduction from the surrounding warmer environment.

The heating conditioning sequence began with the specimen at approximately the target temperature of the cooling process (10°C). This was done in order to allow for future nondestructive testing of specimens at low and high temperatures progressively. As with the temperature combination iterations with the cooling process, those for the heating process followed the same logic. The target end temperature was set at 40°C ± 0.1°C for the specimen.

Initially, 60 min of conditioning time was the target for achievement of thermal equilibrium within the specimen. This target conditioning time was used as a basis for sizing of the heater and chiller used with the system. Since this system is anticipated to be a prototype for a production-based system, limiting the time required for conditioning was deemed critical for practical use. After several calibration sequences, it was validated that this limited conditioning time was sufficient to achieve the target
temperature but that an additional 30 min would allow for further stabilization. Further stabilization time is important because the additional energy exchanged via the conditioning process aids in the maintenance of temperature after the conditioning process is halted. Although the specimen may be at the target temperature, the entire mass of the system may not. Therefore, the additional energy exchange can help to bring more of the system to the target temperature, which acts as a thermal blanket around the specimen. The fluid conduits used for the flow of water during the conditioning process are the same as those used to pressurize the system. Therefore, it is necessary to halt the conditioning process in order to pressurize the system and conduct the anticipated battery of testing. For the anticipated battery of testing, an off-line maintenance of temperature time was set at 30 min. This meant that if all testing were not accomplished within the 30 min, a new sequence of heating/cooling would need to be accomplished to again ensure the specimen was at the proper temperature.

5.3.1 Cooling Calibration Results

For the target temperature of 10°C, the chiller was initially set at 7°C. Initial conditions for the specimen and circulating water were 27.1°C and 25.0°C respectively. The chiller set temperature was held for 40 min at which time the set temperature was increased to 8°C and maintained for an additional 50 min. The specimen reached the target temperature of 10°C after a total of 61 min of conditioning time. Further conditioning was conducted for 29 min at which time the specimen stabilized to 9.9°C. The chiller was then turned off thereby terminating the flow of conditioned water through the system. The specimen core temperature was monitored for an additional 30 min wherein the end temperature of the specimen was 10.1°C. This range of temperature (10°C ± 0.1°C) was considered acceptable for the anticipated testing.
As is shown in Figure 5-1, the chilled circulating water achieved the set temperature very rapidly. Prior to stabilizing at the initial set temperature of 7°C, the water temperature is shown to drop to a temperature, which is lower than the set temperature. This is attributed to the response sensitivity of the chiller itself. In order to rapidly lower the temperature of the circulating water, the chiller maximizes the amount of energy that it can draw from the fluid. As the circulating water approaches the set temperature, the chiller decreases the rate of energy transference, thereby decreasing the change in temperature per time. As was observed in all cooling sequences conducted, a $\Delta T$ of 18°C (initial temperature of 25°C to a set temperature of 7°C) was large enough that the efficiency of the chiller exceeded its ability to decrease the rate of heat conduction. As a result, the chiller overshot its target temperature. Additionally, it is shown that for the maintenance of the target temperature inside of the specimen, the chiller must be set to a lower temperature. For a specimen target temperature of 10°C, the chiller is required to be set to 8°C. This loss of 2°C from the time the fluid left the chiller to reaching the interior of the cell is attributed to the conditioning water gaining energy from the ambient temperature room as the fluid is conducted through the distribution panel and the cell itself.

The prescribed protocol for cooling the specimen to 10°C is summarized as

1. Set chiller to 7°C and run for 40 min
2. Change chiller set temperature to 8°C and run for 50 min
3. Discontinue conditioning and allow a maximum of 30 min for off-line testing
4. If additional testing time is required, reinitiate the conditioning process with the chiller set temperature to 8°C and run for 30 min
5.3.2 Heating Calibration Results

Initial conditions for the specimen and circulating water at the commencement of the heating process was 10.9°C and 26.5°C respectively. For the target temperature of 40°C, the heater was initially set at 45°C. The heater set temperature was held for 55 min at which time the set temperature was decreased to 40°C and maintained for an additional 35 min. At the end of the total 90 min of conditioning, the specimen core temperature had reached 40.1°C. The heater was then turned off thereby terminating the flow of conditioned water through the system. The specimen core temperature was monitored for an additional 30 min wherein the end temperature of the specimen was 40.0°C. This range of temperature (40°C ± 0.1°C) was considered acceptable for the anticipated testing.

As is shown in Figure 5-2, the circulating water achieved the set temperature very rapidly at which it was allowed to stabilize while the specimen core temperature increased. Also notable is the near parallelism of the rate of temperature increase in specimen and heater from 0 to 35 min of test time. This parallelism is consistent with the equation for the rate of heat conduction.

The prescribed protocol for cooling the specimen to 40°C is summarized as

1. Set heater to 45°C and run for 55 min
2. Change heater set temperature to 40°C and run for 35 min
3. Discontinue conditioning and allow a maximum of 30 min for off-line testing
4. If additional testing time is required, reinitiate the conditioning process with the heater set temperature to 40°C and run for 30 min

The protocols for cooling and heating were developed using C1 mixes with percent voids of 7.5% ± 0.5%. Fine mixes or those with lower air voids are expected to require
longer conditioning times. This increase in exposure time is owed to the lower volume of water that would be present within the specimen thereby making the conductance of thermal energy less efficient. It is recommended that this protocol be used with the mix used in this research and other coarse mixes with approximately similar air void percentage. For other mixes, a baseline should be developed using the same methodology as presented herein to ensure the amount of time and temperature to stabilize the specimen’s core.

5.4 Summary

Using the ETTS, specimens were conditioned to both high and low temperatures. The methods developed for conditioning achieve target temperature within 60 min and have been shown to maintain that temperature approximately 30 min after the conditioning process is stopped. The time required to achieve low and high temperatures of 10°C and 40°C respectively is a significant improvement over existing systems such as the ECS as discussed in Chapter 2. The reduction of required conditioning time allows for a specimen to be tested consecutively from low to high temperature within a reasonable amount of time to make the system conducive to production testing.

The protocols for heating and cooling of the specimen were developed for a coarse-graded mix design. The higher volume of voids in a coarse mix makes the conductance of thermal energy more expeditious than would occur with a fine mix. This is attributed to the higher conductivity of water as opposed to air or binder material. Testing of fine mixes and coarse mixes whose air void range differs from the test specimens used in this research, require revised conditioning protocols using the same procedures outlined in this chapter.
Figure 5-1. Time vs. Temperature-Specimen to 10°C

Figure 5-2. Time vs. Temperature-Specimen to 40°C
CHAPTER 6
TESTING RESULTS

6.1 Determination of the B-value

Calculation of the pore-pressure coefficient B, commonly referred to as the B-value, was accomplished using Equation 4.1. As is shown in Table 6-1, typical results showed B-values in excess of 0.95.

