INFLUENCE OF TEST METHOD VARIABLES ON Mn/ROAD HOT MIX ASPHALT MIXTURE TEST RESULTS
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Mary Stroup-Gardiner Andrew Drescher
David E. Newcomb Wei Zhang

University of Minnesota
Department of Civil Engineering
500 Pillsbury Drive, S.E.
Minneapolis, MN 55455

Minnesota Department of Transportation
395 John Ireland Boulevard
St. Paul Minnesota, 55155

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At the Minnesota Road Research Project (Mn/ROAD), asphalt concrete mixtures were used to evaluate both warm and cold temperature material properties with selected test methods and a wide range of testing parameters. These parameters were selected to approximate different levels of environmental conditions, traffic speeds, traffic loads, and, in certain cases, confining pressures. The underlying theories used to calculate stress and strain from various loading configurations also were rigorously evaluated to determine the appropriateness of comparing results from one testing configuration to another.

Mn/ROAD mixtures were evaluated as the first step in linking laboratory measurements and test method selection to live traffic pavement responses and performance.

A comparison of axial and diametral testing using harmonic loading showed that experimental results did not agree with theory. That is, the complex deviatoric modulus determined for diametral testing should have been less than the Young's modulus determined from testing axially loaded samples. This was not the case. This suggested that a further examination of the sample instrumentation, testing variability, and the possibility of anisotropic mixture behavior due to particle orientation during compaction are needed to resolve these differences.

Other findings indicated that the influence of load duration is minimized as the test temperature decreases, there was little influence in rest period times in repeated loading tests on modulus, and confining pressure only had a significant influence on modulus above about room temperature.
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by

Mary Stroup-Gardiner
David E. Newcomb
Andrew Drescher
Wei Zhang

University of Minnesota
Civil Engineering Department
500 Pillsbury Dr., S.E.
Minneapolis, Minnesota 55455

for

U.S. Army Corps of Engineers
Cold Regions Research and Engineering Laboratory
72 Lyme Road
Lebanon, New Hampshire

January 21, 1997
## TABLE OF CONTENTS

**INTRODUCTION** .................................................... 1  
Objective .................................................... 4  
Scope .................................................... 4  
**MATERIAL PROPERTIES** .................................................... 5  
Aggregates .................................................... 5  
Asphalt Cement .................................................... 6  
**MIX DESIGNS** .................................................... 7  
Marshall Mix Designs (35, 50, and 75 Blow) .................................................... 8  
   Sample Preparation .................................................... 8  
   Marshall Mix Designs .................................................... 8  
Gyratory Mix Design .................................................... 9  
   Sample Preparation .................................................... 9  
   SHR P Level 1 Mix Design .................................................... 10  
Comparison of Mix Design Results .................................................... 11  
**TEST METHODS** .................................................... 12  
Stiffness/Compliance .................................................... 12  
   Uniaxial vs. Diametral Compression .................................................... 12  
   Uniaxial Testing at Warm Temperatures .................................................... 20  
Tensile Strength at Low Temperatures .................................................... 22  
   Indirect Tensile Strength .................................................... 23  
   SUPERPAVE (SHRP) Indirect Tensile Creep Test .................................................... 24  
   Fraass Brittle Point .................................................... 25  
   DSR .................................................... 26
TABLE OF CONTENTS (CONTINUED)

ANALYSIS ............................................................. 27

Stiffness/Compliance ............................................... 27

Uniaxial (ASTM D3497) ........................................ 27

Diametral (ASTM D4123) ........................................ 28

Comparison of Axial and Diametral Stiffness Measurements ...... 35

Diametrically Loaded Samples - Complex Deviatoric Modulus ...... 38

Axially Loaded Compliance and Creep Modulus .................. 44

Tensile Strength at Low Temperatures ................................ 57

Diametral Compression ............................................ 57

Diametral Compression Creep ..................................... 61

Brittle Point Measurements ....................................... 63

Comparison of Mix and Binder Low Temperature Properties ...... 63

SUMMARY AND CONCLUSIONS ...................................... 64

Theoretical Evaluation of Test Methods ............................ 64

Exceptions to Established Test Procedures ......................... 64

Stiffness/Compliance .............................................. 65

Tensile Strengths at Low Temperatures ............................ 66

REFERENCES .......................................................... 67
TABLE OF TABLES

Table 1. Aggregate Properties for Mn/ROAD Asphalt Concrete Test Cells ................. 6
Table 2. Physical Properties of Asphalt Cements .................................................. 7
Table 3. Marshall Mix Design Results (120/150 Penetration Grade Asphalt Cement) ... 9
Table 4. Gyratory Mix Design Results ............................................................... 10
Table 5. Comparison of Mix Design Results ........................................................ 11
Table 6. Test Methods Selected for Evaluation ...................................................... 12
Table 7. Axially Loaded Complex Modulus and Phase Shift Data Collected at 0.1 Hz . 29
Table 8. Axially Loaded Complex Modulus and Phase Shift Data Collected at 1.0 Hz . 30
Table 9. Precision for Phase Angle Measurements (Axial Loading)
           (120/150 Pen Asphalt Mix Design Mixtures) ............................................. 31
Table 10. Diametral Complex Modulus and Phase Shift Data (0.1 Hz) ...................... 40
Table 11. Diametral Complex Modulus and Phase Shift Data (1.0 Hz) ...................... 41
Table 12. Repeated Load (0.1 Second) Creep Test Results at 25°C After 1 Hr. .......... 46
Table 13. Repeated Load (1.0 Second) Creep Test Results at 25°C After 1 Hr .......... 50
Table 14. Static Creep Results (25°C) ............................................................... 54
Table 15. Static Creep Results (40°C) ............................................................... 55
Table 16. Low Temperature Behavior at Constant Rate of Deformation
           (120/150 Pen Mix Design Materials) ......................................................... 59
Table 17. Low Temperature Behavior at Constant Rate of Deformation
           (AC 20 Mix Design Materials) ................................................................. 60
Table 18. Indirect Tensile Creep Test Results for Mix Design Materials ................. 62
## TABLE OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Layout of the 5- and 10-Year Mainline Asphalt Concrete Test Cells</td>
<td>3</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Layout of the Low Volume Road Asphalt Concrete Test Cells</td>
<td>4</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Test Configurations for Uniaxial (ASTM D3497) and Diametral Compression (ASTM D4123)</td>
<td>14</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Construction of Mohr’s Circles</td>
<td>15</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Typical Loading Sequences for Repeated Loading of Asphalt Concrete</td>
<td>17</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Typical Displacement Response for Repeated Loading of Asphalt Concrete</td>
<td>17</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Definition of Variables (Harmonic Loading of Diametral Samples)</td>
<td>20</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Analysis of Typical Creep Data</td>
<td>22</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Definition of Brittle Point from DSR Testing</td>
<td>27</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Influence of Loading Frequency and Confining Pressure for 120/150 Pen Mixtures (Axial Loading)</td>
<td>32</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Influence of Loading Frequency and Confining Pressure for AC 20 Mixtures (Axial Loading)</td>
<td>32</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Influence of Loading Frequency and Confining Pressure on Phase Angle for 120/150 Pen Mixtures (Axial Loading)</td>
<td>33</td>
</tr>
<tr>
<td>Figure 13</td>
<td>Influence of Load Duration on Resilient Modulus (120/150 Pen Mixtures)</td>
<td>33</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Influence of Load Duration on Resilient Modulus (AC 20 Mixtures)</td>
<td>34</td>
</tr>
<tr>
<td>Figure 15</td>
<td>Influence of Changing Both Load Duration and Rest Period on Resilient Modulus (120/150 Pen Asphalt)</td>
<td>34</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Influence of Changing Both Load Duration and Rest Period on Resilient Modulus (AC 20 Asphalt)</td>
<td>35</td>
</tr>
<tr>
<td>Figure 17</td>
<td>Comparison of Resilient Modulus (Diametral Loading, 1 second Load Duration, 0.5 Hz) and Complex Modulus (Axial Loading, 1 Hz) for 120/150 Pen Mixtures</td>
<td>36</td>
</tr>
<tr>
<td>Figure 18</td>
<td>Comparison of Resilient Modulus (Diametral Loading, 1 second Load Duration, 0.5 Hz) and Complex Modulus (Axial Loading, 1 Hz) for AC 20 Mixtures</td>
<td>37</td>
</tr>
</tbody>
</table>
TABLE OF FIGURES (CONTINUED)

Figure 19. Comparison of Resilient Modulus (Diametral Loading, 0.1 second Load Duration, 0.33 Hz) and Complex Modulus (Axial Loading, 1 Hz) for 120/150 Pen Mixtures .................................................. 37

Figure 20. Comparison of Resilient Modulus (Diametral Loading, 1 second Load Duration, 0.5 Hz) and Complex Modulus (Axial Loading, 1 Hz) for AC 20 Mixtures .................................................. 38

Figure 21. Influence of Loading Frequency on Complex Deviatoric Modulus for 120/150 Pen Mixtures ............................................... 42

Figure 22. Influence of Loading Frequency on Complex Deviatoric Modulus for AC 20 Mixtures .................................................. 42

Figure 23. Influence of Loading Frequency on Phase Angle Measurements .......................... 43

Figure 24. Comparison of Harmonic Loading of Diametral and Axial Samples (120/150 Pen Mixtures) .................................................. 43

Figure 25. Comparison of Harmonic Loading of Diametral and Axial Samples (AC 20 Mixtures) .................................................. 44

Figure 26. Creep Compliance (25°C (77°F)), 120/150 Pen Mixtures ................................. 45

Figure 27. Creep Compliance (25°C (77°F)), AC 20 Mixtures ................................. 56

Figure 28. Creep Compliance (40°C (104°F)), 120/150 Pen Mixtures ................................. 56

Figure 29. Creep Compliance (40°C (104°F)), AC 20 Mixtures ................................. 57

Figure 30. Influence of Vertical Displacement Rates on Tensile Strengths at Cold Temperatures .................................................. 58

Figure 31. Influence of Vertical Displacement Rates on Horizontal Deformation at Cold Temperatures .................................................. 61

Figure 32. Creep Compliance Behavior at Cold Temperatures .................................................. 62
INTRODUCTION

In the late 1950's and early 1960's, the American Association of State Highway Officials (AASHO) undertook a large pavement performance experiment in Ottawa, Illinois, in which large cargo trucks were driven over a number of asphalt and concrete road structures for two years. Pavement conditions, in terms of roughness (ride quality) and distress, were monitored to define when pavement sections had failed. These were empirically related to the initial pavement structures in terms of layer thicknesses and material qualities. The resulting performance equations then formed the basis of how most of the pavements in the United States were designed. Local calibrations of these equations were developed to account for deviations in climatic and soil conditions in different parts of the country.

While the AASHO Road Test equations were adequate for the time period in which they were developed, there were several shortcomings. The AASHO Road Test was conducted over a two-year period, so while the contribution of traffic loadings to failure was well related, the contribution of climate was minimized, and the interaction between traffic and climate could not be adequately described. Also, because of the empirical nature of the equations, changing conditions in traffic loads and new materials could not be incorporated in the design procedure. So, while the empirical equations were relatively simple, they lacked the flexibility to handle change. Some examples of changes in traffic loadings included the use of higher pressure tires (from about 75 psi in the late 50's to 105 psi in the late 80's), higher volumes of truck traffic using roadways due to the closure of railheads and the use of radial tires instead of bias-ply tires (they have different contact pressure distributions and tracking characteristics). New materials such as polymer modified asphalt binders and asphalt-rubber could not be accommodated because they did not fit the model used to describe pavement performance at the AASHO Road Test.

Researchers such as Monismith, Finn, Mahoney, Epps and Newcomb began developing mechanistic-empirical approaches to pavement design which offered an improved flexibility in account for changes in loadings and materials. Most of these models are based on layered elastic analysis wherein loads are described in terms of their magnitude and geometry, and materials in terms of their elastic parameters (Young's modulus and Poisson's ratio). However, such efforts have met with limited success because of a lack of information concerning traffic and seasonal changes.
in material properties. The resulting failure criteria (relationships between pavement responses and performance) have been based on sketchy data, so there has been no widespread movement to adopt mechanistic-empirical design procedures. Thus, there was a need to research pavements on a large scale and explain the performance in mechanistic terms. This was the impetus for the construction of the Minnesota Road Research Project, named Mn/ROAD, located parallel to Interstate 94 (I-94) in Otsego, Minnesota which is approximately 60 km (40 miles) northwest of the Minneapolis-St. Paul metropolitan area. This facility consists of 4.8 km (3 miles) of two-lane interstate as well as 4 km (2.5 miles) closed-loop low volume test track. The I-94 traffic, an estimated 14,000 vehicles per day (15 percent trucks), is periodically diverted onto the high volume facility where 23 heavily instrumented test cells are subjected to controlled loading by a single vehicle circling the two-lane test track. The inside lane is trafficked four days a week with an 80,000 lb truck; the outside lane is trafficked one day a week with a 102,000 lb truck.

The interstate portion of the test facility has been divided into two parts, referred to as the 5-Year and 10-Year Mainline. These interstate sections have been designated for an estimate 5- and 10-Year design life, respectively. Both of these facilities and the low volume road have various portland cement concrete and asphalt concrete test cells. In addition, the low volume road has several aggregate surface cells. Figures 1 and 2 show the various structural layouts of the 5-Year, 10-Year, and Low Volume asphalt concrete test cells, respectively.

Mn/ROAD differs from previously constructed test tracks and accelerated loading facility studies in a number of ways. First, it has 40 asphalt, concrete and gravel-surfcaced pavement sections which span designs from low-volume roads to interstates. The pavement sections were designed so that different combinations of materials, layer thicknesses, design details and drainage schemes could be evaluated. All pavement sections are instrumented to monitor pavement responses including pressures, strains and displacements, and subsurface conditions of moisture content, moisture state, ground water level and temperature.

Before any mechanistic pavement design models can be developed, relationships between material properties, seasonal variations, traffic loadings, and pavement performance must be developed. This report presents the development of a data base for a wide range of material properties for the asphalt concrete mixtures which will eventually be used to construct these models.
Figure 1. Layout of the 5-and 10-Year Mainline Asphalt Concrete Test Cells.
Figure 2. Layout of the Low Volume Road Asphalt Concrete Test Cells.

Objective

The objectives of this research were to:

* Assess mixture temperature susceptibility, low temperature behavior and permanent deformation characteristics for a range laboratory loading conditions.
* Develop estimates of within-laboratory standard deviations for each test method.
* Evaluate theoretical and experimental differences between various test methods.
Scope

Mixtures were obtained from the Mn/ROAD project during the asphalt mix design phase of the project. A full description of the test facility, preconstruction, construction, and post construction testing can be found in the University of Minnesota report “Investigation of Hot Mix Asphalt Mixtures at Mn/ROAD - Final Report” (Stroup-Gardiner and Newcomb, 1997), published by the Minnesota Department of Transportation. These materials represent a total of eight different fine, dense-graded hot mix asphalt (HMA) mixtures. Variables included in these eight mixtures are four asphalt contents for each of two grades of asphalt from the same source. Both the aggregate sources and gradation were constant for all mixtures.

MATERIAL PROPERTIES

Aggregates

Three stockpiles of aggregates were used for the Mn/ROAD asphalt concrete mixtures. The majority of the mix was comprised of two stockpiles obtained from Buffalo Bituminous's Crow River pit in Buffalo, Minnesota; both of these were partially crushed river gravel. The third stockpile was obtained from Meridian, Inc. in St. Cloud, Minnesota and was a 100 percent crushed granite (CA-50) (Mn/DOT, 1987). The physical properties, stockpile gradations, and blending percentages used to prepare the mix design materials and the adjusted percentages used for construction are shown in Table 1.
Table 1. Aggregate Properties for Mn/ROAD Asphalt Concrete Test Cells.

<table>
<thead>
<tr>
<th>Property</th>
<th>Crow River Fines</th>
<th>Crow River Coarse</th>
<th>CA-50</th>
<th>Combined Gradation (Job Mix Formula)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blending Percentages, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mix Design</td>
<td>74</td>
<td>16</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Bulk Specific Gravity</td>
<td>2.731</td>
<td>2.663</td>
<td>2.624</td>
<td>2.708 (Mix)</td>
</tr>
<tr>
<td>Absorption Capacity, %</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Percent Fractured Faces, %</td>
<td>---</td>
<td>61.2</td>
<td>100</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cumulative Percent Passing, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19 mm (3/4 in)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>12.5 mm (5/8 in)</td>
<td>100</td>
<td>75</td>
<td>80</td>
<td>92</td>
</tr>
<tr>
<td>9.0 mm (3/8 in)</td>
<td>99</td>
<td>53</td>
<td>37</td>
<td>82</td>
</tr>
<tr>
<td>4.75 mm (No. 4)</td>
<td>94</td>
<td>19</td>
<td>4</td>
<td>67</td>
</tr>
<tr>
<td>2.0 mm (No. 10)</td>
<td>82</td>
<td>11</td>
<td>---</td>
<td>57</td>
</tr>
<tr>
<td>1.0 mm (No. 20)</td>
<td>63</td>
<td>8</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>0.45 mm (No. 40)</td>
<td>39</td>
<td>6</td>
<td>---</td>
<td>27</td>
</tr>
<tr>
<td>0.25 mm (No. 80)</td>
<td>10</td>
<td>4</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>0.125 mm (No. 100)</td>
<td>8</td>
<td>3</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>0.075 mm (No. 200)</td>
<td>4.9</td>
<td>2.4</td>
<td>---</td>
<td>4</td>
</tr>
</tbody>
</table>

**Asphalt Cement**

Two grades of binder, a 120/150 penetration grade and an AC 20 viscosity grade, were supplied by the Koch Refinery in Rosemount, Minnesota. A comparison of the binder properties and the relevant binder specifications are shown in Table 2.
Table 2. Physical Properties of Asphalt Cements.

<table>
<thead>
<tr>
<th>Property</th>
<th>Koch 120/150 Penetration Grade</th>
<th>ASTM D946 Specification</th>
<th>Koch AC 20 Specification</th>
<th>ASTM D3381 Specification Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity, 60°C (140°F), Poise</td>
<td>846</td>
<td>---</td>
<td>1987</td>
<td>2,000 ± 400</td>
</tr>
<tr>
<td>Viscosity, 135°C (275°F), cSt</td>
<td>271</td>
<td>---</td>
<td>397</td>
<td>210 min</td>
</tr>
<tr>
<td>Penetration, 25°C (77°F), 0.1 mm</td>
<td>130</td>
<td>120 min</td>
<td>76</td>
<td>40 min</td>
</tr>
<tr>
<td>Ductility, 25°C (77°F), 5 cm/min</td>
<td>120+</td>
<td>---</td>
<td>120+</td>
<td>---</td>
</tr>
<tr>
<td>Flash Point, °C (°F) min</td>
<td>318 (605)</td>
<td>218 (425) min</td>
<td>---</td>
<td>232 (450) min</td>
</tr>
</tbody>
</table>

Tests on Residue from Thin Film Oven Test

<table>
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<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity, 60°C (140°F), Poise</td>
<td>1,880</td>
<td>---</td>
<td>4662</td>
<td>10,000 max</td>
</tr>
<tr>
<td>Viscosity, 135°C (275°F), cSt</td>
<td>439</td>
<td>---</td>
<td>579</td>
<td>---</td>
</tr>
<tr>
<td>Penetration, 25°C (77°F), 0.1 mm</td>
<td>71</td>
<td>---</td>
<td>45</td>
<td>---</td>
</tr>
<tr>
<td>Ductility, 25°C (77°F), 5 cm/min</td>
<td>120+</td>
<td>100 min</td>
<td>120+</td>
<td>20 min</td>
</tr>
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SUPERPAVE (SHRP) Binder Specifications

<table>
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<td>PG 58 - 22</td>
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</table>

---: Not applicable

MIX DESIGNS

Preconstruction work consisted of completing four mix designs: 1) 35-blow Marshall, 2) 50-blow Marshall, 3) 75-blow Marshall, and 4) the SHRP Level 1 (volumetric mix design). The first three were performed by the Minnesota Department of Transportation (Mn/DOT) Materials, Research and Engineering Laboratory in Maplewood, Minnesota. The Asphalt Institute in Lexington, Kentucky performed the SHRP mix design.
Mix designs were limited to determining the optimum binder content for mixtures prepared with the 120/150 pen asphalt cement. The same optimum asphalt content was used with the AC-20 so that the binder content for comparisons of the 120/150 and AC 20 test cells would have a consistent amount of asphalt. Mixing temperatures were adjusted to achieve an equivalent viscosity.

**Marshall Mix Designs (35, 50, and 75 Blow)**

**Sample Preparation**

The appropriate percentages of each of three aggregate stockpiles were combined and heated to 150°C (300°F) for at least 4 hours prior to mixing. The asphalt cement was heated to 135°C (275°F) for a maximum of 4 hours. A large mixer was used to prepare approximately 10 kg (22 lb) batches at each of five asphalt cement contents. Each batch was used to prepare five samples; three samples were compacted for mix design testing and the remainder was used for determining the theoretical maximum specific gravity. Samples were compacted immediately after mixing with a rotating base, bevel head Marshall hammer.

**Marshall Mix Designs**

Testing included determining the bulk and theoretical specific gravities, air voids, Marshall stabilities, flow, voids in mineral aggregate (VMA), and the percent of voids filled with asphalt (VFA). The results of the testing are shown in Table 3. The optimum asphalt content was selected as the percentage that would produce 4 percent air voids. Based on this criterion and the data in Table 2.3, the optimum binder contents were selected as 6.4, 6.1, and 5.9 percent by weight of total mix for the 35, 50, and 75 blow mix designs, respectively.
Table 3. Marshall Mix Design Results (120/150 Penetration Grade Asphalt Cement).

(Reported by Mn/DOT)

<table>
<thead>
<tr>
<th>Asphalt Content</th>
<th>Air Voids, %</th>
<th>VMA, %</th>
<th>VFA, %</th>
<th>Marshall Stability, kN (lb)</th>
<th>Marshall Flow, 0.25 mm (0.01 in)</th>
<th>Density kg/m³ (lb/ft³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35 Blow Mix Design</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>8.0</td>
<td>18.0</td>
<td>55.4</td>
<td>2,172 (966)</td>
<td>10</td>
<td>2,275 (142.0)</td>
</tr>
<tr>
<td>5.5</td>
<td>6.6</td>
<td>17.7</td>
<td>62.8</td>
<td>2,115 (941)</td>
<td>10</td>
<td>2,294 (143.2)</td>
</tr>
<tr>
<td>6.0</td>
<td>5.0</td>
<td>17.4</td>
<td>71.3</td>
<td>2,439 (1,085)</td>
<td>11</td>
<td>2,315 (144.5)</td>
</tr>
<tr>
<td>6.5</td>
<td>3.7</td>
<td>17.4</td>
<td>78.7</td>
<td>2,455 (1,092)</td>
<td>10</td>
<td>2,328 (145.3)</td>
</tr>
<tr>
<td>50 Blow Mix Design</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>7.1</td>
<td>17.2</td>
<td>58.7</td>
<td>2,272 (1,278)</td>
<td>11</td>
<td>2,297 (143.4)</td>
</tr>
<tr>
<td>5.5</td>
<td>6.2</td>
<td>17.2</td>
<td>64.0</td>
<td>2,621 (1,166)</td>
<td>10</td>
<td>2,307 (144.0)</td>
</tr>
<tr>
<td>6.0</td>
<td>4.3</td>
<td>16.8</td>
<td>74.4</td>
<td>2,779 (1,236)</td>
<td>9</td>
<td>2,331 (145.5)</td>
</tr>
<tr>
<td>6.5</td>
<td>3.0</td>
<td>16.8</td>
<td>82.2</td>
<td>2,734 (1,216)</td>
<td>9</td>
<td>2,344 (146.3)</td>
</tr>
<tr>
<td>75 Blow Mix Design</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>6.5</td>
<td>16.6</td>
<td>60.9</td>
<td>3,287 (1,462)</td>
<td>10</td>
<td>2,312 (144.3)</td>
</tr>
<tr>
<td>5.5</td>
<td>5.4</td>
<td>16.5</td>
<td>67.2</td>
<td>3,536 (1,573)</td>
<td>9</td>
<td>2,329 (145.4)</td>
</tr>
<tr>
<td>6.0</td>
<td>4.0</td>
<td>16.6</td>
<td>75.9</td>
<td>3,324 (1,480)</td>
<td>10</td>
<td>2,339 (146.0)</td>
</tr>
<tr>
<td>6.5</td>
<td>2.3</td>
<td>16.2</td>
<td>85.8</td>
<td>3,424 (1,523)</td>
<td>10</td>
<td>2,361 (147.4)</td>
</tr>
</tbody>
</table>

1: Percent by weight of mixture.

Gyratory Mix Design

Sample Preparation

Aggregates and asphalt cement were batched as described in the Asphalt Institute's Manual Series No. 2 on "Mix Design Methods" (TAI, 1988). Once mixed, the loose-mix was stored for 4 hours in an oven set at the desired compaction temperature which was approximately 135°C (275°F). A set of three samples for each of four percentages of asphalt contents was then compacted using a Rainhart gyratory compactor with a 1.25° angle of gyration, and a rotational speed of 30 rpm. Samples were cooled and extruded as in the Marshall mix design method.
SHRP Level 1 Mix Design

The SHRP Level 1 mix design uses a volumetric approach to select an optimum asphalt content for the predetermined aggregate gradation based on Marshall mix design. Once a gradation is selected, as was the case for the Mn/ROAD materials, a set of three samples is fabricated for the optimum asphalt content and ± 0.5 percent of optimum asphalt cement contents. The change in density during compaction was monitored at three levels of compaction (i.e., numbers of gyrations) during sample fabrication. The criteria for selecting the optimum asphalt content at a predetermined number of maximum gyrations was:

1. A maximum density less than 89 percent at the initial number of gyrations.
2. Four percent air voids at the design compactive effort.
3. A maximum density less than 98 percent at the maximum number of gyrations.

The gyratory mix design results, based on a design number of 100 gyrations (selected by the Asphalt Institute), for the Mn/ROAD aggregate gradation are shown in Table 4. Based on these results, the optimum asphalt content was selected as 5.6 percent.

The numbers of gyrations at which the density was monitored was dependent upon the desired compactive effort and was selected by the Asphalt Institute from (TAI, 1992). This selection was based upon the anticipated in-service average high air temperature and the estimated level of design traffic.

Table 4. Gyratory Mix Design Results.

<table>
<thead>
<tr>
<th>Asphalt Content1, %</th>
<th>Air Voids, %</th>
<th>VMA, %</th>
<th>VFA, %</th>
<th>Density with Numbers of Gyrations, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>4.7</td>
<td>6.4</td>
<td>15.7</td>
<td>59.0</td>
<td>88.8</td>
</tr>
<tr>
<td>5.2</td>
<td>5.1</td>
<td>15.5</td>
<td>67.0</td>
<td>89.9</td>
</tr>
<tr>
<td>5.7</td>
<td>3.8</td>
<td>15.5</td>
<td>76.0</td>
<td>91.1</td>
</tr>
<tr>
<td>6.2</td>
<td>2.8</td>
<td>15.7</td>
<td>82.0</td>
<td>92.1</td>
</tr>
</tbody>
</table>

1: Percent by total weight of mixture.
Comparison of Mix Design Results

Table 5 compares the optimum binder contents and the corresponding VMA and VFA for each of the four mix designs. As expected, both the asphalt content and the VMA decreased as the compactive effort increased. The VFA is approximately 78 percent for the 35 blow Marshall mix design. This decreased to approximately 74 to 75 percent for the remaining mix designs.

Table 5. Comparison of Mix Design Results.