Table 6-1. Data for the B-value

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Initial Pore-pressure (psi)</th>
<th>Final Pore-pressure (psi)</th>
<th>Initial Confining Pressure (psi)</th>
<th>Final Confining Pressure (psi)</th>
<th>B-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>J2</td>
<td>62.73</td>
<td>65.25</td>
<td>64.70</td>
<td>67.31</td>
<td>0.965</td>
</tr>
<tr>
<td>J14</td>
<td>62.27</td>
<td>64.12</td>
<td>65.21</td>
<td>67.14</td>
<td>0.960</td>
</tr>
<tr>
<td>J16</td>
<td>62.44</td>
<td>64.20</td>
<td>65.21</td>
<td>67.06</td>
<td>0.951</td>
</tr>
<tr>
<td>J17</td>
<td>61.89</td>
<td>64.49</td>
<td>64.13</td>
<td>66.87</td>
<td>0.948</td>
</tr>
<tr>
<td>J18</td>
<td>63.53</td>
<td>65.46</td>
<td>67.81</td>
<td>69.83</td>
<td>0.955</td>
</tr>
<tr>
<td>J22</td>
<td>65.71</td>
<td>69.32</td>
<td>67.56</td>
<td>71.34</td>
<td>0.955</td>
</tr>
</tbody>
</table>

6.2 Hydraulic Conductivity

6.2.1 Falling-Head

The first step in reducing the collected data was to calculate the hydraulic conductivity at each time step. This was accomplished by converting the recorded reading from the top pressure transducer to an equivalent head in centimeters. With this, Equation 4.2 was used for each time step. Next, all data taken when the top pressure transducer read more than 2 psi or less than 0 psi was excluded from further analysis. Of the remaining data, the steady hydraulic conductivity termination criterion was applied to determine if the hydraulic conductivity reading at each time step was within 25% of the mean of the previous four readings. This analysis began at the time step in which the top
pressure was recorded as 2 psi and continued to the reading which first indicated zero pressure at the top of the specimen. If a reading was found to fall out of the 25% allowance, all readings taken past that time step were excluded from the data set. The average of the included data was taken as the representative hydraulic conductivity of the specimen.

The gradient applied across the specimen was calculated as the average of the head at the beginning and end of the data set, divided by the length of the specimen. The gradient of each tested specimen was in the range of 4 to 8. This range corresponds with the lowest gradient used in the constant-head testing and yields approximately the same hydraulic conductivity as with that test (see Figure 6-1). Ideally, a gradient of 5 would have been used with each falling-head test. However, with such a low driving pressure, a precise average gradient over the duration of the test was difficult to achieve.

![Gradient Across Specimen vs. Hydraulic Conductivity](image)

Figure 6-1. Gradient Across Specimen vs. Hydraulic Conductivity
Table 6-2 shows the calculated hydraulic conductivity for three of the tested specimens. The reported data illustrates the importance of performing at least three tests on each specimen and then averaging the resulting values for hydraulic conductivity. The relatively low conductivity of the tested coarse mix necessitates multiple testing to compensate for any variation in regards to the manner in which the material conducts fluid through its network of interconnected voids.

Table 6-2. Falling-Head Hydraulic Conductivity Results (cm/s)

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Specimen Number (% Air Voids)</th>
<th>J8 (7.70)</th>
<th>J14 (7.37)</th>
<th>J15 (7.64)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hydrualic Conductivity</td>
<td>Average Gradient</td>
<td>Hydraulic Conductivity</td>
<td>Average Gradient</td>
</tr>
<tr>
<td>1</td>
<td>1.992 x 10^{-4}</td>
<td>4.65</td>
<td>3.096 x 10^{-4}</td>
<td>7.40</td>
</tr>
<tr>
<td>2</td>
<td>3.360 x 10^{-4}</td>
<td>4.65</td>
<td>2.161 x 10^{-4}</td>
<td>8.46</td>
</tr>
<tr>
<td>3</td>
<td>2.860 x 10^{-4}</td>
<td>4.44</td>
<td>1.664 x 10^{-4}</td>
<td>8.88</td>
</tr>
<tr>
<td>Average</td>
<td>2.737 x 10^{-4}</td>
<td>4.67</td>
<td>2.307 x 10^{-4}</td>
<td>8.64</td>
</tr>
</tbody>
</table>

6.2.2 Constant-Head

For each specimen tested, the collected data was reduced and an average value for the hydraulic conductivity was taken over the sum of the time steps. This value (k) represents a point on a graph of hydraulic conductivity versus gradient. Figure 6-1 shows a typical result of these points produced a peaked curve. The section of the curve leading up to its highest value of k is nearly linear and substantiates Darcy’s equation, n=ki, as previously discussed. As the gradient (i) across the specimen is increased, so too does the velocity (n) of the fluid through the specimen as well as the hydraulic conductivity (k). However, as the gradient is increased further, this relationship no longer holds true and a decrease of hydraulic conductivity is observed. With soils, this decrease is attributed to the consolidation of particles about the supply end of the specimen that effectively lowers the void ratio and restricts the flow of fluid. The higher stiffness of
HMA coupled with the adhesive ability of the binder to maintain the positioning of the particles in the mixture makes consolidation, with relatively low applied pressures, less likely of a factor for the reduction in hydraulic conductivity. A more viable explanation comes from revisiting Darcy’s equation. For the hydraulic conductivity to increase in response to larger gradients, the product of these two requires a corresponding increase of fluid velocity through the specimen.

The paths of flow through the specimen are made up of many channels of flow and are not always parallel to the direction of flow. These tortuous paths are not of a constant diameter or geometric cross section. The irregularities both in alignment and geometric constituent gives rise to frictional factors and turbulent flow paths. As is identified in hydraulics, as the velocity of a fluid through a pipe increases, so too do the frictional factors and the effects of constriction and expansions along the length of the conduit (Munson, et al. 1998). Therefore, there is a point of transition where an increase in the gradient goes from expediting the transmission of fluid through the specimen to a condition where it applies more pressure onto the fluid than the network of voids within the specimen is capable of conducting.

As shown in Table 6-3, for all the specimens tested, the optimum hydraulic conductivity occurred with a gradient of between 25 and 35. Following these optimum peaks, a slight change in rate of decreasing hydraulic conductivity was seen for each plot. This discontinuity in rate suggests that a chaotic relationship occurs between the three variables in Darcy’s equation in the range past the optimum hydraulic conductivity.
Table 6-3. Constant-Head Hydraulic Conductivity Results (cm/s)

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>J8</th>
<th>J14</th>
<th>J15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent Air Voids</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>3.484 x 10^{-4}</td>
<td>4.922 x 10^{-4}</td>
<td>2.191 x 10^{-4}</td>
</tr>
<tr>
<td>10</td>
<td>4.461 x 10^{-4}</td>
<td>5.385 x 10^{-4}</td>
<td>5.582 x 10^{-4}</td>
</tr>
<tr>
<td>15</td>
<td>7.401 x 10^{-4}</td>
<td>7.433 x 10^{-4}</td>
<td>7.214 x 10^{-4}</td>
</tr>
<tr>
<td>20</td>
<td>9.619 x 10^{-4}</td>
<td>7.698 x 10^{-4}</td>
<td>9.950 x 10^{-4}</td>
</tr>
<tr>
<td>25</td>
<td>1.157 x 10^{-3}</td>
<td>9.544 x 10^{-4}</td>
<td>1.196 x 10^{-3}</td>
</tr>
<tr>
<td>30</td>
<td>1.004 x 10^{-3}</td>
<td>1.013 x 10^{-3}</td>
<td>9.679 x 10^{-4}</td>
</tr>
<tr>
<td>35</td>
<td>9.449 x 10^{-4}</td>
<td>8.903 x 10^{-4}</td>
<td>9.045 x 10^{-4}</td>
</tr>
<tr>
<td>40</td>
<td>9.623 x 10^{-4}</td>
<td>7.340 x 10^{-4}</td>
<td>9.962 x 10^{-4}</td>
</tr>
<tr>
<td>45</td>
<td>9.022 x 10^{-4}</td>
<td>7.287 x 10^{-4}</td>
<td>9.186 x 10^{-4}</td>
</tr>
<tr>
<td>50</td>
<td>7.830 x 10^{-4}</td>
<td>6.330 x 10^{-4}</td>
<td>8.004 x 10^{-4}</td>
</tr>
<tr>
<td>55</td>
<td>7.119 x 10^{-4}</td>
<td>5.550 x 10^{-4}</td>
<td>7.443 x 10^{-4}</td>
</tr>
</tbody>
</table>

6.2.3 Conclusions

The hydraulic conductivity of HMA was successfully determined using the ETTS. The method developed for falling-head hydraulic conductivity testing proved effective in determining the permeability of HMA specimens rapidly in a controlled environment. A comparison of the average hydraulic conductivity, as shown in Table 6-2, for three consecutive tests shows that within the air void range of specimens tested, 7.37% to 7.70%, the value of permeability is approximately equal. These values are consistent with those typical achieved using the apparatus described in the discussion of the Florida method of falling-head hydraulic conductivity testing. However, with the improved system, continuity and steady-state conditions are detectable using the criteria discussed in section 4.2.1.

Testing using the constant-head configuration produced an increase in hydraulic conductivity with increasing gradient until a gradient of approximately 25. As an increasing gradient was applied past this value, the hydraulic conductivity was shown to decrease. This trend is reasonable considering the arduous network of interconnected...
voids the permeant must pass through. Also, this trend demonstrates that hydraulic conductivity of HMA is more a function of the structure of the material than the imposed end conditions. Figure 6-1 illustrates a typical plot of constant-head results along with those found with the falling-head configuration. At a gradient of 5, the result of the constant-head test is approximately equal to those found with the falling-head test. This is to be expected since the specimen was influenced by similar end conditions. Figure 6-3 shows that an optimum hydraulic conductivity occurred within the gradient range of 25 to 30.

6.3 Compression

6.3.1 Test Results

Upon completion of each compression test, the cell was disassembled and the specimens examined. All specimens tested presented a uniform bulging that started from each end and terminated, at a maximum, centered on the longitudinal axis. A shear failure line was observed in each specimen angled from the longitudinal axis. Along this line, adhesive failure of the binder was evident with partially removed binder-coated aggregate.

Data collected from the compression tests were reduced and from these data Mohr’s circles and p’-q’ plots were made to determine the angle of internal friction, Φ, and the angle of the modified failure envelope, α, respectively. The axial load values taken during the test were converted to stress based upon the corrected cross-sectional area of the specimen at each time step. During the shearing of the specimen, the cross-sectional area increases requiring that it be considered for accurate determination of the stress applied to the specimen at each time step. The corrected area was calculated by using Equation 6.1.
\[ A_c' = \frac{A_c}{1 - \varepsilon_v} \]  

(6.1)

where 

- \( A_c' \) = Corrected area at each time step (in\(^2\))
- \( A_c \) = Cross-sectional area of specimen at start of test (in\(^2\))
- \( \varepsilon_v \) = Vertical strain at each time step (in/in)

The point of failure for each test was defined at the time step in which a loss of vertical stress capacity occurred. As is shown in Figure 6-2, a typical plot of applied axial stress versus time showed a sudden decrease in the stress capacity of the specimen followed by a steady increase, which was maintained until the termination of the test. The increase in stress capacity following failure is attributed to the reconfiguration and subsequent strengthening of the specimen’s matrix and strain hardening of the binder.

Stress conditions at the defined time of failure were used to create a plot of Mohr’s circles. The angle of internal friction, \( \Phi \), was calculated by using Equation 6.2. As is shown in Table 6-4, the calculated angle of internal friction was approximately 58°. This angle approximates the failure line as observed on the specimen. The value of cohesion, \( c \), was found by graphically plotting a line tangent to the Mohr’s circles and calculating the intercept with the shear stress axis. A corresponding plot of the Mohr’s circles and the failure line is shown in Figure 6-3.

In addition to the Mohr diagram, a \( q' \) against \( p' \) plot and data were calculated to more clearly show the failure line. The ends of these stress paths correspond with the coordinates of the top of the Mohr circles. The effective stress state parameters \( q' \) and \( p' \) were again calculated using the data collected at the point of failure for the specimen. By using Equations 6.3 to 6.5, Table 6-5 was generated.
Figure 6-2. Typical Time vs. Axial Load Plot

Figure 6-3. Mohr’s Circles with Failure Line
Table 6-4. Angle of Internal Friction Results

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Confining Pressure (psi)</th>
<th>Backpressure (psi)</th>
<th>$\sigma_3'$ final (psi)</th>
<th>$\sigma_1'$ final (psi)</th>
<th>$\Phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>J18</td>
<td>15.11</td>
<td>5.33</td>
<td>9.99</td>
<td>165.38</td>
<td>62.38°</td>
</tr>
<tr>
<td>J14</td>
<td>24.93</td>
<td>7.18</td>
<td>26.02</td>
<td>282.72</td>
<td>56.24°</td>
</tr>
<tr>
<td>J2</td>
<td>34.83</td>
<td>5.68</td>
<td>24.74</td>
<td>319.70</td>
<td>58.91°</td>
</tr>
</tbody>
</table>

Table 6-5. Modified Failure Envelope Angle Values

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Q' initial (psi)</th>
<th>P' initial (psi)</th>
<th>Q' final (psi)</th>
<th>P' final (psi)</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>J18</td>
<td>0</td>
<td>8.15</td>
<td>77.70</td>
<td>87.68</td>
<td>41.54°</td>
</tr>
<tr>
<td>J14</td>
<td>0</td>
<td>16.82</td>
<td>128.94</td>
<td>154.95</td>
<td>39.76°</td>
</tr>
<tr>
<td>J2</td>
<td>0</td>
<td>26.99</td>
<td>147.48</td>
<td>172.22</td>
<td>40.57°</td>
</tr>
</tbody>
</table>

\[ S I N \ \phi = \frac{\sigma_1' - \sigma_3'}{\sigma_1 + \sigma_3'} \] \hspace{1cm} (6.2)

\[ q' = \frac{\sigma_1' - \sigma_3'}{2} \] \hspace{1cm} (6.3)

\[ p' = \frac{\sigma_1' + \sigma_3'}{2} \] \hspace{1cm} (6.4)

\[ T A N \ \alpha = \frac{q'}{p'} \] \hspace{1cm} (6.5)

\[ c = \frac{a}{C o s \ \phi} \] \hspace{1cm} (6.6)

The modified failure envelope angle was used to define the modified line or what is more commonly refereed to as the K$\ell$-Line. The value which the K$\ell$-Line intercepts the q’ axis is defined as “a”. This value is related to the value of cohesion, c, by Equation 6.6.
This equation was used to determine the reasonableness of the vertical positioning of the $K_f$-Line. A plot of the stress paths and the resulting $K_f$-Line is shown in Figure 6-4.

![Figure 6-4. CU Test Stress Paths](image)

### 6.3.2 Conclusions

A set of three specimens was failed in undrained compression by applying an axial load at a constant rate of displacement. The specimens were confined with 15, 25, and 35 psi respectively. From the test data, values for angles of internal friction and modified failure envelope were calculated. The values for the angle of internal friction ranged from $56.24^\circ$ to $62.38^\circ$. A failure line, plotted tangent to Mohr’s circles of the three tests, produced an angle of internal friction of $58^\circ$.

All three specimens used in the test set showed an increase in pore-pressure prior to dilating and then a decrease in pore-pressure, which went negative prior to the termination of the test. This response is typical of undrained materials tested in compression where the structure of the specimen reconfigures to support the increasing axial load and then dilates.
6.4 Resilient Modulus

6.4.1 Test Results

Resilient modulus was calculated for each test as the applied stress divided by the resulting strain. Displacement data was taken from the LVDT readings therefore, the gage length was equal to the length of the gage struts of the LVDT holder. A typical plot of axial displacement versus time is shown in Figure 6-5. Results of undrained resilient modulus testing at 10°C and 40°C are shown in Table 6-6.

The drained resilient modulus test was conducted at 40°C and followed the undrained test at that temperature. The undrained test was run consecutively for a total of 9 tests. With each successive test, the specimen goes from an effective state to a total stress state. As is shown in Table 6-5, the first of nine drained resilient modulus tests resulted in slightly higher modulus values than the undrained tests.