<table>
<thead>
<tr>
<th>Mix Design Method</th>
<th>Optimum Asphalt Cement Content</th>
<th>VMA %</th>
<th>VFA %</th>
</tr>
</thead>
<tbody>
<tr>
<td>35 Blow Marshall</td>
<td>6.4</td>
<td>17.4</td>
<td>78.5</td>
</tr>
<tr>
<td>50 Blow Marshall</td>
<td>6.1</td>
<td>16.8</td>
<td>74.4</td>
</tr>
<tr>
<td>75 Blow Marshall</td>
<td>5.9</td>
<td>16.5</td>
<td>75.0</td>
</tr>
<tr>
<td>SHRP Gyratory Level 1</td>
<td>5.6</td>
<td>15.5</td>
<td>74.0</td>
</tr>
</tbody>
</table>

While the SHRP Level 1 mix design was used for selecting a gyratory-based optimum binder content, the SHRP gyratory Level 2, or preferably Level 3, mix design is recommended for the design of a high traffic level facility such as Mn/ROAD. Both of these design levels select the optimum asphalt cement content based not only on volumetric parameters but also an evaluation of mixture properties. These advanced levels of mix design were not completed for Mn/ROAD because construction preceded the final development of SHRP equipment and test methods. It is anticipated that this work will be completed at a later date.
TEST METHODS

Test methods selected for evaluation are shown in Table 6.

Table 6. Test Methods Selected for Evaluation.

<table>
<thead>
<tr>
<th>Category of Mixture Behavior</th>
<th>Selected Test Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness/Compliance</td>
<td>Axially loaded:</td>
</tr>
<tr>
<td></td>
<td>Dynamic loading (ASTM 3497)</td>
</tr>
<tr>
<td></td>
<td>Repeated loading</td>
</tr>
<tr>
<td></td>
<td>Static loading</td>
</tr>
<tr>
<td></td>
<td>Diametrically loaded:</td>
</tr>
<tr>
<td></td>
<td>Repeated loading (ASTM D4123)</td>
</tr>
<tr>
<td></td>
<td>Dynamic loading</td>
</tr>
<tr>
<td>Tensile Strength at Low Temperatures</td>
<td>Diametrically loaded:</td>
</tr>
<tr>
<td></td>
<td>Constant rate of vertical deformation (NCHRP AAMAS)</td>
</tr>
<tr>
<td></td>
<td>Constant vertical stress (SHRP)</td>
</tr>
</tbody>
</table>

Stiffness/Compliance

Temperature susceptibility refers to how material stiffness changes with temperature. In the case of asphalt concrete mixtures, temperature susceptibility is assessed by evaluating the change in the slope mixture stiffness versus temperature. A greater slope indicates more temperature susceptibility. While this appears to be a straight forward definition, there are several methods for measuring mixture stiffness.

Uniaxial vs. Diametral Compression

Stiffness measurements from the axial harmonic loading, sometimes referred to as cyclic or dynamic loading, of tall asphalt concrete cylinders (100 mm in diameter by 200 mm tall) is described in the American Society for Testing and Materials (ASTM) D3497 (ASTM, 1996). Since the mid-1970's, a repeated load (load pulse followed by rest period) diametral compression (i.e., indirect tension) test has more commonly been used to obtain estimates of mixture stiffness (ASTM D4123) (ASTM, 1996). This ASTM D4123 method has the advantages of using standard size specimens and less
material. It is also easier to instrument and test these samples. Figure 3 shows the typical test set-ups for each ASTM test method. Note that ASTM D4123 has an option for additional instrumentation which includes measured vertical deformations in the calculation of stiffness. The amount of information obtained from each test method depends upon the number of parameters measured. Calculations of material functions range from straightforward to complex, depending upon the number of parameters measured and the testing geometry. The quality of the data depends on the accuracy of measurements which is in turn influenced by sensor selection, placement, sample preparation and mixture volumetrics.

In order to fully describe material behavior, one must be able to construct Mohr’s circles for both stress and strain. For example, an axially loaded tall cylinder (Figure 4) requires inputs of of vertical stress, \(\sigma_1\), and horizontal stress (confining pressure), \(\sigma_3\). The required measured outputs are vertical strain, \(\varepsilon_1\), and horizontal strain, \(\varepsilon_3\).

Mathematically, these parameters can be expressed in terms of stress and strain tensors:

\[
[\sigma_{ij}] = [\sigma_{ii}] + [\tau_{ij}] \quad (1)
\]

\[
[\varepsilon_{ij}] = [\varepsilon_{ii}] + [\varepsilon_{ij}] \quad (2)
\]

where:

- \(\sigma_{ij}\) = total stress tensor
- \(\sigma_{ii}\) = volumetric stress tensor
- \(\sigma_{ij}\) = deviatoric stress tensor
- \(\varepsilon_{ij}\) = total strain tensor
- \(\varepsilon_{ii}\) = volumetric strain tensor
- \(\varepsilon_{ij}\) = deviatoric strain tensor

Since the test method described in ASTM D3479 only specifies vertical stress input and a vertical strain measurement, there is insufficient information to construct either of the Mohr’s circles. Therefore, this test can be considered to measure only Young’s modulus:

\[
E = \frac{\sigma_1}{\varepsilon_1} \quad (3)
\]
Figure 3. Test Configurations for Uniaxial (ASTM D3497) and Diametral Compression (ASTM D4123).
The first configuration shown in Figure 3 for diametrically loaded samples is also used for estimating resilient modulus (Young's modulus) per ASTM D4123. The second configuration includes a vertical deformation measurement which permits the use of the elastic-based equations shown in ASTM D4123 to estimate mixture stiffness:

\[ E_{RT} = \frac{P(\nuRT + 0.27)}{t \Delta H_T} \quad (4) \]

\[ \nuRT = \frac{3.59}{\Delta V_T} \Delta H_T - 0.27 \quad (5) \]

where:

- \( E_{RT} \) = total resilient modulus of elasticity
- \( \nu_{RT} \) = total resilient Poisson's ratio
- \( t \) = thickness of specimen
- \( \Delta H_T \) = total recoverable horizontal deformation (Figure 3)
- \( \Delta V_T \) = total recoverable vertical deformation (Figure 3)
When the first configuration (without vertical deformation measurements) is used, Poisson's ratio as defined in ASTM D4123 (equation 5) cannot be calculated. This value must be assumed in order to estimate the modulus (equation 4). Typical values assumed for Poisson's ratio of asphalt concrete are 0.2, 0.35, and 0.5 for test temperatures of 1°C (34°F) or colder, 25°C (77°F), and 40°C (104°F), respectively.

Repeated loading is defined as a short haversine load pulse applied to the sample followed by a rest period. Frequency refers to the total time between each load application; commonly used frequencies are 0.33, 0.5, and 1.0 Hz. For a 0.1 second load duration, this means that the rest period durations are 2.9, 1.9, and 0.9 seconds, respectively. Figures 5 and 6 show typical vertical load pulses and corresponding horizontal deformations, respectively, for this test. Figure 6 shows that the total deformation is time-dependent (viscous) which means that $E_{RT}$ and $v_{RT}$ will also be time-dependent.

A methodology rigorously developed using the elastic-viscoelastic correspondence principle, and Laplace and Fourier transforms (Wang et al., 1996) showed these elastic parameters (equations 4 and 5) were more appropriately expressed as:

$$E = \frac{P}{L \Delta U_{2R}} (0.27 + v) \quad (6)$$

$$v = 3.59 \frac{\Delta U_{2R}}{\Delta V_{2R}} - 0.27 \quad (7)$$

where:

- $P$ = load
- $L$ = length of cylinder

Both $\Delta U_{2R}$ and $\Delta V_{2R}$ are the geometrically dependent change in length of the horizontal and vertical diameter:

$$\Delta U_{2R} = \frac{P}{EL} (I_1 - \omega I_2); \quad \Delta V_{2R} = \frac{P}{EL} (I_4 - \omega I_3) \quad (8)$$

Values for $I_1$, $I_2$, $I_3$, and $I_4$ can be obtained from Table 1 in Appendix A.
Figure 5. Typical Loading Sequences for Repeated Loading of Asphalt Concrete.

Figure 6. Typical Displacement Response for Repeated Loading of Asphalt Concrete.
When harmonic (sinusoidal) loading is used instead of repeated loading, elastic theory can be used to obtain a viscoelastic solution in terms of frequency-dependent compliances. The elastic solution is subjected to an integral transformation in which both Young's modulus, $E$, and Poisson's ratio, $\nu$, are replaced by the appropriate transforms (in this case, Fourier integral transform) of viscoelastic compliances followed by the inverse integral transform. This leads to the following replacement rule:

\[
E - \frac{3}{2J_d^* (\omega) + J_v^* (\omega)} \tag{9}
\]

\[
u - \frac{J_d^* (\omega) - J_v^* (\omega)}{2J_d^* (\omega) + J_v^* (\omega)} \tag{10}
\]

where:

$J_d^*$ = deviatoric complex compliance

$J_v^*$ = volumetric complex compliance

$\omega$ = harmonic frequency

The full development of these equations are presented in Appendix B.

The data presented in Appendix B suggests that the volumetric complex compliance is constant, elastic, and small compared to the deviatoric complex compliance. For the case where the volumetric complex compliance is negligible, equations 9 and 10 reduce to:

\[
E - \frac{1.5}{J_d^*}; \quad \nu - 0.5 \tag{11}
\]

Since complex shear modulus is the inverse of the complex shear compliance, this suggests that the complex shear modulus determined from diametral specimens harmonically loaded will be approximately 66 percent of the elastic modulus.
The geometry-specific equations used for calculations in the analysis section are:

\[ J_{d1} = \left[ 0.745 \Delta U_0 2\pi(\omega) \cos \delta_u(\omega) + 1.635 \Delta V_{0.05R}(\omega) \cos \delta_v(\omega) \right] \frac{L}{P_0} \] (12)

\[ J_{d2} = - \left[ 0.745 \Delta U_0 2\pi(\omega) \sin \delta_u(\omega) + 1.635 \Delta V_{0.05R}(\omega) \sin \delta_v(\omega) \right] \frac{L}{P_0} \] (13)

where:
- \( J_{d1} \) and \( J_{d2} \) = vector components of the complex deviatoric compliance, \( J_d^* \)
- \( \delta_u \) = mean phase angle for horizontal measurements, radians
- \( \delta_v \) = mean phase angle for vertical measurements, radians
- \( L \) = sample thickness
- \( P_0 \) = amplitude of harmonic load

These definitions are shown graphically in Figure 7. Note the upward inclination of the displacement response (\( \Delta U_0 \)). This is due to the accumulation of incremental permanent deformations (i.e., creep). Because of this inclination, the phase angle measured for the loading portion (\( \delta_u^l \)) of the test will be larger than the phase angle measured for the unloading portion (\( \delta_u^u \)). The correct phase angle measurement to use in equations 12 and 13 is the average of these two measurements. This conclusion is derived in Appendix C.

The complex deviatoric compliance, \( J_d^* \), is:

\[ J_d^* = |(J_{d1}^2 + J_{d2}^2)^{1/2}| \] (14)

Since the complex deviatoric modulus, \( G_d^* \), is the inverse of the complex deviatoric compliance:

\[ G_d^* = \frac{1}{|J_d^*|} \] (15)

The complex modulus can be decomposed into in-phase and an out-of-phase components:
\[ G_{d1} = G_\delta \cos \delta_d, \quad G_{d2} = G_\delta \sin \delta_d \]

where:
\[ \delta_d = \arctan \left( \frac{J_{d2}}{J_{d1}} \right) \]

Figure 7. Definition of Variables (Harmonic Loading of Diametral Samples).

Uniaxial Testing at Warm Temperatures

Cylindrical samples of 100 mm diameter by 200 mm tall (4 by 8 in) were used for this testing. Sample preparation is described in detail in the University of Minnesota report “Investigation of Hot Mix Asphalt Mixtures at Mn/ROAD - Final Report” (Stroup-Gardiner and Newcomb, 1997). A rubber membrane (when confining pressure was used) was placed over each sample, and then the sample was conditioned overnight at the test temperature. A collar holding three LVDT's was placed over the center one-third of the sample, and the sample was placed in a standard triaxial chamber. The exterior plexiglass cylinder was then placed over the cell prior to mounting the entire fixture and sample in the load frame. The following pressures were used: none, and 200 kPa (30 psi).
Repeated Load Axial Creep: Repeated loads consisting of a short haversine load pulse followed by a rest period were applied for one hour. Both the load durations and frequencies corresponded with those used for resilient modulus testing (ASTM D4123). The compliance for each 1-hour test was calculated as:

\[ J(t) = \frac{\epsilon(t)}{\sigma_o} \]  

(17)

where:

- \( J(t) \) = Creep compliance at any time, \( t \), 1/kPa
- \( \epsilon(t) \) = strain over center 1/3 of sample at any time, \( t \)
- \( \sigma_o \) = applied constant stress (load/area), kPa

The creep modulus at a given time was taken as the inverse of \( J(t) \).

Static Axial Creep: Once the repeated load testing was completed, the same samples were immediately used for the static creep test. MTS Testar hardware and control software was used to apply a static preconditioning axial load which was the same as the desired test load for 5 minutes. The load was removed for 2 minutes, and the sample was allowed to recover. The static load was then reapplied for 1 hour; data was collected throughout this time period. At the end of 1 hour, the load was removed and the sample recovery was monitored for 20 minutes. Samples were tested at 25 and 40°C (77 and 104°F). Originally, testing was to be performed at 1°C (34°F) but was dropped in favor of adding the SHRP constant stress test for the evaluation of low temperature creep behavior. The same equipment used for dynamic modulus was used for this testing (Figure 1).

Data were used to determine the creep compliance and modulus at 30 minutes, and the elastic, plastic, and viscous components of the material response. The 30-minute time interval for the creep modulus and compliance (equation 17) was selected because most samples survived at least this long at the more extreme ranges of testing conditions (e.g. no confining pressure, warm temperatures). Figure 8 shows the typical presentation of creep compliance data. As indicated in this figure, a steady state creep compliance, \( J_0 \), is defined by extrapolating the slope to \( t = 0 \) (Macosko, 1994). The slope itself is the inverse of the viscosity at a low shear rate, \( \eta \). Or in other words, the time dependent creep compliance can be expressed as:
Tensile Strength at Low Temperatures

Thermal cracking occurs when the pavement's ability to dissipate stresses due to thermal contraction is exceeded as a result of either a significant one-time drop in temperatures or by thermal cycling. Over the last several decades, several mixture tests have been used to characterize the low temperature properties of asphalt mixtures. In the early 1980's the National Cooperative Highway Research Program (NCHRP) Asphalt-Aggregate Mixture Analysis System (AAMAS) used measurements of indirect tensile strength at various rates of vertical deformation to evaluate the low temperature behavior of compacted asphalt mixtures (Von Quintas, et al., 1990). SHRP researchers used two other methods for assessing low temperature properties: 1) thermal stress restrained
specimen test (TSRST) (Jung and Vinson, 1993), and 2) indirect tensile creep (Buttler and Roque, 1994).

Other research has shown binder properties to have the most influence on the low temperature behavior of mixtures (Jung and Vinson, 1994). Low temperature binder properties have been routinely evaluated by a number of countries by measuring the Fraass brittle point. Recent research has shown that the dynamic shear rheometer (DSR) can also be used to measure a DSR brittle point which was well correlated with both the Fraass brittle point and the SHRP bending beam rheometer (BBR) limiting stiffness temperature (Stroup-Gardiner, et al., 1996).

Mixture tests selected for evaluation in this research program were the indirect tensile strength, and the indirect tensile creep tests. Binder tests evaluated were the Fraass and the DSR brittle point and are presented for the purpose of correlation to mixture testing.

**Indirect Tensile Strength**

A compacted cylindrical sample [100 mm (4 in) diameter by 65 mm (2.5 in) tall] was loaded diametrically at a constant rate of vertical displacement, and both the resulting load and the full diameter horizontal displacement were measured (Von Quintas, et al., 1990). While the AAMAS research recommended a rate of vertical displacement of 1.25 mm/min (0.05 in/min), a range of rates [0.025, 0.25, and 2.5 mm/min (0.001, 0.01, and 0.1 in/min)] was ultimately selected so that the influence of displacement rates at various test temperatures on tensile strengths could be evaluated. A set of three replicates were tested at each temperature [-18°C (0°F), and 1°C (34°F)] and deformation rate.

The maximum tensile strength was calculated as:

\[
TS = \frac{2 \cdot P}{\pi \cdot t \cdot D}
\]  

(19)

where:

- \(TS\) = tensile strength, kPa (psi)
- \(P\) = load, kN (lb.)
- \(t\) = sample thickness, m (in)
D = sample diameter, m (in)
The horizontal deformation which corresponded to the maximum tensile strength was also measured.

**SUPERPAVE (SHRP) Indirect Tensile Creep Test**

This test used a diametrically loaded sample to determine the creep compliance over a range of times and temperatures. Results were used to construct a master creep compliance curve where the slope, m, is a mixture property used in the SUPERPAVE performance model.

The SHRP M-005 test method called for mounting both the horizontal and vertical sensors over the center 25 mm (1 in) of the sample (Harrigan, et al., 1994). However, the only sensors available to perform this work at the University of Minnesota were standard MTS extensometers. Therefore, the standard full sample diameter collar-mounted pair of extensometers were used to measure the horizontal displacements. The vertical extensometer was adapted to mount on small knife edges epoxied to the sample surface and measurements were taken over the center 25 mm (1 in). Figure 3 shows the final configuration used for this test. Equations 6 and 7 were modified to include a time factor:

\[
\frac{1}{E(t)} = \frac{P}{L \Delta u_{2R}(t)} (0.27 + u(t))
\]  

\[
u(t) = 3.59 \frac{\Delta u_{2R}(t)}{\Delta V_{2R}(t)} - 0.27
\]

A load level for each of the four test temperatures was selected so that about 100 to 500 micro strain in 1,000 seconds was achieved. The strain was then held constant and the stress was allowed to relax. Typical loads used were: 200 to 275 kPa (30 to 40 psi) at -15°C (5°F), 140 to 200 kPa (20 to 30 psi) at -10°C (14°F), 70 to 140 kPa (10 to 20 psi) at -5°C (23°F), 35 to 70 kPa (5 to 10 psi) at 5°C (41°F), and 35 kPa (5 psi) at 15°C (59°F).
The Fraass brittle point test has been standardized by the Institute of Petroleum (IP-80/53). In this test, the temperature at which a thin coating of binder on a spring steel plate cracks when repeatedly flexed is reported. It was found that the Fraass brittle point corresponded to a stiffness modulus of between 0.8 to $2 \times 10^8$ Pa which was close to the theoretical maximum binder stiffness of $2.7 \times 10^9$ Pa (Thenoux, et al., 1988). Two concerns noted in the literature were: 1) the test was actually a fatigue test because of the repeated flexing of the same sample, and 2) that test results could not be obtained below about -35°C due to testing limitations.

Research indicated the testing precision could be improved with modifications to the sample preparation and temperature measurement system (Thenoux, et al., 1988). A temperature of about 90°C (194°F) was suggested for coating the plate and a maximum of no more than 3 minutes for the complete preparation of a set of three plates. This reduced the age hardening of the binder and produced more consistent test results. A thermocouple in direct contact with the back of the sample plate during testing was suggested in place of the conventional mercury thermometer behind, but not in contact with, the plate. When both measurements were used simultaneously, a temperature difference of between 5 and 6°C was observed with the thermocouple reading always recording the lower temperature. Using these improvements, the repeatability for two tests decreased from ± 2 to ±1°C.

Based on this information, testing for this research project was conducted according to the Institute of Petroleum method IP 80/53 with the following exceptions. A calibrated hot plate was used to prepare one sample at a time at a temperature of 100°C (212°F). A slightly higher temperature than recommended in the literature was used in order to be consistent with the temperature needed to prepare samples for a separate polymer-modified asphalt study. One sample was prepared at a time and the sample plates were on the hot plate no longer than one minute. A thermocouple in contact with the back of the sample plate was used to monitor the temperature in the chamber in place of a mercury thermometer.
A Rheometrics RAA® dynamic shear rheometer, meeting the equipment requirements outlined in the American Association of State Highway and Transportation Officials (AASHTO) provisional test method, was used to conduct frequency sweeps from 0.1 to 100 rad/sec every 10°C between -60 and 30°C. The 8 mm plates with a gap of 2 mm were used for temperatures from 0 to 30°C. Torsion bars 2.5 mm thick, 12.5 mm wide and 40 mm long were used for test temperatures from -60 to 0°C. Strains for all tests were selected so that the response was within the linear viscoelastic range. While only the results at 10 rad/sec were used to estimate the brittle point, the full frequency sweeps were used to construct master curve at a reference temperature of 30°C to assure that there were no testing and data analysis problems when changing between 8 mm diameter plates and torsion bar configurations.

The brittle point, \( T_b \), was defined as the end of elastic behavior and the onset of viscoelastic behavior. This corresponds to the temperature above which the phase angle, \( \delta \), is no longer 0°C. However, it has been shown that the phase angle does not always decrease to 0° but either levels off or only decreases very slowly below about 10°C (Stroup-Gardiner, et al., 1996). This agrees with previous results that identified creep behavior in asphalts below \( T_b \) (Anderson, et al., 1994). Therefore \( T_b \) from DSR phase angle measurements was defined as the temperature where the slope of a line drawn through the data at \( \delta \) equals 45° and the 0°C data crosses the 10° phase angle point (Figure 9). There was a good correlation between the DSR \( T_b \) and the bending beam rheometer (BBR) \( (a=8.4649, b=0.9405, r^2 =0.81) \) and the Fraass brittle point \( (a= 2.6911, b = 0.8311, r^2 = 0.85) \) when testing unmodified asphalts (Stroup-Gardiner, et al., 1996).
Figure 9. Definition of Brittle Point from DSR Testing (Stroup-Gardiner, et al., 1996).

ANALYSIS

Stiffness/Compliance

Uniaxial (ASTM D3497)

Testing was conducted at 1, 10, 25, and 40°C (34, 50, 77, and 104°F) using two different frequencies (0.1 and 1.0 Hz) in either an unconfined or confined [207 kPa (30 psi)] state. Test results for an average of three samples tested are shown in Tables 7 and 8.

Figure 10 provides an example of typical test results. Increasing the loading frequency from 0.1 to 1.0 Hz uniformly increased the modulus. Little difference in modulus due to confining pressure was seen for testing at moderate to cold test temperatures [25°C (77°F) and colder]. There was a noticeable decrease in modulus when confining pressure was eliminated at the warmer 40°C
(104°F) test temperature. The affect of increased asphalt viscosity was only noticeable at the warm 40° (104°F) test temperature (Figure 11); the stiffness of the mixture increased with an increase in binder stiffness.

The phase angle response was not apparently affected by changes in confining pressure. It was, however, influenced by the loading frequency. Figure 12 shows that the phase angle appears to decrease with increasing frequency but it is difficult to draw to firm conclusions due to the large testing variability associated with this measurement (Table 9).

*Diametral (ASTM D4123)*

Testing was conducted at -18, 1, 10, 25, and 40°C (0, 34, 50, 77, and 104°F) using three different frequencies (0.33, 0.5, and 1.0 Hz), and a load duration of 0.1 seconds. Additonal testing was conducted with a 1.0 second load duration at a total of 5 frequencies: 0.033, 0.05, 0.1, 0.33, and 0.5 Hz. The first three frequencies were selected so that the load to rest ratio for the 1.0 second load duration would be the same as those for the 0.1 second load to rest ratios. The last two frequencies were selected so that the influence of the load duration on modulus values could be assessed.

Changes in the rest period while holding the load duration constant apparently had no affect on the moduli. Equations 4 and 5 with assumed Poisson's ratios were used to calculate these data. Similar moduli were obtained using either the 0.1 or 1 second load durations for test temperatures at or below 10°C (50°F) (Figures 11 and 12). Above this temperature, increasing the load duration resulted in a decrease in moduli. Increasing both the rest period and the load duration resulted in a slightly greater difference in moduli (Figures 13 and 14).
Table 7. Axially Loaded Complex Modulus and Phase Shift Data Collected at 0.1 Hz

<table>
<thead>
<tr>
<th>Mix Design Mixtures</th>
<th>120/150 Pen</th>
<th>AC 20</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unconfined</td>
<td>207 kPa (30 psi)</td>
</tr>
<tr>
<td></td>
<td>Complex Modulus, MPa (ksi)</td>
<td>Mean Phase Angle, °</td>
</tr>
<tr>
<td></td>
<td>Unconfined</td>
<td>1°C (34°F)</td>
</tr>
<tr>
<td>35 Blow</td>
<td>3991 (578)</td>
<td>29.7</td>
</tr>
<tr>
<td>50 Blow</td>
<td>5,379 (780)</td>
<td>26.1</td>
</tr>
<tr>
<td>75 Blow</td>
<td>4,697 (681)</td>
<td>25.8</td>
</tr>
<tr>
<td>Gyratory</td>
<td>Not Tested Due to Limited Materials</td>
<td></td>
</tr>
<tr>
<td>10°C (50°F)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35 Blow</td>
<td>1,696 (246)</td>
<td>36.6</td>
</tr>
<tr>
<td>50 Blow</td>
<td>3,070 (445)</td>
<td>28.7</td>
</tr>
<tr>
<td>75 Blow</td>
<td>2,214 (321)</td>
<td>39.2</td>
</tr>
<tr>
<td>Gyratory</td>
<td>Not Tested Due to Limited Materials</td>
<td></td>
</tr>
<tr>
<td>25°C (77°F)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35 Blow</td>
<td>869 (126)</td>
<td>44.5</td>
</tr>
<tr>
<td>50 Blow</td>
<td>981 (142)</td>
<td>37.3</td>
</tr>
<tr>
<td>75 Blow</td>
<td>817 (119)</td>
<td>43.1</td>
</tr>
<tr>
<td>Gyratory</td>
<td>Not Tested Due to Limited Materials</td>
<td></td>
</tr>
<tr>
<td>40°C (104°F)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35 Blow</td>
<td>211 (31)</td>
<td>33.2</td>
</tr>
<tr>
<td>50 Blow</td>
<td>259 (38)</td>
<td>35.2</td>
</tr>
<tr>
<td>75 Blow</td>
<td>210 (31)</td>
<td>33.1</td>
</tr>
<tr>
<td>Gyratory</td>
<td>Not Tested Due to Limited Materials</td>
<td></td>
</tr>
</tbody>
</table>

29
Table 8. Axially Loaded Complex Modulus and Phase Shift Data Collected at 1.0 Hz

<table>
<thead>
<tr>
<th>Mix Design Mixture</th>
<th>120/150 Pen</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>AC 20</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>207 kPa (30 psi)</td>
<td>Unconfined</td>
<td>Complex Modulus, MPa (ksi)</td>
<td>Mean Phase Angle, °</td>
<td>Complex Modulus, MPa (ksi)</td>
<td>Mean Phase Angle, °</td>
<td>Unconfined</td>
<td>Complex Modulus, MPa (ksi)</td>
<td>Mean Phase Angle, °</td>
</tr>
<tr>
<td>1°C (34°F)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35 Blow</td>
<td></td>
<td>6,540 (948)</td>
<td>7.1</td>
<td>6,546 (949)</td>
<td>3.5</td>
<td>10,692 (1,550)</td>
<td>27.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 Blow</td>
<td></td>
<td>7,798 (1,130)</td>
<td>16.3</td>
<td>8,811 (1,278)</td>
<td>10.9</td>
<td>10,098 (1,464)</td>
<td>25.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75 Blow</td>
<td></td>
<td>7,757 (1,124)</td>
<td>12.3</td>
<td>7,053 (1,023)</td>
<td>3.7</td>
<td>10,245 (1,485)</td>
<td>31.3</td>
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</tr>
<tr>
<td>Gyratory*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10°C (50°F)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35 Blow</td>
<td></td>
<td>3,667 (532)</td>
<td>21.6</td>
<td>3,734 (541)</td>
<td>26.2</td>
<td>5,694 (825)</td>
<td>25.1</td>
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</tr>
<tr>
<td>50 Blow</td>
<td></td>
<td>4,752 (689)</td>
<td>17.7</td>
<td>5,581 (809)</td>
<td>18.4</td>
<td>6,542 (949)</td>
<td>35.8</td>
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<tr>
<td>75 Blow</td>
<td></td>
<td>4,725 (685)</td>
<td>28.9</td>
<td>4,627 (671)</td>
<td>22.1</td>
<td>5,550 (805)</td>
<td>34.7</td>
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<tr>
<td>Gyratory*</td>
<td></td>
<td></td>
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<tr>
<td>25°C (77°F)</td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>35 Blow</td>
<td></td>
<td>2,075 (301)</td>
<td>36.0</td>
<td>2,176 (316)</td>
<td>42.7</td>
<td>2,079 (301)</td>
<td>44.7</td>
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</tr>
<tr>
<td>50 Blow</td>
<td></td>
<td>2,311 (335)</td>
<td>33.9</td>
<td>2,634 (382)</td>
<td>34.2</td>
<td>2,235 (324)</td>
<td>36.2</td>
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</tr>
<tr>
<td>75 Blow</td>
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<td>2,043 (296)</td>
<td>40.0</td>
<td>2,388 (346)</td>
<td>38.6</td>
<td>2,576 (373)</td>
<td>39.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gyratory*</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>40°C (104°F)</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35 Blow</td>
<td></td>
<td>435 (63)</td>
<td>36.7</td>
<td>571 (83)</td>
<td>29.6</td>
<td>677 (98)</td>
<td>47.1</td>
<td></td>
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</tr>
<tr>
<td>50 Blow</td>
<td></td>
<td>496 (72)</td>
<td>38.7</td>
<td>730 (106)</td>
<td>33.4</td>
<td>807 (117)</td>
<td>46.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75 Blow</td>
<td></td>
<td>471 (68)</td>
<td>35.7</td>
<td>700 (102)</td>
<td>27.9</td>
<td>792 (115)</td>
<td>50.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gyratory*</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</table>
Table 9. Precision for Phase Angle Measurements (Axial Loading) (120/150 Pen Asphalt Mix Design Mixtures).