Table 6-6. Undrained Resilient Modulus Test Results

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Test Temperature (°C)</th>
<th>Gage Length (in)</th>
<th>Strain (10^{-6}\text{ in/in})</th>
<th>Applied Stress (psi)</th>
<th>Resilient Modulus (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J2</td>
<td>10</td>
<td>1.9968</td>
<td>89</td>
<td>87.6</td>
<td>995,337</td>
</tr>
<tr>
<td>J14</td>
<td>10</td>
<td>1.9968</td>
<td>71</td>
<td>87.6</td>
<td>1,321,725</td>
</tr>
<tr>
<td>J18</td>
<td>10</td>
<td>1.9968</td>
<td>50</td>
<td>87.6</td>
<td>1,784,181</td>
</tr>
<tr>
<td>J2</td>
<td>40</td>
<td>1.9968</td>
<td>258</td>
<td>39.8</td>
<td>154,285</td>
</tr>
<tr>
<td>J14</td>
<td>40</td>
<td>1.9968</td>
<td>201</td>
<td>39.8</td>
<td>201,468</td>
</tr>
<tr>
<td>J18</td>
<td>40</td>
<td>1.9968</td>
<td>240</td>
<td>39.8</td>
<td>167,121</td>
</tr>
</tbody>
</table>

As the sequence of drained resilient modulus tests were run, the material’s modulus increased and then stabilized at an approximate value. This trend was seen in the average of the pore-pressure as recorded on the top and bottom of the specimen. The top pressure, as would be expected, recorded negative pressure due to the head of water in the specimen, which created a vacuum. The relatively small deformation of the specimen
during the cyclic loading was not substantial enough to force any volume of water out of the specimen. As a result, any water present within the specimen would excite a small pressure increase when deformed. As is shown in Table 6.8, the average pore-pressure reading was approximately 0.5 psi.

Table 6-7. Drained Resilient Modulus Test Results

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Test Temperature (°C)</th>
<th>Gage Length (in)</th>
<th>Strain (10^-6 in/in)</th>
<th>Applied Stress (psi)</th>
<th>Resilient Modulus (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J2</td>
<td>10</td>
<td>1.9968</td>
<td>89</td>
<td>87.6</td>
<td>995,337</td>
</tr>
<tr>
<td>J14</td>
<td>10</td>
<td>1.9968</td>
<td>71</td>
<td>87.6</td>
<td>1,321,725</td>
</tr>
<tr>
<td>J18</td>
<td>10</td>
<td>1.9968</td>
<td>50</td>
<td>87.6</td>
<td>1,784,181</td>
</tr>
<tr>
<td>J2</td>
<td>40</td>
<td>1.9968</td>
<td>258</td>
<td>39.8</td>
<td>154,285</td>
</tr>
<tr>
<td>J14</td>
<td>40</td>
<td>1.9968</td>
<td>201</td>
<td>39.8</td>
<td>201,468</td>
</tr>
<tr>
<td>J18</td>
<td>40</td>
<td>1.9968</td>
<td>240</td>
<td>39.8</td>
<td>167,121</td>
</tr>
</tbody>
</table>

Table 6-8. Consecutive Drained Resilient Modulus Test Results (Specimen J14)

<table>
<thead>
<tr>
<th>Time (min.)</th>
<th>Test Temperature (°C)</th>
<th>Gage Length (in)</th>
<th>Strain (10^-6 in/in)</th>
<th>Applied Stress (psi)</th>
<th>Resilient Modulus (psi)</th>
<th>Average Pore-pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>40</td>
<td>1.9968</td>
<td>184</td>
<td>39.8</td>
<td>250,543</td>
<td>0.42</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>1.9968</td>
<td>143</td>
<td>39.8</td>
<td>329,629</td>
<td>0.55</td>
</tr>
<tr>
<td>10</td>
<td>40</td>
<td>1.9968</td>
<td>131</td>
<td>39.8</td>
<td>354,542</td>
<td>0.53</td>
</tr>
<tr>
<td>15</td>
<td>40</td>
<td>1.9968</td>
<td>150</td>
<td>39.8</td>
<td>319,197</td>
<td>0.54</td>
</tr>
<tr>
<td>20</td>
<td>40</td>
<td>1.9968</td>
<td>144</td>
<td>39.8</td>
<td>320,494</td>
<td>0.56</td>
</tr>
<tr>
<td>30</td>
<td>40</td>
<td>1.9968</td>
<td>144</td>
<td>39.8</td>
<td>345,517</td>
<td>0.59</td>
</tr>
<tr>
<td>40</td>
<td>40</td>
<td>1.9968</td>
<td>131</td>
<td>39.8</td>
<td>364,788</td>
<td>0.55</td>
</tr>
<tr>
<td>50</td>
<td>40</td>
<td>1.9968</td>
<td>138</td>
<td>39.8</td>
<td>361,816</td>
<td>0.53</td>
</tr>
<tr>
<td>60</td>
<td>40</td>
<td>1.9968</td>
<td>144</td>
<td>39.8</td>
<td>374,813</td>
<td>0.52</td>
</tr>
</tbody>
</table>

The generation of cyclic pore-pressure was a fundamental interest of this research. The data collected during the resilient modulus tests were reduced and plotted to determine if the pore water within the specimen could respond to the cyclic application of stresses. As discussed in Chapter 4, stress was applied onto the specimen axially, via confining pressure, and directly into the specimen delivered from the bottom platen. All stresses were induced by a controlled volume changer. However, each path of stress
Figure 6-5. Typical Resilient Modulus Response

due to the specimen was different thereby necessitating testing to ensure that a cyclic response was possible. For example, fluid distribution to the specimen via the bottom platen is more arduous than that delivered to the confining water. Any flexibility with the system would be amplified by the pore-pressure reading during cyclic stress application. As is shown in Figures 6-6 and 6-7, pore water pressure responded to a cyclic loading in the axial direction producing a response complimentary to the sequence of the resilient modulus test. At strains of approximately $200 \times 10^{-6}$ in/in, pore-pressure was increased in excess of 1 psi. Under resilient cyclic loading, the pore-pressure shows a profile of increase and decrease similar to that which the specimen has during loading, unloading, and rest. This is expected since the increase in pore-pressure corresponds to a decrease in the volume of voids within the specimen.

The response for cyclic pore-pressure increase to the specimen via the base platen produced a similar trend except that the clarity of the profile was not as pronounced as
that of the axial induced stress. Figures 6-8 and 6-9 show typical plots of this method of loading. Although the peak pore-pressure is discernable, the recovery portion of each of the six cycles is slightly sporadic.

Pore-pressure increase through confining stress application produced a trend similar to that of displacement during a resilient modulus test. As shown in Figures 6-10 and 6-11, as the cyclic loading progressed, residual pore-pressure developed. This excess pore-pressure is believed caused by one, or a combination, of the following:

- As a cyclic load is applied to the specimen, a slight deformation occurs which decreases the volume of the interconnected voids thereby increasing the pore-pressure
- The 0.9 sec rest period is not sufficient to allow a stabilization of the excited pore-pressure therefore, cyclic loading continues to increase the pore-pressure

6.4.2 Conclusions

Specimens were tested for resilient modulus at 10°C and 40°C in the undrained condition and at 40°C in the drained condition. Strain was induced onto the specimen by a direct method (axial loading), and indirect methods (confining stress and pore-pressure). With the undrained tests, a pore-pressure increase was recorded during the loading of the specimen. Test data showed that the pore-pressure increase recorded as a result of the direct method could also be achieved by the indirect methods.

As intuitively expected, specimens tested at the lower temperature showed higher values of resilient modulus than those tested at the higher temperature. A comparison of undrained and drained specimens at 40°C indicated an increase in resilient modulus when the specimen was allowed to drain. These results are reasonable since an undrained specimen will exhibit an increase in pore-pressure when loaded which will impose a lateral stress onto the specimen thereby producing a lateral strain. Since the volume of
the specimen is conserved and constant during testing, the lateral strain will contribute to higher values of axial strain than would be achieved in a drained test.