| Mixture | Confining Press., psi | Phase Angle Statistics, 0.1 Hz | | Phase Angle Statistics, 1 Hz | | |
|---------|-----------------------|--------------------------------|-------------|-----------------------------|-------------|
|         |                       | Mean Phase Angle Statistics | | Mean Phase Angle Statistics | | |
|         |                       | 0.1 Hz Set                  | | 1 Hz Set                    | | |
|         |                       | Dev., "                   | | Dev., "                   | | |
|         |                       | CV, %                     | | CV, %                     | | |
|         |                       | Last 5 Cycles              | | Last 5 Cycles              | | |
|         |                       | Stand. Dev., "             | | Stand. Dev., "             | | |
|         |                       | CV, %                     | | CV, %                     | | |
| 0       | 35                    | 33.5                       | | 6.26                       | | 3.78                     | | 6.27                       | | 5.06                     | | 14.1                     | |
| 0       | 30                    | 31.9                       | | 6.23                       | | 5.56                     | | 5.53                       | | 99.5                     | | 4.88                     | | 13.2                     | |
| 0       | 75                    | 26.1                       | | 6.44                       | | 13.9                     | | 6.67                       | | 48.0                     | | 6.90                     | | 49.6                     | |
| 0       | 30                    | 29.4                       | | 6.37                       | | 4.69                     | | 4.79                       | | 102.0                    | | **                       | | **                       | |
| 38.8    | 35                    | 43.3                       | | 9.30                       | | 27.3                     | | 6.74                       | | 24.7                     | | 7.30                     | | 26.7                     | |
| 37.4    | 30                    | 43.3                       | | 9.30                       | | 27.3                     | | 6.74                       | | 24.7                     | | 7.30                     | | 26.7                     | |
| 4.98    | 75                    | 43.3                       | | 9.30                       | | 27.3                     | | 6.74                       | | 24.7                     | | 7.30                     | | 26.7                     | |
| 5.62    | 30                    | 43.3                       | | 9.30                       | | 27.3                     | | 6.74                       | | 24.7                     | | 7.30                     | | 26.7                     | |
| 12.8    | 35                    | 46.4                       | | 7.02                       | | 37.8                     | | 16.2                       | | 42.8                     | | 16.83                    | | 44.5                     | |
| 15.0    | 30                    | 46.4                       | | 7.02                       | | 37.8                     | | 16.2                       | | 42.8                     | | 16.83                    | | 44.5                     | |
| 14.0    | 75                    | 46.4                       | | 7.02                       | | 37.8                     | | 16.2                       | | 42.8                     | | 16.83                    | | 44.5                     | |
| 14.6    | 30                    | 46.4                       | | 7.02                       | | 37.8                     | | 16.2                       | | 42.8                     | | 16.83                    | | 44.5                     | |
| 20.4    | 35                    | 47.5                       | | 3.92                       | | 47.6                     | | 8.61                       | | 18.1                     | | 12.88                    | | 27.1                     | |
| 24.8    | 30                    | 47.5                       | | 3.92                       | | 47.6                     | | 8.61                       | | 18.1                     | | 12.88                    | | 27.1                     | |
| 16.5    | 75                    | 47.5                       | | 3.92                       | | 47.6                     | | 8.61                       | | 18.1                     | | 12.88                    | | 27.1                     | |
| 23.1    | 30                    | 47.5                       | | 3.92                       | | 47.6                     | | 8.61                       | | 18.1                     | | 12.88                    | | 27.1                     | |
| 37.8    | 35                    | 41.3                       | | 4.09                       | | 41.3                     | | 9.72                       | | 23.5                     | | 17.05                    | | 27.1                     | |
| 44.0    | 30                    | 41.3                       | | 4.09                       | | 41.3                     | | 9.72                       | | 23.5                     | | 17.05                    | | 27.1                     | |
| 42.8    | 75                    | 41.3                       | | 4.09                       | | 41.3                     | | 9.72                       | | 23.5                     | | 17.05                    | | 27.1                     | |
| 29.6    | 30                    | 41.3                       | | 4.09                       | | 41.3                     | | 9.72                       | | 23.5                     | | 17.05                    | | 27.1                     | |
| 16.83   | 35                    | 47.5                       | | 3.92                       | | 47.6                     | | 8.61                       | | 18.1                     | | 12.88                    | | 27.1                     | |
| 16.05   | 30                    | 47.5                       | | 3.92                       | | 47.6                     | | 8.61                       | | 18.1                     | | 12.88                    | | 27.1                     | |
| 36.5    | 75                    | 47.5                       | | 3.92                       | | 47.6                     | | 8.61                       | | 18.1                     | | 12.88                    | | 27.1                     | |
| 27.1    | 30                    | 47.5                       | | 3.92                       | | 47.6                     | | 8.61                       | | 18.1                     | | 12.88                    | | 27.1                     | |
| 41.3    | 35                    | 47.5                       | | 3.92                       | | 47.6                     | | 8.61                       | | 18.1                     | | 12.88                    | | 27.1                     | |
| 27.1    | 30                    | 47.5                       | | 3.92                       | | 47.6                     | | 8.61                       | | 18.1                     | | 12.88                    | | 27.1                     | |
| 35.0    | 50                    | 25.63                      | | 9.2                        | | 35.7                     | | 7.81                       | | 21.9                     | | 11.52                    | | 10.1                     | |
| 29.0    | 10                   | 25.63                      | | 9.2                        | | 35.7                     | | 7.81                       | | 21.9                     | | 11.52                    | | 10.1                     | |
| 22.3    | 30                    | 25.63                      | | 9.2                        | | 35.7                     | | 7.81                       | | 21.9                     | | 11.52                    | | 10.1                     | |
Figure 10. Influence of Loading Frequency and Confining Pressure for 120/150 Pen Mixtures (Axial Loading).

Figure 11. Influence of Loading Frequency and Confining Pressure for AC 20 Mixtures (Axial Loading).
Figure 12. Influence of Loading Frequency and Confining Pressure on Phase Angle for 120/150 Pen Mixtures (Axial Loading)

Figure 13. Influence of Load Duration on Resilient Modulus (120/150 Pen Mixtures).
Resilient Modulus, MPa

Figure 14. Influence of Load Duration on Resilient Modulus (AC 20 Mixtures).

Resilient Modulus, MPa

Figure 15. Influence of Changing Both Load Duration and Rest Period on Resilient Modulus (120/150 Pen Asphalt).

34
Comparison of Axial and Diametral Stiffness Measurements

Direct comparisons of these two test methods cannot be made as ASTM D3497 measures a Young’s modulus using harmonic loading, and ASTM D4123 uses a repeated load/rest sequence to estimate Young’s modulus. For purposes of discussion, typical results for the faster dynamic frequency (1 Hz) and the 1-second load duration with the shortest rest period (0.5 Hz) are compared in Figures 15 and 16. In the majority of the cases, the axially loaded samples showed consistently higher moduli. These results suggest dynamic testing of axially loaded samples produces moduli that are slightly, but uniformly, higher than those from repeated load diametral testing (i.e., resilient modulus \( M_r \)).

The most common loading duration for ASTM D4123 is 0.1 second. Typical data for this load duration is compared to the 1 Hz dynamic loading of the axial sample data (Figures 17 and 18). For temperatures below about 25°C (77°F), stiffness as determined using ASTM D4123 are consistently higher than those determined with dynamic testing of axially loaded samples. Because
there is no "correct" value, no conclusions can be drawn as to which method provides the most accurate measurement of stiffness.

However, the conclusion can be drawn that values of stiffness measurements are dependent upon the type of test method used and test method variables selected. Each test method produces distinctly different states of stress within the sample. Also, the orientation of the sample is different for each method. Any partial orientation production during sample preparation could result in compacted samples with anisotropic behavior. That is, a compacted sample may have axially determined material properties that are substantially different than laterally measured material properties.

Figure 17. Comparison of Resilient Modulus (Diametral Loading, 1 second load duration, 0.5 Hz) and Complex Modulus (Axial Loading, 1 Hz) for 120/150 Pen Mixtures.
Figure 18. Comparison of Resilient Modulus (Diametral Loading, 1 second load duration, 0.5 Hz) and Complex Modulus (Axial Loading, 1 Hz) for AC 20 Mixtures.

Figure 19. Comparison of Resilient Modulus (Diametral Loading, 0.1 second load duration, 0.33 Hz) and Complex Modulus (Axial Loading, 1 Hz) for 120/150 Pen Mixtures.
Diametrally Loaded Samples - Complex Deviatoric Modulus

Diametrally loaded samples, instrumented to measure both vertical and horizontal displacements, were used to determine the complex deviatoric modulus, \( G'' \), as calculated using equation 15. The results are shown in Tables 10 and 11 for loading frequencies of 0.1 and 1 Hz, respectively.

As was seen with the harmonically loaded (axial) samples (Figures 12 and 13) and the repeated load (diametral) samples (Figures 12 through 13), a faster harmonic loading frequency (diametral) resulted in a greater stiffness (Figures 21 and 22).

Mixtures exhibited a moderate increase in elastic behavior when the loading frequency was increased from 0.1 to 1 Hz. That is, there is a smaller phase angle for mixtures loaded at 1 Hz than at 0.1 Hz (Figure 23). Figure 23 also suggests that the softer asphalt (120/150 Pen) produces a slightly more viscous response when compared to the stiffer AC 20 asphalt. However, the large standard deviations associated (Tables 10 and 11) with measurements of the phase angle make it impossible to draw valid conclusions.
As noted previously, analysis of axial testing produces estimates of Young’s modulus, $E$, while the diametral testing is used to estimate the deviatoric modulus, $G_d$. Based on elastic theory, $G$ should be between about one-third to one-half of the value of $E$ for Poisson’s ratio between the limits of 0.5 and 0. Figures 24 and 25 compare the results for harmonically loaded axial and diametral samples. In Figure 25, both results are similar. However, Figure 24 which represents typical results for most of the mixtures tested, shows that Young’s modulus, $E$, was substantially lower than the deviatoric modulus, $G_d$. The theoretically expected relationships were not confirmed by the experimental results which implies that the two testing configurations do not produce interchangeable material property measurements. Again, this may reflect both the differences in the state of stress and anisotropic behavior.

This difference could be due to both experimental and mixture variables. It is possible that the sensor systems for measuring deformations and loads need to be improved so that more reliable (less variable) results are obtained. Also, the vertical sensors for the diametral testing were mounted over the center 25 mm (1 in.) so it is possible that this measurement did not reflect a true representative volume of the whole mixture because of the aggregate size and distribution within the limited sensor range. It is also reasonable to assume that compaction of the samples results in specific particle orientations which could lead to anisotropic behavior of the mixtures. Harmonic loading of axial samples loads the sample along the same axis as the compactive effort while diametral testing loads the sample perpendicular to the compactive effort. Further research is needed to identify the specific reasons for the non-interchangeable stiffnesses from these two tests.
Table 10. Diametral Complex Modulus and Phase Shift Data (0.1 Hz).

<table>
<thead>
<tr>
<th>Mix Design Mixtures</th>
<th>120/150 Pen</th>
<th>AC 20</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Complex Modulus, MPa (ksi)</td>
<td>Phase Angle, °</td>
</tr>
<tr>
<td></td>
<td>-18°C (0°F)</td>
<td></td>
</tr>
<tr>
<td>35 Blow</td>
<td>18,023 ± 6,646 (2,613 ± 964)</td>
<td>15.38 ± 9.4</td>
</tr>
<tr>
<td>50 Blow</td>
<td>9,188 (1,322)</td>
<td>15.71 ± 7.7</td>
</tr>
<tr>
<td>75 Blow</td>
<td>25,472 ± 17,499 (3,693 ± 2,537)</td>
<td>33.57 ± 42.2</td>
</tr>
<tr>
<td>Gyratory</td>
<td>28,390 (4,117)</td>
<td>3.39 ± 1.3</td>
</tr>
<tr>
<td></td>
<td>25°C (77°F)</td>
<td></td>
</tr>
<tr>
<td>35 Blow</td>
<td>1,163 ± 444 (169 ± 64)</td>
<td>36.55 ± 3.1</td>
</tr>
<tr>
<td>50 Blow</td>
<td>1,036 ± 110 (150 ± 16)</td>
<td>37.30 ± 5.4</td>
</tr>
<tr>
<td>Gyratory</td>
<td>1,211 ± 339 (176 ± 49)</td>
<td>34.44 ± 4.3</td>
</tr>
<tr>
<td></td>
<td>40°C (104°F)</td>
<td></td>
</tr>
</tbody>
</table>

Disk Damaged Data Lost
Table 11. Diametral Complex Modulus and Phase Shift Data (1.0 Hz).

<table>
<thead>
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<th>Mix Design Mixtures</th>
<th>120/150 Pen</th>
<th>AC 20</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Complex Modulus, MPa (ksi)</td>
<td>Phase Angle, °</td>
</tr>
<tr>
<td></td>
<td>-18°C (0°F)</td>
<td></td>
</tr>
<tr>
<td>35 Blow</td>
<td>21,752 ± 5,897 (3,154 ± 855)</td>
<td>6.67 ± 3.0</td>
</tr>
<tr>
<td>50 Blow</td>
<td>15,457 ± 4,904 (2,241 ± 711)</td>
<td>3.75 ± 2.2</td>
</tr>
<tr>
<td>75 Blow</td>
<td>27,613 ± 28,535 (4,004 ± 4,138)</td>
<td>20.67 ± 30.4</td>
</tr>
<tr>
<td>Gyratory</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>1°C (34°F)</td>
<td></td>
</tr>
<tr>
<td>35 Blow</td>
<td>8,090 ± 1,529 (1,173 ± 222)</td>
<td>17.46 ± 3.3</td>
</tr>
<tr>
<td>50 Blow</td>
<td>7,929 ± 1,451 (1,130 ± 210)</td>
<td>15.13 ± 0.8</td>
</tr>
<tr>
<td>75 Blow</td>
<td>10,140 ± 2,257 (1,470 ± 371)</td>
<td>14.99 ± 1.0</td>
</tr>
<tr>
<td>Gyratory</td>
<td>12,351 ± 5,383 (1,791 ± 781)</td>
<td>14.05 ± 2.4</td>
</tr>
<tr>
<td></td>
<td>25°C (77°F)</td>
<td></td>
</tr>
<tr>
<td>35 Blow</td>
<td>2,696 ± 1,051 (391 ± 152)</td>
<td>34.43 ± 2.8</td>
</tr>
<tr>
<td>50 Blow</td>
<td>2,359 ± 383 (342 ± 55)</td>
<td>35.94 ± 4.0</td>
</tr>
<tr>
<td>75 Blow</td>
<td>2,381 ± 324 (345 ± 47)</td>
<td>34.41 ± 1.5</td>
</tr>
<tr>
<td>Gyratory</td>
<td>2,530 ± 735 (367 ± 107)</td>
<td>30.05 ± 3.4</td>
</tr>
<tr>
<td></td>
<td>40°C (104°F)</td>
<td></td>
</tr>
<tr>
<td>35 Blow</td>
<td>Testing Difficulties</td>
<td></td>
</tr>
<tr>
<td>50 Blow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75 Blow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gyratory</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

41
Figure 21. Influence of Loading Frequency on Complex Deviatoric Modulus for 120/150 Pen Mixtures.

Figure 22. Influence of Loading Frequency on Complex Deviatoric Modulus for AC 20 Mixtures.
Figure 23. Influence of Loading Frequency on Phase Angle Measurements.

Figure 24. Comparison of Harmonic Loading of Diametral and Axial Samples (120/150 Pen Mixtures).
Axially Loaded Compliance and Creep Modulus

Both the creep modulus and compliance for repeated load creep tests are shown in Tables 12 and 13 and represent the average of three tests unless otherwise noted. The average static creep test results are shown in Tables 14 and 15. Since both repeated load creep tests were designed to apply a total load duration of only 2, 3 and 6 minutes, all samples were theoretically subjected to the same total load durations, regardless of individual load pulse durations. The majority of the data support this assumption as there was little statistical difference between either static or repeated load creep modulus and compliance (Tables 14 and 15).

When testing within the linear viscoelastic range, the data from the repeated load and static creep tests can be combined to generate one creep compliance curve for the material. A set of typical results are shown in Figures 26 and 27. When testing at the cooler 25°C (77°F), the higher asphalt
content (35 blow mix design) 120/150 pen mixtures exhibited a lower mix viscosity. That is, the slope, \(1/\eta_o\), was greater for this mix than for the remaining mixtures (Figure 29). The mix viscosity was similar for all of the AC 20 mixtures (Figure 30) at this test temperature.

When the test temperature was increased to \(40^\circ C\) \((104^\circ F)\), the higher asphalt content 120/150 pen mixtures (35 blow mix design materials) failed before the end of the testing sequence (Figure 31). The lowest asphalt content 120/150 pen mixtures had the greatest steady state compliance. This may reflect the large testing variability at this temperature or possibly suggest that an optimum asphalt content is needed to achieve the lowest steady state compliance for a given combination of asphalt grade and aggregate properties (e.g., surface texture, porosity, gradation, etc.). The results for the same test temperature for the AC 20 mixtures suggest that the differences between the various asphalt content mixtures may more likely be due to testing variability (Figure 32, Table 18).

![Figure 26. Creep Compliance (25\(^\circ\) (77\(^\circ\)F), 120/150 Pen Mixtures).](image-url)
Table 12. Repeated Load (0.1 Second) Creep Test Results at 25°C After 1 Hr. (120/150 Pen Asphalt)

<table>
<thead>
<tr>
<th>Test Temp. °C (°F)</th>
<th>Confining Pressure kPa (psi)</th>
<th>Frequency Between Loads, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.33 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Creep Modulus MPa (ksi)</td>
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<tr>
<td></td>
<td></td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td>207 (30)</td>
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<tr>
<td></td>
<td></td>
<td>50 Blow Marshall Mixtures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>207 (30)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>75 Blow Marshall Mixtures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>207 (30)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gyratory Mix Design¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td>207 (30)</td>
</tr>
</tbody>
</table>

1: Used Modified Marshall compactor to fabricate samples. Numbers of blows based on obtaining 4% voids.
Table 12 (Continued). Repeated Load (0.1 Second) Creep Test Results at 40°C After 1 Hr. (120/150 Pen Asphalt)

<table>
<thead>
<tr>
<th>Test Temp. °C (°F)</th>
<th>Confining Pressure kPa (psi)</th>
<th>Frequency Between Loads, Hz</th>
<th>0.33 Hz</th>
<th>0.5 Hz</th>
<th>1.0 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Creep Modulus MPa (ksi)</td>
<td>Creep Compliance MPa (ksi⁻¹)</td>
<td>Creep Modulus MPa (ksi)</td>
<td>Creep Compliance MPa (ksi⁻¹)</td>
</tr>
<tr>
<td>40 (104)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35 Blow Marshall Mixtures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>39 ± 11 (6 ± 2)</td>
<td>0.025 (0.18)</td>
<td>23 ± 6 (3 ± 0.8)</td>
<td>0.044 (0.30)</td>
<td>12 ± 3 (2 ± 0.4)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>42 ± 12 (6 ± 2)</td>
<td>0.023 (0.16)</td>
<td>32 ± 12 (5 ± 2)</td>
<td>0.031 (0.21)</td>
<td>23 ± 8 (3 ± 1)</td>
</tr>
<tr>
<td>50 Blow Marshall Mixtures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>50 ± 10 (7 ± 2)</td>
<td>0.020 (0.14)</td>
<td>40 ± 8 (6 ± 1)</td>
<td>0.024 (0.17)</td>
<td>35 ± 5 (5 ± 0.8)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>87 ± 39 (13 ± 6)</td>
<td>0.011 (0.08)</td>
<td>65 ± 33 (9 ± 5)</td>
<td>0.015 (0.11)</td>
<td>58 ± 36 (9 ± 5)</td>
</tr>
<tr>
<td>75 Blow Marshall Mixtures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>58 ± 14 (8 ± 2)</td>
<td>0.017 (0.12)</td>
<td>47 ± 11 (7 ± 2)</td>
<td>0.021 (0.15)</td>
<td>44 ± 11 (6 ± 2)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>55 ± 23 (8 ± 3)</td>
<td>0.018 (0.13)</td>
<td>40 ± 12 (6 ± 2)</td>
<td>0.025 (0.17)</td>
<td>34 ± 10 (5 ± 1)</td>
</tr>
<tr>
<td>Gyratory Mix Design</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>23 ± 3 (3 ± 0.5)</td>
<td>0.043 (0.30)</td>
<td>18 ± 2 (3 ± 0.3)</td>
<td>0.055 (0.38)</td>
<td>17 ± 3 (2 ± 0.4)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>86 ± 46 (13 ± 7)</td>
<td>0.012 (0.08)</td>
<td>68 ± 32 (10 ± 5)</td>
<td>0.015 (0.10)</td>
<td>57 ± 26 (8 ± 4)</td>
</tr>
</tbody>
</table>

1: Used Modified Marshall compactor to fabricate samples. Numbers of blows based on obtaining 4% voids.
<table>
<thead>
<tr>
<th>Test Temp.  °C (°F)</th>
<th>Confining Pressure kPa (psi)</th>
<th>Creep Modulus MPa (ksi)</th>
<th>Creep Compliance MPa⁻¹ (kis⁻¹)</th>
<th>0.33 Hz</th>
<th>0.5 Hz</th>
<th>1.0 Hz</th>
<th>0.33 Hz</th>
<th>0.5 Hz</th>
<th>1.0 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 (77)</td>
<td>None</td>
<td>204 ± 128 (30 ± 19)</td>
<td>0.005 (0.03)</td>
<td></td>
<td></td>
<td></td>
<td>170 ± 104 (25 ± 15)</td>
<td>0.006 (0.04)</td>
<td>170 ± 72 (25 ± 10)</td>
</tr>
<tr>
<td></td>
<td>207 (30)</td>
<td>573 ± 235 (83 ± 35)</td>
<td>0.002 (0.01)</td>
<td>170 ± 41 (25 ± 15)</td>
<td>0.006 (0.04)</td>
<td>170 ± 72 (25 ± 10)</td>
<td>0.006 (0.04)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 Blow Marshall Mixtures</td>
<td>None</td>
<td>222 ± 36 (32 ± 5)</td>
<td>0.005 (0.03)</td>
<td></td>
<td></td>
<td></td>
<td>150 ± 34 (22 ± 5)</td>
<td>0.007 (0.05)</td>
<td>130 ± 24 (19 ± 3)</td>
</tr>
<tr>
<td></td>
<td>207 (30)</td>
<td>407 ± 286 (59 ± 42)</td>
<td>0.003 (0.02)</td>
<td>418 ± 321 (61 ± 47)</td>
<td>0.002 (0.02)</td>
<td>445 ± 357 (65 ± 63)</td>
<td>0.002 (0.02)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75 Blow Marshall Mixtures</td>
<td>None</td>
<td>92 ± 38 (14 ± 6)</td>
<td>0.010 (0.07)</td>
<td></td>
<td></td>
<td></td>
<td>73 ± 41 (11 ± 6)</td>
<td>0.014 (0.09)</td>
<td>69 ± 32 (10 ± 5)</td>
</tr>
<tr>
<td></td>
<td>207 (30)</td>
<td>513 ± 166 (74 ± 24)</td>
<td>0.002 (0.01)</td>
<td>499 ± 174 (72 ± 25)</td>
<td>0.002 (0.01)</td>
<td>488 ± 129 (71 ± 20)</td>
<td>0.002 (0.01)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Gyratory Mix Design

None                          | Insufficient Material to Complete this Test
207 (30)                      |
Table 12 (Continued). Repeated Load (0.1 Second) Creep Test Results 40°C After 1 Hr. (AC 20 Asphalt)

<table>
<thead>
<tr>
<th>Test Temp. °C (°F)</th>
<th>Confining Pressure kPa (psi)</th>
<th>Frequency Between Loads, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.33 Hz</td>
<td>0.5 Hz</td>
</tr>
<tr>
<td></td>
<td>Creep Modulus MPa (ksi)</td>
<td>Creep Compliance MPa⁻¹ (ksi⁻¹)</td>
</tr>
<tr>
<td>40 (104)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>43 ± 3 (6 ± 0.4)</td>
</tr>
<tr>
<td></td>
<td>207 (30)</td>
<td>145 ± 11 (21 ± 2)</td>
</tr>
<tr>
<td>50 Blow Marshall Mixtures</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>46 ± 11 (7 ± 2)</td>
</tr>
<tr>
<td></td>
<td>207 (30)</td>
<td>146 ± 32 (21 ± 5)</td>
</tr>
<tr>
<td>75 Blow Marshall Mixtures</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>42 ± 10 (6 ± 1)</td>
</tr>
<tr>
<td></td>
<td>207 (30)</td>
<td>84 ± 19 (12 ± 3)</td>
</tr>
<tr>
<td>Gyratory Mix Design</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>Insufficient Material to Complete this Test</td>
</tr>
<tr>
<td></td>
<td>207 (30)</td>
<td></td>
</tr>
</tbody>
</table>
Table 13. Repeated Load (1.0 Second) Creep Test Results 25°C After 1 Hr.
(120/150 Pen Asphalt)

<table>
<thead>
<tr>
<th>Test Temp. °C (°F)</th>
<th>Confining Pressure kPa (psi)</th>
<th>Frequency Between Loads, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.033 Hz</td>
</tr>
<tr>
<td></td>
<td>Creep Modulus MPa (ksi)</td>
<td>Creep Compliance MPa⁻¹ (ksi⁻¹)</td>
</tr>
<tr>
<td>25 (77)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>87 ± 17 (13 ± 3)</td>
<td>0.011 (0.08)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>364 ± 163 (53 ± 24)</td>
<td>0.003 (0.02)</td>
</tr>
<tr>
<td>35 Blow Marshall Mixtures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>89 ± 17 (13 ± 3)</td>
<td>0.011 (0.08)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>192 ± 46 (28 ± 7)</td>
<td>0.005 (0.04)</td>
</tr>
<tr>
<td>50 Blow Marshall Mixtures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>186 ± 38 (27 ± 6)</td>
<td>0.005 (0.04)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>388 ± 98 (56 ± 14)</td>
<td>0.003 (0.02)</td>
</tr>
<tr>
<td>75 Blow Marshall Mixtures</td>
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</tr>
<tr>
<td>None</td>
<td>112 ± 37 (16 ± 5)</td>
<td>0.009 (0.06)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>252 ± 30 (37 ± 4)</td>
<td>0.005 (0.03)</td>
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<td>Gyratory Mix Design¹</td>
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</tr>
<tr>
<td>None</td>
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</tr>
<tr>
<td>207 (30)</td>
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</tr>
</tbody>
</table>