During drained testing, a negligible pore-pressure increase was noted. A total of 9 consecutive tests were conducted on the drained specimen at 5 min intervals up to the 20 min mark and then every 10 min up to the 60 min mark. No notable change in pore-pressure was evident over the duration of the tests. The average pore-pressure during loading remained constant at approximately 0.5 psi. The relatively low strain applied to the specimen combined with the allowance for the specimen to drain during loading, makes the low pore-pressure increase reasonable. Additionally, the frictional contributions imposed by the wall of the interconnected voids combined with the irregular path of these voids, will prevent the complete draining of permeant thereby allowing for a notable, though be it small, increase in pore-pressure with loading.

![Figure 6-6. Axially Loaded Specimen at 10°C – Pore-Pressure Response](image)
Figure 6-7. Axially Loaded Specimen at 40°C - Pore-Pressure Response

Figure 6-8. Base Platen Loaded Specimen at 10°C - Pore-Pressure Response
Figure 6-9.  Base Platen Loaded Specimen at 40°C - Pore-Pressure Response

Figure 6-10.  Confining Stress Loaded Specimen at 10°C – Pore-Pressure Response
Figure 6-11. Confining Stress Loaded Specimen at 40°C – Pore-Pressure Response

6.5 Complex Modulus

Dynamic complex modulus is derived as the relationship between the applied stress and the corresponding strain. The complex modulus, $E^*$, is defined as

$$|E^*| = \frac{\sigma_o}{\varepsilon_o}$$  \hspace{2cm} (6.7)

where
- $\sigma_o$ = Applied stress (psi)
- $\varepsilon_o$ = Vertical strain (in/in)

The phase angle, $\Phi$, is the angle, which the strain lags behind the stress. The phase angle is calculated as

$$\phi = (t_{lag} \times f) \times 360$$ \hspace{2cm} (6.8)

where
- $t_{lag}$ = Time difference between signals (sec)
- $f$ = Frequency of the dynamic load (Hz)

The modulus of viscoelastic materials can be separated into a viscous portion, $E''$, and an elastic portion, $E'$. The equations for these properties are defined as
\[ E'' = \frac{|E^*|}{\sin \phi} \quad (6.9) \]

\[ E' = \frac{|E^*|}{\cos \phi} \quad (6.10) \]

6.5.1 Results of Specimens Tested at 40°C

Plots were created to visually examine the cyclic pore-pressure response to the four frequencies used. For specimens tested in the undrained condition, plots were made at 1 Hz, 4 Hz, 10 Hz, and 16 Hz. The specimens tested in the drained condition only required a plot for the 1 Hz frequency. This was due to the typical response of the pore-pressure at all four frequencies. As is shown in Figures 6-13 through 6-16, pore-pressure response decreased and became less defined as the load frequency increased. Although an increase and decrease in pore-pressure is indicated at the 10 Hz and 16 Hz frequencies, the pressure does not follow the cyclic axial loading. The 1 Hz and 4 Hz frequencies better indicate a trend of pore-pressure response to cyclic loading. As is clearly shown in Figure 6-14, at the 4 Hz frequency a time lag exists between the load application and the corresponding pore-pressure response. This lag is similar to the time lag between the response strain and the applied load. Since an increase in pore-pressure is directly related to a decrease on volume of voids, it is logical to conclude a relationship between strain and pore-pressure.

Drained testing at 40°C indicated a negligible response of pore-pressure with cyclic loading as is shown in Figure 6-17. This is primarily due to the small strains imposed on the specimen. Capillary forces that existed within the interconnected voids precluded
complete drainage of the permeant. Therefore, any water entrained in the specimen will remain within the interconnected voids during cyclic loading.

Complex modulus results indicated an increase in modulus with an increase in cyclic load frequency. A negligible difference was found between specimens tested in the undrained and drained conditions. Compared to baseline testing with a dry specimen, both the undrained and drained complex moduli were significantly higher. This suggests that the presence of water has a tendency to stiffen the structure of the specimen. As is shown in Figure 6-18, this relationship existed with all frequencies of cyclic loading.

6.5.2 Results of Specimens Tested at 10°C

As with the testing at 40°C, plots were made of the data collected at 10°C. The trends found at the aforementioned temperature were also found at the lower temperature as is presented in Figures 6-19 through 6-22. A time lag between the pore-pressure and the applied load was again seen at the 4 Hz loading frequency. At frequencies of 10 Hz and 16 Hz, it was difficult to discern a pore-pressure response trend corresponding to the cyclic load. Similarly, the drained test, shown in Figure 6-22, did not show any significant pore-pressure response with cyclic loading.

The similarity in trend was also indicated in regards to the values of dynamic modulus at the tested frequencies. Again, testing of undrained and drained specimens produced a significantly higher modulus than dry specimens.

6.5.3 Conclusions

Complex modulus testing was accomplished on specimens at low and high temperature, 10°C and 40°C respectively. Pore-pressure response was recorded in both the drained and undrained conditions. In the undrained condition at both low and high temperature, a pore-pressure response was observed at the lower frequencies of load
application (1 Hz and 4 Hz). The pore water response lagged behind the cyclic load application. This lag is similar to the time lag between the response strain and the applied load. The time lag of pore-pressure is reasonable to expect since it is strain of the specimen that causes the volume of voids to decrease and increase the pore-pressure.

At the higher frequencies tested, 10 Hz and 16 Hz, a pore-pressure response was difficult to discern. This lack of response is most likely attributed to the shortness of time the pressure has to develop due to the abbreviated load contact time. This trend indicates that pore-pressure response is dependent on the frequency of load application. Furthermore, this relationship between frequency of load application and the development of pore-pressure may indicate that more damage occurs, as a result of pore-pressure increase, in pavements that support slow speed traffic than those which support high speed traffic.

In the drained condition, a small but notable pore-pressure response was indicated at each of the frequencies tested. However, a plot of pore-pressure response versus time did not produce a discernable trend of increase or decrease with the cyclic loading of the specimen. This is attributed to the relatively small strains imposed on the specimen, which are not substantial enough to produce a well-defined pore-pressure response from the unconfined ends.
Figure 6-12. Stress-Strain Response of the Complex Modulus Test

Figure 6-13. 1 Hz Cyclic Loading at 40°C (Undrained)
Figure 6-14. 4 Hz Cyclic Loading at 40°C (Undrained)

Figure 6-15. 10 Hz Cyclic Loading at 40°C (Undrained)
Figure 6-16. 16 Hz Cyclic Loading at 40°C (Undrained)

B.P. = 9.7 psi
Conf. = 15.4 psi

Figure 6-17. 1 Hz Cyclic Loading at 40°C (Drained)

B.P. = 0.3 psi
Conf. = 1.8 psi
Figure 6-18. Comparison of Dynamic Modulus at 40°C

Figure 6-19. 1 Hz Cyclic Loading at 10°C (Undrained)
Figure 6-20. 4 Hz Cyclic Loading at 10°C (Undrained)

Figure 6-21. 16 Hz Cyclic Loading at 10°C (Undrained)
Figure 6-22. 16 Hz Cyclic Loading at 10°C (Drained)

Figure 6-23. Comparison of Dynamic Modulus at 10°C
CHAPTER 7
SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 Summary

In this thesis, a system was developed that is capable of monitoring the pore-pressure response to static and cyclic loading of HMA. The system is capable of saturating HMA specimens and temperature conditioning them at both high and low temperatures. The time required for the achievement of these temperatures has been minimized such that the system can perform production testing of specimens more efficiently. To ensure a threshold saturation level, a method has been developed to determine Skempton’s B parameter. Protocols have been developed which allow complex and resilient modulus testing, and compression testing. Additionally, the system has been designed such that falling and constant-head hydraulic conductivity testing can be accomplished.

7.2 Conclusions

The ETTS has proven capable of inducing pore-pressure and monitoring the corresponding response in HMA specimens. A summary of findings can be concluded as the following:

- Coarse HMA specimens can be effectively saturated using flushing, and vacuum and backpressure saturation techniques. The specimens can be temperature conditioned at both high and low temperatures and maintained throughout the duration of testing.

- The hydraulic conductivity of HMA specimens will increase and then decrease as the pressure gradient across the specimen is increased.
• Pore-pressure response is notable at low strain depending upon frequency of cyclic loading.

• In cyclic testing, the development of pore-pressure is dependent upon the contact time of the load. At high frequencies there is no notable fluctuation in pore-pressure. In complex modulus testing, a cyclic pore-pressure response was seen at load frequencies of 1 Hz and 4 Hz but was not evident at 10 Hz and 16 Hz.

• Higher loads were required with specimens tested a low temperature to achieve the equivalent pore-pressure excitation of high temperature specimens.

• Pore-pressure can be induced to an HMA specimen by indirect methods such as an increase in confining stress or axial load application. Pore-pressure excitation within the specimen is independent of the method of application.

• Pore-pressure does not occur immediately upon the application of a cyclic load but lags depending upon the configuration of the interconnected voids and loading frequency.

• As the size and percentage of interconnected voids decreases, the specimen becomes less efficient in stabilizing a pressure gradient across its length.

### 7.3 Recommendations

#### 7.2.1 Recommendations for Testing Procedures

The testing procedures developed were initially completed in order to determine the competence of the ETTS with regards to the testing of HMA. The mixture and range of air voids used allowed for the comparison of test results with a well-known mix. Although testing on different parameter mixes, such as a fine mix, is not anticipated to alter the developed protocols for testing, those for the saturation and conditioning of the specimen are expected to be different. For example, coarser graded mixtures have been shown to contain larger individual voids thereby having a higher potential for interconnected voids (Cooley et al. 2001). Therefore, it can be presumed that a greater effort will be required to saturate a fine mix than a coarse mix. A more aggressive saturation procedure will need to be investigated for testing of fine mixes. Additionally, since water is a better conductor of thermal energy than air, it is expected that new
heating and cooling envelopes will need to be developed to ensure proper core temperature when testing fine mixes.

Methods to conduct extension testing (extensile failure) using the ETTS still need to be developed. The work done indicates that increasing the confining stress while maintaining a constant axial stress is not effective with this system. The ability of the computer-controlled load frame to adjust to small increases in force, as applied via the piston, precludes the use of a membrane as a medium for pore-pressure transfer. It is recommended that a method of specimen preparation similar to that used by Visser (1998) be examined to determine if increasing the confining stress and maintaining a constant axial stress can achieve fracture of HMA. With sandstone specimens, Visser (1998) capped both ends with an impermeable epoxy. The circumferential area of the specimens were not coated but rather left exposed to the confining pressure. The epoxy coating prevented confining pressure from acting onto the top platen via the network of voids in the specimen.

Another variation of Visser’s (1998) work, which should be explored with HMA, is to establish a high isotropic pressure and then allow a constant rate displacement of the piston while maintaining a constant confining pressure.

Although pore-pressure readings would not be able to be collected during these testing, the tensile strength of HMA could still be determined. Additionally, the specimen could still be temperature conditioned. However, the specimen would have to be pre saturated and an assurance of B-value would not be possible with capped ends and the absence of a membrane.
With the design, construction, and proof testing of the ETTS complete, future testing can proceed with a more defined and acute scope of work. Additional research should be conducted with this system for a parametric study of pore-pressure response. Parameters such as load application frequency and magnitude should be introduced to ascertain correlations between these and moisture-induced damage to HMA.

7.2.2 Recommendations for ETTS Construction and Design

As a prototype, the ETTS performed extremely well. However, as with all first generation systems, several areas for improvement were discovered following manufacture. If a new cell were to be constructed in the future, the following design modifications are suggested:

- Utilize a thicker walled confining cylinder. By procuring a thicker walled cylinder, problems associated with the deformation of the existing cylinder can be avoided. It is recommended that the thicker walled cylinder be centerless ground both outside and inside to achieve a truly round end profile. This improvement will make installation of the cylinder and alignment over the o-rings more easily achievable.

- Adjust the locations of the LVDT cable slots in the baseplate. Presently, two of the cable slots exit through the back of the baseplate and two others, one on each side, through the sides of the plate. It was found that the cables exiting from the sides interfered with bolts contained in the load frame, which hold the cell firmly to it. Future baseplate design should conduct all four of these slots to the back of the baseplate allowing for an uninterrupted routing to the data acquisition system.

- Delete spanner wrench holes from the base platen. These holes allowed for use of a spanner wrench to tighten the base platen and compress the o-ring between it and the base plate. After assembling the cell, it was found that adequate compression of the o-ring could be achieved by hand tightening. The addition of the spanner wrench holes added additional cost to the manufacture, which was not required.

- Modify placement of top pressure transducer to the inside of the piston. The pressure transducer which monitors the pressure at the top of the specimen is removed from this point by a length of tubing that runs from the piston and out through the top plate. This added length may attribute to additional response time of the recording of pore-pressure. It is recommended that pistons constructed in the future incorporate a thru hole from the top of the piston to the bottom, which will create a dedicated conduit for the placement of a micro pressure transducer. This
micro pressure transducer could be situated such that its diaphragm is flush with the bottom of the piston. This improvement would assure immediate response to pressure fluctuations at the top of the specimen.

- Decrease National Pipe Thread (NPT) designation for port at the top of the piston. The female fitting tap at the top of the piston allows for the transport of water from the specimen to the outside of the cell. The size of this tap was oversized in the design process in order to allow for the purchase of a readily available fitting. The correspondingly large fitting limits the stroke length of the piston since the top of this fitting will contact the bottom of the top plate. A smaller NPT designation will require that a less common fitting be procured. However, the added cost for this fitting will allow for a greater stroke length of the piston.

- Add handles to the base plate. The weight of the cell coupled with the added weight of contained water made positioning of the cell in the load frame awkward and difficult. The addition of handles affixed to the base plate would allow a more controlled way to position the cell.

- Decrease diameter of four thru holes in the confining ring. These thru holes allow alignment of the confining ring with the bolt heads that fasten the top plate to the struts. The thru holes in the existing design were made larger than the diameter of the bolt heads allowing for flexibility with positioning. The over-sizing inadvertently allowed the o-ring on the top of the top plate to be slightly exposed along the circumference of the thru holes. At high pressures, the o-ring would bulge at this exposure and compromise the containment of pressure. To restrain the o-ring, smooth washers were placed between the bolt head and the top plate thereby restraining the o-ring. By reducing the diameter of the thru holes, these washers will not be required.

- Decrease tolerance between the piston and piston sleeve. The superior performance of the u-cup seals allow for a reduction of the specified tolerance between the two components. Although the diameter and tolerance of the piston should still be maintained, since this diameter must compliment the specimen’s, the inside diameter of the piston sleeve can be increased and the tolerance decreased to reduce the cost to manufacture.

In addition to modifications to the cell, the support system can be improved to provide better performance. The following are suggestions for modification of the existing system:

- Incorporate a larger volume burette for hydraulic conductivity testing. The 50 mL capacity burette presently used performs extremely well. However, during constant-head hydraulic conductivity testing, the test time is limited due to the limited capacity of the burette. The addition of a larger volume burette will
increase the length of time steady-state flow can be maintained thereby allowing an increased amount of data for the determination of conductivity.