¹: Used Modified Marshall compactor to fabricate samples. Numbers of blows based on obtaining 4% voids.
Table 13 (Continued). Repeated Load (1.0 Second) Creep Test Results 40°C After 1 Hr. (120/150 Pen Asphalt)

<table>
<thead>
<tr>
<th>Test Temp. °C (°F)</th>
<th>Confining Pressure kPa (psi)</th>
<th>Frequency Between Loads, Hz</th>
<th>0.033 Hz</th>
<th>0.05 Hz</th>
<th>0.1 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Creep Modulus MPa (ksi)</td>
<td>Creep Compliance MPa⁻¹ (ksi⁻¹)</td>
<td>Creep Modulus MPa (ksi)</td>
<td>Creep Compliance MPa⁻¹ (ksi⁻¹)</td>
</tr>
<tr>
<td>40 (104)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>35 Blow Marshall Mixtures</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>24 ± 2 (3 ± 0.3)</td>
<td>0.042 (0.29)</td>
<td>15 ± 0 (2 ± 0)</td>
<td>0.066 (0.45)</td>
<td>7 ± 1 (1 ± 0.2)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>35 ± 8 (5 ± 1)</td>
<td>0.029 (0.20)</td>
<td>25 ± 4 (4 ± 0.6)</td>
<td>0.041 (0.28)</td>
<td>19 ± 3 (4 ± 0.6)</td>
</tr>
<tr>
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</tr>
<tr>
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<td>50 Blow Marshall Mixtures</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>33 ± 4 (5 ± 0.6)</td>
<td>0.030 (0.21)</td>
<td>30 ± 5 (4 ± 0.8)</td>
<td>0.034 (0.23)</td>
<td>27 ± 6 (4 ± 0.9)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>67 ± 8 (10 ± 1)</td>
<td>0.015 (0.10)</td>
<td>47 ± 4 (7 ± 0.5)</td>
<td>0.021 (0.15)</td>
<td>39 ± 5 (6 ± 0.7)</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>75 Blow Marshall Mixtures</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>35 ± 3 (5 ± 0.4)</td>
<td>0.029 (0.20)</td>
<td>28 ± 1 (4 ± 0.2)</td>
<td>0.036 (0.25)</td>
<td>27 ± 2 (4 ± 0.2)</td>
</tr>
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<td>207 (30)</td>
<td>50 ± 21 (7 ± 3)</td>
<td>0.020 (0.14)</td>
<td>34 ± 7 (5 ± 1)</td>
<td>0.029 (0.20)</td>
<td>28 ± 4 (4 ± 0.6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gyratory Mix Design¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>24 ± 4 (3 ± 0.5)</td>
<td>0.042 (0.29)</td>
<td>20 ± 4 (3 ± 0.5)</td>
<td>0.051 (0.35)</td>
<td>16 ± 3 (2 ± 0.5)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>68 ± 1 (10 ± 0.1)</td>
<td>0.015 (0.10)</td>
<td>53 ± 1 (8 ± 0.1)</td>
<td>0.019 (0.13)</td>
<td>51 ± 2 (7 ± 0.3)</td>
</tr>
</tbody>
</table>

1: Used Modified Marshall compactor to fabricate samples. Numbers of blows based on obtaining 4% voids.
Table 13 (Continued). Repeated Load (1.0 Second) Creep Test Results 25°C After 1 Hr. (AC 20 Asphalt)

<table>
<thead>
<tr>
<th>Test Temp. °C (°F)</th>
<th>Confining Pressure kPa (psi)</th>
<th>Frequency Between Loads, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Creep Modulus MPa (ksi)</td>
<td>Creep Compliance MPa$^{-1}$ (ksi$^{-1}$)</td>
</tr>
<tr>
<td></td>
<td>0.033 Hz</td>
<td>0.05 Hz</td>
</tr>
<tr>
<td>25 (77)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>97 ± 14 (14 ± 2)</td>
<td>78 ± 18 (11 ± 3)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>400 ± 12 (58 ± 2)</td>
<td>303 ± 28 (44 ± 4)</td>
</tr>
<tr>
<td>50 Blow Marshall Mixtures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>341 ± 106 (50 ± 15)</td>
<td>216 ± 31 (31 ± 5)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>242 ± 55 (35 ± 8)</td>
<td>194 ± 22 (28 ± 3)</td>
</tr>
<tr>
<td>75 Blow Marshall Mixtures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>94 ± 10 (14 ± 2)</td>
<td>70 ± 8 (10 ± 1)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>270 ± 90 (39 ± 13)</td>
<td>233 ± 85 (34 ± 12)</td>
</tr>
<tr>
<td>Gyratory Mix Design</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>Insufficient Material to Complete this Test</td>
<td></td>
</tr>
<tr>
<td>207 (30)</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>Test Temp. °C (°F)</td>
<td>Confining Pressure kPa (psi)</td>
<td>0.033 Hz</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td></td>
<td>Creep Modulus MPa (ksi)</td>
<td>Creep Compliance MPa (ksi')</td>
</tr>
<tr>
<td>40 (104)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>31 ± 5 (5 ± 0.7)</td>
<td>0.032 (0.22)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>36 ± 8 (5 ± 1)</td>
<td>0.028 (0.19)</td>
</tr>
<tr>
<td>35 Blow Marshall Mixtures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>27 ± 0 (4 ± 0)</td>
<td>0.037 (0.26)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>52 ± 23 (8 ± 3)</td>
<td>0.019 (0.13)</td>
</tr>
<tr>
<td>50 Blow Marshall Mixtures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>45 ± 3 (7 ± 0.4)</td>
<td>0.022 (0.15)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>58 ± 5 (8 ± 0.7)</td>
<td>0.017 (0.12)</td>
</tr>
<tr>
<td>75 Blow Marshall Mixtures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td>207 (30)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gyratory Mix Design</td>
<td>Insufficient Material to Complete This Test</td>
<td></td>
</tr>
</tbody>
</table>
Table 14. Static Creep Results (25°C).

<table>
<thead>
<tr>
<th>Test Temp. °C (°F)</th>
<th>Confining Pressure kPa (psi)</th>
<th>Creep Modulus MPa (ksi)</th>
<th>Creep Compliance MPa (^{-1}) (ksi(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>120/150 Pen AC 20</td>
<td>120/150 Pen AC 20</td>
</tr>
<tr>
<td>25 (77)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>35 Blow Marshall Mixtures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>55 (8) ± 17 (3) 38 (6) ± 2 (0.2)</td>
<td>56 (8) ± 8 (1) 39 (6) ± 10 (2)</td>
<td>0.018 (0.13) 0.027 (0.18) 0.018 (0.12) 0.025 (0.17)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>67 (10) ± 1 (0.1) 63 (9) ± 26 (4)</td>
<td>93 (13) ± 34 (5) 103 (15) ± 8 (1)</td>
<td>0.015 (0.10) 0.016 (11) 0.011 (0.08) 0.010 (0.07)</td>
</tr>
<tr>
<td></td>
<td>50 Blow Marshall Mixtures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>58 (8) ± 2 (0.2) 45 (7) ± 11 (2)</td>
<td>54 (8) ± 13 (2) 67 (10) ± 6 (0.8)</td>
<td>0.017 (0.12) 0.022 (0.15) 0.019 (0.13) 0.015 (0.10)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>60 (9) ± 3 (0.5) 69 (10) ± 14 (2)</td>
<td>107 (16) ± 36 (5) 84 (12) ± 9 (1)</td>
<td>0.017 (0.09) 0.014 (0.10) 0.009 (0.06) 0.012 (0.08)</td>
</tr>
<tr>
<td></td>
<td>75 Blow Marshall Mixtures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>70 (10) ± 4 (0.6) 59 (9) ± 2 (0.3)</td>
<td>38 (6) ± 9 (1) 35 (5) ± 6 (0.9)</td>
<td>0.014 (0.10) 0.017 (0.12) 0.027 (0.18) 0.029 (0.200)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>78 (11) ± 9 (1) 99 (14) ± 17 (3)</td>
<td>118 (17) ± 16 (2) 97 (14) ± 27 (4)</td>
<td>0.013 (0.09) 0.010 (0.07) 0.009 (0.06) 0.010 (0.07)</td>
</tr>
<tr>
<td></td>
<td>Gyratory</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>71 ± 46 (10 ± 7)</td>
<td>Not Available</td>
<td>0.014 (0.10)</td>
</tr>
<tr>
<td>207 (30)</td>
<td>69 ± 17 (10 ± 3)</td>
<td></td>
<td>0.015 (0.10)</td>
</tr>
</tbody>
</table>

NA: indicates only one sample survived testing.
Table 15. Static Creep Results (40°C).

<table>
<thead>
<tr>
<th>Test Temp. °C (°F)</th>
<th>Confining Pressure kPa (psi)</th>
<th>Creep Modulus MPa (ksi)</th>
<th>Creep Compliance MPa¹ (ksi¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>120/150 Pen</td>
<td>AC 20</td>
</tr>
<tr>
<td>40 (104)</td>
<td>50 Blow Marshall Mixtures</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>Failed</td>
<td>23 (3) ± 6 (0.8)</td>
</tr>
<tr>
<td></td>
<td>Failed</td>
<td>16 (2) ± 0.8 (0.1)</td>
<td>Failed</td>
</tr>
<tr>
<td></td>
<td>207 (30)</td>
<td>Failed</td>
<td>52 (8) ± 7 (1)</td>
</tr>
<tr>
<td></td>
<td>11 (2) ± 3 (0.5)</td>
<td></td>
<td>Failed</td>
</tr>
<tr>
<td>50 Blow Marshall Mixtures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>16 (2) ± 11 (2)</td>
<td>10 (1) ± NA</td>
</tr>
<tr>
<td></td>
<td>19 (3) ± 4 (0.6)</td>
<td>38 (5) ± NA</td>
<td>0.053 (0.37)</td>
</tr>
<tr>
<td></td>
<td>207 (30)</td>
<td>21 (3) ± 3 (0.4)</td>
<td>60 (9) ± 19 (3)</td>
</tr>
<tr>
<td></td>
<td>25 (4) ± 4 (0.6)</td>
<td>14 (2) ± 3 (0.5)</td>
<td>0.040 (0.28)</td>
</tr>
<tr>
<td>75 Blow Marshall Mixtures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>26 (4) ± 7 (1.0)</td>
<td>24 (4) ± NA</td>
</tr>
<tr>
<td></td>
<td>21 (3) ± 1 (0.2)</td>
<td>10 (1) ± NA</td>
<td>0.047 (0.32)</td>
</tr>
<tr>
<td></td>
<td>207 (30)</td>
<td>20 (3) ± 5 (0.8)</td>
<td>31 (5) ± 8 (1)</td>
</tr>
<tr>
<td></td>
<td>21 (3) ± (0.2)</td>
<td>28 (4) ± 0.7 (0.1)</td>
<td>0.047 (0.32)</td>
</tr>
<tr>
<td></td>
<td>Gyratory</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>11 ± 1 (2 ± 0.2)</td>
<td>Not Available</td>
</tr>
<tr>
<td></td>
<td>207 (30)</td>
<td>31 ± 11 (5 ± 2)</td>
<td></td>
</tr>
</tbody>
</table>

NA: indicates only one sample survived testing.
**Figure 27. Creep Compliance (25° (77°F), AC 20 Mixtures).**

**Figure 28. Creep Compliance (40° (104°F), 120/150 Pen Mixtures).**
Figure 29. Creep Compliance (40°F (104°C), AC 20 Mixtures).

**Tensile Strength at Low Temperatures**

**Diametral Compression**

The test results presented in Tables 16 and 17 represent the average of three replicates. The standard deviation associated with a set of three samples is also shown in this table. At the cold test temperature [-18°C (0°F)], increasing the vertical displacement rate from 0.25 to 2.5 mm/min (0.01 to 0.1 in/min) did not show a statistically significant increase in the measured tensile strength. The tensile strengths for both the 120/150 pen and AC 20 mixtures at -18°C (0°F) were similar (Figure 30). When the test temperature was increased to 1°C (34°F), increasing the displacement rate significantly increases the measured tensile strength. There was also a significant different between mixtures due to the grade of asphalt. The stiffer AC 20 mixtures typically showed greater tensile strengths than the 120/150 pen mixtures (Figure 30).
Figure 31 shows no dependence upon the displacement rate for the corresponding horizontal strains at the -18°C (0°F) test temperature. At 1°C (34°F), the tensile strength for the 120/150 pen mixtures was lower and the that for the AC 20 and the corresponding horizontal deformations were greater than those the AC 20 mixtures indicating a dependence of the results on the displacement rate selected for the test.

![Graph showing influence of vertical displacement rates on tensile strengths at cold temperatures.](image)

**Figure 30. Influence of Vertical Displacement Rates on Tensile Strengths at Cold Temperatures.**
Table 16. Low Temperature Behavior at Constant Rate of Deformation (120/150 Pen Mix Design Materials).