- Replace all steel valves with stainless steel valves. The valves used in the water distribution system are made of steel. The aggressive environments these valves operate in have caused them to rust and contribute contaminants to the distribution network. Replacing these valves with more costly stainless steel valves would create a corrosion-resistant distribution network and prevent any contaminants in the permeant.
APPENDIX A
TRIAXIAL CELL FABRICATION DRAWINGS
Figure A-1. Enhanced Triaxial Cell Fabrication Drawings – Title Sheet
Figure A-2. Cell Profile
Figure A-3. Base Plate
Figure A-4. Top Plate
Figure A-6. Piston Sleeve
Figure A-7. Strut

STRUT - TOP VIEW

STRUT - SIDE VIEW

STRUT - SECTION DD
Figure A-8. Piston
Figure A-9. Piston Plate Cover
Figure A-10. Base Platen
Figure A-11. Riser
Figure A-12. LVDT Holder
Figure A-13. Connection Detail

TOP PLATE/STRUT CONNECTION

TOP PLATE/CONFIRMING RING CONNECTION

PISTON ASSEMBLY DETAIL

UNIVERSITY OF FLORIDA

156
Figure A-14. Water Distribution Schematic
APPENDIX B
CONSTANT-HEAD HYDRAULIC CONDUCTIVITY EQUATION
DERIVATION FOR USE WITH THE ENHANCED TRIAXIAL CELL

\[ q = -kA = -k \frac{dH}{dZ} \]  \hspace{1cm} (B.1)

\[ dH = H_2 - H_1 \]  \hspace{1cm} (B.2)

Use the Bernoulli Equation for Steady, Inviscid, Incompressible Flow

\[ \frac{P_1 + \rho V_1^2}{2} + \gamma Z_1 = \frac{P_2 + \rho V_2^2}{2} + \gamma Z_2 \hspace{1cm} \text{where} \gamma = \rho g \]

Divide through by \( \gamma \)

\[ \frac{P_1 + \rho V_1^2}{2 \rho g} + \frac{Z_1}{\rho g} = \frac{P_2 + \rho V_2^2}{2 \rho g} + \frac{Z_2}{\rho g} \]

Assume \( \frac{V^2}{2g} \) Small and Negligible (Velocity Small)

\[ \frac{P_1}{\rho g} + \frac{Z_1}{\rho g} = \frac{P_2}{\rho g} + Z_2 \]

Head on Bottom of Specimen = \( \frac{P_1}{\rho g} + Z_1 \)

Head on Top of Specimen = \( \frac{P_2}{\rho g} + Z_2 \)

At a Time \( t \), \( H_1 = \frac{P_1}{\rho g} + Z_1 \) and \( H_2 = \frac{P_2}{\rho g} + Z_2 + h_b \) where \( h_b = \Delta H \) in Burette

Since \( H_1 \) remains constant throughout the test (water level in volume changer and pressure is unchanged) Equation B.2 becomes:

\[ dH = \left[ \frac{P_2}{\rho g} + Z_2 + h_b \right] - \left[ \frac{P_1}{\rho g} + Z_1 \right] \]
\[ dH = \left[ \frac{P_2 - P_1}{\rho g} + (Z_2 - Z_1) + h_B \right] \]

\[ dZ = \text{Length of specimen, } L \]

Therefore, Equation B.1 becomes:

\[ q = \frac{-kA}{L} \left[ \frac{P_2 - P_1}{\rho g} + (Z_2 - Z_1) + h_B \right] \]  \hspace{1cm} (B.3)

**Quantity of water flowing through specimen at time \( t \)**

\[ = q = a \frac{dh_B}{dt} \]  \hspace{1cm} (B.4)

where: \( a = \text{cross sectional area of burette} \)

Set Equations B.3 and B.4 equal

\[ a \frac{dh_B}{dt} = \frac{-kA}{L} \left[ \frac{P_2 - P_1}{\rho g} + (Z_2 - Z_1) + h_B \right] \]

Divide through by "\( a \)"

\[ \frac{dh_B}{dt} = \frac{-kA}{La} \left[ \frac{P_2 - P_1}{\rho g} + (Z_2 - Z_1) + h_B \right] \]

Define: \[ C_1 = \frac{-kA}{La} \left[ \frac{P_2 - P_1}{\rho g} + (Z_2 - Z_1) \right] \]

\[ C_2 = \frac{-kA}{La} \]

\[ \therefore \frac{dh_B}{dt} = C_1 + C_2 h_B \]

\[ \Rightarrow dt = \frac{dh_B}{C_1 + C_2 h_B} \]

\[ \int_0^t \frac{dh_B}{C_1 + C_2 h_B} = \int_0^t dt \]

\[ \Rightarrow \frac{1}{C_2} \ln(C_1 + C_2 h_B) = t \]

\[ \Rightarrow \frac{1}{C_2} \left[ \ln(C_1 + C_2 h_B) - \ln(C_1) \right] = t \]

\[ \Rightarrow \frac{1}{C_2} \left[ \ln \left( \frac{C_1 + C_2 h_B}{C_1} \right) \right] = t \]

\[ \Rightarrow \frac{1}{C_2} \ln \left( 1 + \frac{C_2 h_B}{C_1} \right) = t \]
\[
\frac{C_2}{C_1} = \left[ \frac{-kA}{La} \right] \frac{P_2 - P_1}{\rho g} + (Z_2 - Z_1) = \left[ \frac{1}{P_2 - P_1} \right] \frac{1}{\rho g} + (Z_2 - Z_1)
\]

\[
\rightarrow \frac{1}{-kA} \ln \left[ 1 + \frac{h_B}{P_2 - P_1} \frac{1}{\rho g} + (Z_2 - Z_1) \right] = t
\]

\[
\rightarrow \frac{-La}{kA} \ln \left[ 1 + \frac{h_B}{P_2 - P_1} \frac{1}{\rho g} + (Z_2 - Z_1) \right] = t
\]

\[
\rightarrow k = -\frac{aL}{At} \ln \left[ \frac{P_2 - P_1}{\rho g} + (Z_2 - Z_1) + h_B \right]
\]

\[
\Rightarrow k = -\frac{aL}{At} \ln \left[ \frac{h_{FINAL}}{h_{INITIAL}} \right]
\]

\[
\therefore k = -\frac{aL}{At} \ln \left[ \frac{(P_2 - P_1) + (Z_2 - Z_1) + h_B}{(P_2 - P_1) + (Z_2 - Z_1)} \right]
\]

**Definition of Variables**

- \(a\) = Cross-sectional area of burette (cm\(^2\))
- \(L\) = Length of specimen (cm)
- \(A\) = Cross-sectional area of specimen (cm\(^2\))
- \(t\) = Elapsed test time (sec)
- \(P_1\) = Headwater pressure from volume changer (kg/cm\(^2\))
- \(P_2\) = Tailwater pressure from air supply (kg/cm\(^2\))
- \(Z_1\) = Height from datum to center of volume changer (cm)
Definition of Variables (cont.)

\[ Z_2 = \text{Height from datum to initial burette reading (cm)} \]
\[ h_B = \text{Final burette reading at time } t \text{ minus the initial burette reading (cm)} \]
\[ \rho = \text{Density of water at } 25^\circ \text{C } = .999 \text{ g/cm}^3 \approx 1 \text{ g/cm}^3 \]
\[ g = \text{Gravitational constant } = 1 \text{ cm/s} \]
APPENDIX C
TESTING PROTOCOLS

Specimen Saturation and $B$-value Determination Protocol

1. Cut ends of gyratory compacted specimen such that the finished ends are perpendicular to the longitudinal axis. Finished length of specimen should be approximately 5.5 inches (139.7 mm).

2. Place specimen in a water-filled vacuum chamber and induce a pressure of –26 inHg for 5 min. At the end of 5 min, release the vacuum and allow the specimen to rest for 1 min. Repeat this process until no air is observed exiting the specimen.

3. Remove the specimen from the chamber and place in a water-filled sink ensuring that the specimen in entirely submerged. Place the membrane over specimen being careful as not to puncture it on exposed aggregate. Position the membrane so that there is approximately 1.5 inches of excess on each end of the specimen. Roll the excess membrane back onto the specimen and then place four o-rings, two on each end, on top of the overlapping membrane.

4. Prepare the triaxial cell for the installation of the specimen by forcing de-aired water through the distribution panel with the volume changer. The water should be conducted through the valve leading to the bottom platen. Continue to force water through until there is no visible air exiting from the face of the base platen.

5. Remove the specimen form the sink and place in a water-filled container for transport to the cell. Place the specimen into the cell being careful not to damage the membrane. Lower the piston onto the top face of the specimen and align it so that it is positioned centric to both the top and bottom platens. Since both ends of the specimen were cut, the specimen should align properly with both platens making a complete contact with the ends. Roll the excess ends of the membrane over both the top and bottom platens and secure the o-rings over the membrane positioned vertically in the grooves contained in each platen.

6. Force de-aired water through the specimen with a gradient of approximately 5. Air pressure acting on the top of the de-aired water storage container should transmit water. This water will be conducted through the distribution panel and delivered to the bottom of the specimen. At this point, the water will pass through the specimen and be collected in the graduated burette. Continue to force water through the specimen until no visible air is detected in the burette.

7. During the forcing of water process, the membrane will balloon around the specimen allowing for any entrapped air around the circumferential surface to exit through the
top platen. Examine the membrane for any sign of leakage or damage, which may compromise the membrane during testing.

8. Initiate a vacuum saturation process by closing the bottom valve and applying a pressure of –26 inHg onto the top of the burette. When the vacuum is achieved, close the top valve and open the bottom valve thereby allowing water to enter through the bottom of the specimen. When the flow of water into the specimen has ceased, close the bottom valve, open the top valve, and reapply a vacuum via the burette. Continue this process until no visible air is detected in the burette.

9. Install the confining cylinder and confining ring, and tighten all fasteners. Fill the cell with de-aired water from the base allowing air to evacuate the cell via the opening in the top plate. Close the bottom valve and open the top valve leading to the specimen. Apply 5 psi confining stress to the specimen allowing any water between the ballooned membrane and the circumferential surface of the specimen to exit through the top platen. Open the bottom valve.

10. Initiate a backpressure saturate process by incrementally increasing the confining pressure and top and bottom pressures while not exceeding an effective stress of 5 psi. Once the confining and top and bottom pressures are approximately 60 psi and 55 psi respectively, stop the increase of pressure and allow the specimen to stabilize for 30 min.

11. Close the top and bottom valves leading to the specimen. Increase the confining pressure in increments of approximately 0.25 psi. After each increase, calculate the $B$-value by using Equation 4.1. Continue with the incremental increase of confining pressure until the optimal $B$-value is achieved. Typically, the optimum value is reached within a range confining pressure increase of 0.25 to 2.0 psi.

Falling-Head Hydraulic Conductivity Testing Protocol

1. Close the bottom valve leading to the specimen. Open top valve. Disconnect the influent line (leading to the base of the specimen) from the distribution panel. Apply a confining stress of 5 psi.

2. Fill the graduated burette so that it contains approximately 45 mL of de-aired water. Apply a pressure of 3 psi to the column of water in the burette. This pressure will be conducted through the water in the burette and to that contained within the specimen via the top valve and platen. Close the top valve.

3. To begin the test, open the bottom valve while simultaneously initiating the data acquisition process. Recordings should be made of time, and confining, top, and bottom pressures.

4. When the bottom pressure transducer reads approximately 0 psi, close the bottom valve and stop the acquisition of data.
5. To prepare for a second test, open the top valve, apply 3 psi of pressure to the burette, and close the top valve.

6. Repeat sequence for a minimum of three tests and calculate conductivity by using Equation 4.2.

Constant-Head Hydraulic Conductivity Testing Protocol

1. With both the top and bottom valves open, apply a confining stress of 10 psi.

2. Close top valve, and drain the burette so that it contains approximately 5 mL of water. Open the top valve.

3. Test the conductivity of the specimen at gradients ranging from 5 to 55 in increments of 5.

4. Apply a top and bottom pressure of 1 psi using the air distribution panel. Pressure to the top of the specimen is received from the air over water configuration of the burette. Pressure to the bottom of the specimen is received from an air over water configuration of the water storage container, which conducts water to the specimen via the water distribution panel.

5. Using the pressure values per gradient, adjust the pressure to the bottom (influent) of the specimen while maintaining 1 psi at the top platen (effluent).

6. When the pressures are achieved, record the starting level of the rising water in the burette while simultaneously initiating data acquisition of: time, and top bottom, and confining pressures.

7. Allow the test too proceed until the burette is filled with water. Record the final burette reading while simultaneously stopping the acquisition of data.

8. Close the top and bottom valves and drain the burette.

9. Begin the next gradient by opening the top and bottom valves and establishing the required bottom (influent) pressure.

10. Calculate the conductivity at each time step using Equation 4.4.
Table C-1. Initial Conditions for Constant-Head Conductivity Testing per Gradient

<table>
<thead>
<tr>
<th>Gradient</th>
<th>Applied Stress (psi)</th>
<th>Average Effective Stress Across Specimen (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Confining</td>
<td>Top</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>25</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>35</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>40</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>45</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>50</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td>55</td>
<td>12</td>
<td>1</td>
</tr>
</tbody>
</table>
## APPENDIX D
### PERCENT AIR VOID RESULTS

Table D-1. Percent Air Void Results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Compacted Ht. (mm)</th>
<th>Specimen Weight</th>
<th>G_mb</th>
<th>G_mm</th>
<th>%AV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Air</td>
<td>SSD</td>
<td>Water</td>
<td></td>
</tr>
<tr>
<td>J2</td>
<td>174.0</td>
<td>2379.4</td>
<td>2403.1</td>
<td>1347.4</td>
<td>2.254</td>
</tr>
<tr>
<td>J8</td>
<td>174.5</td>
<td>2630.7</td>
<td>2645.5</td>
<td>1478.4</td>
<td>2.254</td>
</tr>
<tr>
<td>J14</td>
<td>174.5</td>
<td>2621.0</td>
<td>2632.5</td>
<td>1473.8</td>
<td>2.262</td>
</tr>
<tr>
<td>J15</td>
<td>174.5</td>
<td>2631.9</td>
<td>2641.6</td>
<td>1474.7</td>
<td>2.255</td>
</tr>
<tr>
<td>J16</td>
<td>174.5</td>
<td>2449.3</td>
<td>2463.4</td>
<td>1378.6</td>
<td>2.258</td>
</tr>
<tr>
<td>J17</td>
<td>174.5</td>
<td>2458.9</td>
<td>2477.4</td>
<td>1383.8</td>
<td>2.248</td>
</tr>
<tr>
<td>J18</td>
<td>174.5</td>
<td>2442.3</td>
<td>2462.2</td>
<td>1376.1</td>
<td>2.249</td>
</tr>
<tr>
<td>J22</td>
<td>174.0</td>
<td>2414.4</td>
<td>2436.9</td>
<td>1363.2</td>
<td>2.249</td>
</tr>
<tr>
<td>J23</td>
<td>174.0</td>
<td>3005.4</td>
<td>3038.4</td>
<td>1708.4</td>
<td>2.260</td>
</tr>
</tbody>
</table>
LIST OF REFERENCES


BIOGRAPHICAL SKETCH

Jeffrey Wade Frank was born to James and Linda Frank in Danbury, Connecticut, on August 20, 1970. He continued to live in Connecticut graduating from Bethel High School in 1988. After graduation, he joined the U.S. Navy, where he served 6 years with the Naval Construction Forces (better known as the SeaBees). During this time, he had the opportunity to perform duties as an engineering technician at stations within the United States and around the world including Turkey, Sicily, and Guam. Upon honorable discharge from the military, he began general studies at Santa Fe Community College in Gainesville, Florida. Obtaining an Associate of Arts degree in 1997, he applied for and was accepted into the College of Civil Engineering at the University of Florida, where he completed a Bachelor of Science degree in May 2001. During this time, he worked as a cooperative student at the State Materials Office of the Florida Department of Transportation, where he became interested in bituminous material research. This interest inspired him to pursue a research project, and eventually a Master of Engineering degree.

Mr. Frank presently lives in Jacksonville, Florida, with his wife of 6 years, Amy; and daughter Sara. He is employed by PBS&J as a project engineer. He and Amy are expecting their second daughter, Rebecca, in June.