<table>
<thead>
<tr>
<th>Constant Rate of Vertical Deformation mm/min (in/min)</th>
<th>Test Temperature, °C (°F)</th>
<th>Maximum Tensile Strength kPa (psi)</th>
<th>Corresponding Horizontal Strain με</th>
<th>Maximum Tensile Strength kPa (psi)</th>
<th>Corresponding Horizontal Strain με</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-18°C (0°F)</td>
<td></td>
<td></td>
<td>1°C (34°F)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>120/150 Pen Asphalt, 35 Blow Marshall Mixtures</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.025 (0.001)</td>
<td>2,862 (415)</td>
<td>970 ± 80</td>
<td>663 (96)</td>
<td>3,852 ± 300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>± 66 (10)</td>
<td></td>
<td>± 18 (3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.25 (0.01)</td>
<td>3,262 (473)</td>
<td>820 ± 30</td>
<td>1,131 (164)</td>
<td>3,794 ± 600</td>
<td></td>
</tr>
<tr>
<td></td>
<td>± 129 (19)</td>
<td></td>
<td>± 15 (2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5 (0.1)</td>
<td>3,545 (514)</td>
<td>783 ± 70</td>
<td>1,897 (275)</td>
<td>2,704 ± 700</td>
<td></td>
</tr>
<tr>
<td></td>
<td>± 230 (33)</td>
<td></td>
<td>± 45 (7)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>120/150 Pen Asphalt, 50 Blow Marshall Mixtures</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.025 (0.001)</td>
<td>3,296 (478)</td>
<td>694 ± 80</td>
<td>717 (104)</td>
<td>3,673 ± 700</td>
<td></td>
</tr>
<tr>
<td></td>
<td>± 82 (12)</td>
<td></td>
<td>± 41 (6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.25 (0.01)</td>
<td>3,897 (565)</td>
<td>450 ± 50</td>
<td>1,103 (160)</td>
<td>3,951 ± 800</td>
<td></td>
</tr>
<tr>
<td></td>
<td>± 175 (25)</td>
<td></td>
<td>± 54 (8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5 (0.1)</td>
<td>3,993 (579)</td>
<td>232 ± 70</td>
<td>2,303 (334)</td>
<td>2,664 ± 200</td>
<td></td>
</tr>
<tr>
<td></td>
<td>± 508 (74)</td>
<td></td>
<td>± 88 (13)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>120/150 Pen Asphalt, 75 Blow Marshall Mixtures</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.025 (0.001)</td>
<td>3,510 (509)</td>
<td>694 ± 50</td>
<td>772 (112)</td>
<td>3,527 ± 100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>± 35 (5)</td>
<td></td>
<td>± 26 (4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.25 (0.01)</td>
<td>3,770 (547)</td>
<td>602 ± 30</td>
<td>1,276 (185)</td>
<td>3,188 ± 500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>± 107 (16)</td>
<td></td>
<td>± 131 (18)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5 (0.1)</td>
<td>3,620 (525)</td>
<td>323 ± 10</td>
<td>1,993 (289)</td>
<td>2,817 ± 400</td>
<td></td>
</tr>
<tr>
<td></td>
<td>± 344 (50)</td>
<td></td>
<td>± 188 (27)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>120/150 Pen Asphalt, Gyratory Mixtures</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.025 (0.001)</td>
<td>3,268 (474)</td>
<td>655 ± 58</td>
<td>850 (124) ± 94 (14)</td>
<td>1,280 ± 866</td>
<td></td>
</tr>
<tr>
<td></td>
<td>± 372 (54)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.25 (0.01)</td>
<td>3,227 (468)</td>
<td>696 ± 12</td>
<td>1,330 (193) ± 131 (19)</td>
<td>1,200 ± 2,008</td>
<td></td>
</tr>
<tr>
<td></td>
<td>± 166 (24)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5 (0.1)</td>
<td>Not Tested</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant Rate of Vertical Deformation mm/min (in/min)</td>
<td>Test Temperature, °C (°F)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------------------------------------------</td>
<td>--------------------------</td>
<td>--------------------------</td>
<td>--------------------------</td>
<td>--------------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-18°C (0°F)</td>
<td>1°C (34°F)</td>
<td>1°C (34°F)</td>
<td>1°C (34°F)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum Tensile Strength kPa (psi)</td>
<td>Corresponding Horizontal Strain $\mu e$</td>
<td>Maximum Tensile Strength kPa (psi)</td>
<td>Corresponding Horizontal Strain $\mu e$</td>
<td></td>
</tr>
<tr>
<td>AC 20 Asphalt, 35 Blow Marshall Mixtures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.025 (0.001)</td>
<td>3,248 (471)              $\pm$ 234 (34)</td>
<td>258 ± 160</td>
<td>1,021 (148)              $\pm$ 69 (10)</td>
<td>1,870 ± 380</td>
<td></td>
</tr>
<tr>
<td>0.25 (0.01)</td>
<td>3,241 (470)              $\pm$317 (46)</td>
<td>449 ± 80</td>
<td>1,813 (263)              $\pm$58 (8)</td>
<td>1,850 ± 40</td>
<td></td>
</tr>
<tr>
<td>2.5 (0.1)</td>
<td>3,490 (506)              $\pm$235 (34)</td>
<td>188 ± 18</td>
<td>2,393 (347)              $\pm$317 (46)</td>
<td>1,480 ± 150</td>
<td></td>
</tr>
<tr>
<td>AC 20 Asphalt, 50 Blow Marshall Mixtures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.025 (0.001)</td>
<td>3,310 (480)              $\pm$110 (16)</td>
<td>190 ± 77</td>
<td>1,069 (155)              $\pm$35 (5)</td>
<td>1,390 ± 260</td>
<td></td>
</tr>
<tr>
<td>0.25 (0.01)</td>
<td>3,407 (494)              $\pm$207 (30)</td>
<td>516 ± 206</td>
<td>1,848 (268)              $\pm$83 (12)</td>
<td>1,640 ± 150</td>
<td></td>
</tr>
<tr>
<td>2.5 (0.1)</td>
<td>3,855 (529)              $\pm$166 (24)</td>
<td>206 ± 51</td>
<td>2,758 (400)              $\pm$179 (26)</td>
<td>1,310 ± 320</td>
<td></td>
</tr>
<tr>
<td>AC 20 Asphalt, 75 Blow Marshall Mixtures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.025 (0.001)</td>
<td>3,317 (481)              $\pm$269 (39)</td>
<td>256 ± 79</td>
<td>1,097 (159)              $\pm$35 (5)</td>
<td>1,890 ± 130</td>
<td></td>
</tr>
<tr>
<td>0.25 (0.01)</td>
<td>3,538 (513)              $\pm$166 (24)</td>
<td>212 ± 35</td>
<td>1,828 (265)              $\pm$117 (17)</td>
<td>1,600 ± 250</td>
<td></td>
</tr>
<tr>
<td>2.5 (0.1)</td>
<td>3,600 (522)              $\pm$96 (14)</td>
<td>230 ± 34</td>
<td>2,655 (385)              $\pm$256 (37)</td>
<td>1,710 ± 200</td>
<td></td>
</tr>
<tr>
<td>AC 20 Asphalt, Gyratory Mixtures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.025 (0.001)</td>
<td>3,014 (437)              $\pm$297 (43)</td>
<td>360 ± 129</td>
<td>972 (141)                $\pm$55 (8)</td>
<td>2,639 ± 227</td>
<td></td>
</tr>
<tr>
<td>0.25 (0.01)</td>
<td>3,207 (465)              $\pm$393 (57)</td>
<td>651 ± 183</td>
<td>2,524 (366)              $\pm$117 (17)</td>
<td>1,652 ± 67</td>
<td></td>
</tr>
<tr>
<td>2.5 (0.1)</td>
<td>Not Tested</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 31. Influence of Vertical Displacement Rates on Horizontal Deformation at Cold Temperatures.

**Diametral Compression Creep**

The test results shown in Table 18 represent the average of three tests. These data show little affect of changes in asphalt content on creep compliance for any given test temperature and grade of asphalt. Creep compliance increased with temperature with differences between the two grades of asphalt being accentuated at the warmer temperatures (Figure 32). The compliance for both the 120/150 pen and AC 20 mixtures were similar at -20°C (-5°). Above this temperature, the compliance of the 120/150 pen asphalt mixtures became increasingly greater with increasing test temperatures.
Table 18. Indirect Tensile Creep Test Results for Mix Design Materials.

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Creep Compliance at 1,000 sec, 1/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test Temperature</td>
</tr>
<tr>
<td></td>
<td>0°C (-18°F)</td>
</tr>
<tr>
<td>120/150 Pen Asphalt Mix Design Mixture</td>
<td></td>
</tr>
<tr>
<td>35 Blow</td>
<td>0.0259</td>
</tr>
<tr>
<td>50 Blow</td>
<td>0.0207</td>
</tr>
<tr>
<td>75 Blow</td>
<td>No Data</td>
</tr>
<tr>
<td>Gyratory</td>
<td>0.0226</td>
</tr>
<tr>
<td>AC 20 Asphalt Mix Design Mixtures</td>
<td></td>
</tr>
<tr>
<td>35 Blow</td>
<td>0.0069</td>
</tr>
<tr>
<td>50 Blow</td>
<td>0.0126</td>
</tr>
<tr>
<td>75 Blow</td>
<td>0.0085</td>
</tr>
<tr>
<td>Gyratory</td>
<td>0.0134</td>
</tr>
</tbody>
</table>

Figure 32. Creep Compliance Behavior at Cold Temperatures.
Brittle Point Measurements

The Fraass brittle point temperatures were -19 and -15 (-2 and 5°F) for the 120/150 pen and AC 20 asphalts, respectively, and -26 and -21°C (-15 and -6°F) for the DSR test. Each method predicts different brittle point temperatures because of the difference in loading rates between the two tests and sample fatigue in the binder film in the Fraass test (Stroup-Gardiner, et al., 1996). The Fraass test consistently estimated the brittle point between 4°C and 5°C warmer than the DSR.

The BBR data compiled by Mn/DOT, show the 120/150 and AC 20 asphalts would be classified as PG grades 58-28 and PG 58-22 binders, respectively. The previously derived empirical equation for predicting BBR results from DSR testing (Stroup-Gardiner, 1997):

\[ BBR \ Temp = -8.319 + 0.982 \times (DSR \ Temp) \] (22)

Using the DSR data for these two asphalts in this equation, the predicted BBR temperatures for the 120/150 pen and AC 20 asphalts are -33 and -29°C (-27 and -20°F), respectively. Using the DSR results to select the cold end of the PG grade, both asphalts would be graded as a PG58-28.

Comparison of Mix and Binder Low Temperature Properties

Compliance of the 120/150 pen mixtures increased substantially above about -15°C. Below this temperature, there was little change in compliance. Similar behavior was noted for the AC 20 mixtures, but with a warmer temperature (-10°C) marking the point below which there was little change in compliance. It was anticipated that the temperature associated with the onset of approximately steady compliance would also mark the beginning of brittle binder behavior. Therefore, this temperature from the low temperature mixture testing should be related to the Fraass and DSR brittle points. For both grades of asphalt, the compliance became consistent at warmer temperatures than either brittle point would suggest. This is expected because the mixture testing rate of displacement is greater than either the Fraass or DSR testing and should be seen as a stiffer response.
SUMMARY AND CONCLUSIONS

Theoretical Evaluation of Test Methods

A thorough theoretical evaluation of calculations of stress and strain from axially and diametrical loaded samples was completed. A rigorous methodology was developed using the elastic-viscoelastic correspondence principle, and Laplace and Fourier transforms to more appropriately express the standard diametral compression testing equations shown in ASTM D4123 as a function of platen width, sample diameter and distance over which displacement is measured. The full development of these equations is shown in Appendix A. When harmonic (sinusoidal) loading is used instead of the conventional repeated loading, the elastic theory was modified to obtain a viscoelastic solution in terms of frequency-dependent compliances. The full development of these equations is shown in Appendix B.

An evaluation of phase angle data obtained from harmonic loading of either axial or diametrical samples showed the accumulation of incremental permanent deformations could result in an incorrect assessment of this parameter. The phase angle is correctly calculated as the average of the phase angle measured for both loading and unloading portion of the material response (Appendix C).

Exceptions to Established Test Procedures

Existing MTS sensors and sample mountings were modified to obtain both horizontal and vertical displacement measurements that were independent of any sample "bulging" for the SUPERPAVE diametral creep test. The SUPERPAVE equations for elastic modulus and Poisson's ratio were redeveloped for this new configuration and the correction factors used to compensate for this problem were eliminated.
Conclusions as to the influence of test method variables on test results are as follows:

1. Increasing the time a load is applied results in a lower calculated mixture stiffness. As the test temperature is decreased, the influence of the load duration is minimized.

2. Changing the rest period between repeated loadings did not have a significant effect on the calculated stiffness, at least for the range of rest periods used in this study.

3. Confining pressure (axially loaded samples) only significantly increased the calculated stiffness at test temperatures above about 25°C (77°F).

4. Increasing loading frequency increases the calculated stiffness and decreases the phase angle. Below a test temperature of 1°C, the phase angle response did not change significantly.

5. In general, harmonic axial loading (ASTM D3497) at a frequency of 1 Hz produces a higher calculated stiffness than does repeated load diametral testing (ASTM D4123) using a load duration of 1 second. When a repeated load duration of 0.1 seconds was used, the resilient modulus was either similar to or greater than the complex modulus (axial loading) at test temperatures warmer than 25°C (77°F).

6. A comparison of axial and diametral testing using an harmonic loading showed that experimental results did not agree with theory. That is, the complex deviatoric modulus determined for diametral testing should have been less than the Young's modulus determined from testing axially loaded samples. This was not the case. A further examination of sample instrumentation, testing variability, and the possibility of anisotropic mixture behavior due to particle orientation during compaction is needed in order to resolve these differences.

7. There was little difference in axial creep compliance between any of the mixture variables when mixtures were tested at 25°C (77°F). When the test temperature was increased to 40°C (104°F), large differences were noticed between the mixture. However, the testing variability also increased substantially, making it difficult to determine if differences were statistically different.
Conclusions as to the influence of test method variables on test results are as follows:

1. Constant rate of vertical deformation of diametrally loaded samples showed that at a test temperature of \(-18^\circ C (0^\circ F)\), changing the loading rate from 0.025 to 0.25 mm/min (0.01 to 0.1 in/min) did not significantly alter the measured tensile strength for a given grade of asphalt.

2. At a warmer test temperature of \(1^\circ C (34^\circ F)\), increasing the loading rate resulted in a corresponding increase in the measured tensile strength. This was accompanied by a corresponding decrease in the horizontal strain at the maximum tensile strength.

3. The diametral compliance of the Mn/ROAD mixtures was dependent only on changes in the grade of asphalt and not changes in asphalt content. The stiffer AC 20 mixtures were less compliant at any given temperature than the 120/150 pen mixtures.

4. Assuming that a creep compliance approaching an approximately horizontal asymptote implied the onset brittle behavior, the temperature difference between the beginning of brittle behavior for the 120/150 pen and AC 20 mixtures was about 5°C. This agrees with the temperature difference between the measured Fraass and DSR brittle points. While the actual temperatures are test dependent, the similarity in the differences between the brittle temperatures for each test implies that the binder dominates the cold temperature behavior. This agrees with previous research.
BIBLIOGRAPHY


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