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ABSTRACT

Low temperature cracking represents a significant problem in asphalt pavements built in Northern US and Canada. As temperature decreases rapidly, thermal stresses develop in the restrained asphalt surface layer and, when the temperature reaches a critical temperature, cracking occurs.

In this thesis, statistical analyses were used to compare thermal stresses that develop in an idealized asphalt pavement layer calculated from experimental data obtained with three different test methods:

1) Asphalt mixture creep test using Bending Beam Rheometer (BBR)
2) Asphalt mixture creep test using Indirect Tensile Test (IDT)
3) Asphalt binder creep test using BBR and an empirical Pavement Constant

Thermal stresses calculated using mixture BBR and mixture IDT data were reasonably identical. Thermal stresses calculated using binder BBR data and an empirical Pavement Constant were significantly different than the other calculated thermal stresses.

The effect of physical hardening on thermal stress evaluation was investigated for a limited number of materials and it was found that this effect can significantly affect thermal stress magnitude.
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Chapter I

Introduction

1.1 Low temperature cracking

Thermal cracking represents a significant pavement distresses in Northern US and Canada. As temperatures drop to values well below 0°C, thermal stresses start to increase in the restrained asphalt pavement layer. When the temperature drops to a critical value, called critical cracking temperature, at which stresses exceed the strength of the material, cracking occurs (Figure 1.1) and stresses are relieved.

![Figure 1.1 Thermal cracking in asphalt pavement](image)

Thermal cracking has serious negative effects on pavement performance since water can penetrate freely in the pavement structure and accelerate the destruction process due to freeze-thaw cycles and traffic loading. Currently, many agencies are struggling to maintain their pavement networks at acceptable conditions. Minnesota alone spent $355 million dollars on pavement structures last year and nationally, the expenditures reached
$45$ billion dollars.

1.2 Problem statement

A number of experimental methods have been developed over the years to characterize asphalt binders and asphalt mixtures behavior at low temperatures. One fundamental test used to characterize viscoelastic materials is the creep test. In this test, a stress is applied instantaneously to the specimen and it is maintained constant for the duration of the test. At the end of the test, the stress is removed and the recovery of the specimen can be monitored if recovery properties are desired. The creep compliance obtained from the experimental data can be used to calculate thermal stresses that develop in a restrained specimen that can be further used to estimate the magnitude of pavement stresses at low temperatures.

For asphalt binder, the results from a creep test performed with the Bending Beam Rheometer (BBR) have been used as part of the current AASHTO specifications for the past two decades. For asphalt mixtures, the results from a creep test performed using the Indirect Tension (IDT) method have been used as part of a current AASHTO method for the past two decades. The IDT requires expensive testing equipment and very few laboratories can perform it. Recently, it was shown that creep tests can be performed on thin mixture beams using the same BBR equipment that is currently used for asphalt binders. This test is very easy to perform and many laboratories have the equipment and training to perform it.
The main objective of this thesis is to compare thermal stresses calculated using binder BBR data, mixture BBR data, and mixture IDT data, respectively, to find out if mixture BBR test is a viable option to calculate thermal stresses. In addition, the effect of isothermal physical hardening on thermal stress calculations is evaluated and discussed.

1.3 Research Approach

The following steps were taken to perform the objectives of this thesis. Creep tests were performed on eleven mixtures using the BBR and the IDT test methods, respectively. BBR binder creep tests were also performed on the four asphalt binders used to prepare the eleven mixtures. The experimental data were used to calculate thermal stresses and statistical analyses were performed to compare the stresses. Critical cracking temperatures ($T_{CR}$) were also estimated and statistical analyses were performed to compare them. Three of the eleven asphalt mixtures were conditioned at different storage times and the effect of physical hardening on thermal stresses were evaluated using statistical tools.
Chapter II

Literature Review

One of the most significant distresses in asphalt pavements built in cold climates is low temperature cracking. As the temperature drops below a critical temperature $T_{CR}$, the thermal stress in asphalt mixture exceeds its strength and cracks form. In order to address this issue, several test methods and analyses were developed. A review is provided in the next paragraphs.

2.1 Evaluation of asphalt binder low temperature properties

Two test methods, the Bending Beam Rheometer (BBR) test and the Direct Tension (DT) test were developed during the Strategic Highway Research Program (SHRP) for evaluating low temperature properties of asphalt binders. (Anderson et al, 1994)

2.1.1 Bending Beam Rheometer (BBR) Test

In this test method, three point bending creep tests are performed on thin asphalt binder beams using the BBR device (AASHTO Designation T 313-02), see Figure 2.1. A constant load of 100g is instantaneously applied and maintained for 240s, and the mid span deflection is measured for the entire duration of the test.

![BBR equipment for asphalt binder testing](image.png)

Figure 2.1 BBR equipment for asphalt binder testing
The creep stiffness $S(t)$, which is the inverse of creep compliance $J(t)$, and m-value $m(t)$ (see Figure 2.2) are calculated from the load and mid span deflection $\delta(t)$ of the beam as follows:

$$S(t) = \frac{\sigma}{\varepsilon(t)} = \frac{P \cdot l^3}{4 \cdot b \cdot h^3 \cdot \delta(t)}$$

[2.1]

where

- $S(t) = \text{time dependent flexural creep stiffness, MPa;}$
- $\sigma = \text{maximum bending stress in the beam, MPa;}$
- $\varepsilon(t) = \text{time dependent bending strain in the beam, mm/mm;}$
- $P = \text{constant applied load (980 \pm 50 mN);}$
- $l = \text{length of specimen (101.6 mm);}$
- $b = \text{width of specimen (12.7 mm);}$
- $h = \text{height of specimen (6.35 mm);}$
- $\delta(t) = \text{deflection of beam, mm;}$
- $t = \text{time, s}$

$$m(t) = \frac{d \log S(t)}{d \log(t)}$$

[2.2]
The m-value is calculated by fitting a second order polynomial to the logS(t) versus log(t) curve:

\[ \log S(t) = a \cdot (\log(t))^2 + b \cdot \log(t) + c \quad [2.3] \]

and

\[ m(t) = |2a \cdot \log(t) + b| \quad [2.4] \]

According to AASHTO T313, a critical temperature is obtained from the lowest temperature at which the following two conditions occur:

\[ S(t_{60}) \leq 300 \text{MPa} \quad [2.5] \]
\[ m(t_{60}) \geq 0.300 \quad [2.6] \]

Then, 10°C are subtracted from this temperature determined from the S(t) and m(t) limits and the resulting temperature is reported as the lower limit of the Performance Grade (PG) of the binder. This temperature correction is needed since low temperature pavement performance is correlated to creep stiffness obtained after 2h of loading. The correction was determined based on Time-Temperature Superposition (TTS) principle for linear viscoelastic materials (Anderson and Kennedy, 1993).

2.1.2 Direct Tension (DT) Test

Direct Tension (DT) test is performed on dog-bone shaped specimen at a constant strain rate of 1%/min until failure occurs (AASHTO Designation T 314-06). Both the failure stress \( \sigma \) and failure strain \( \varepsilon \) are obtained at the same test temperatures used in BBR test. The strength can be used in combination with thermal stress calculation to obtain critical cracking temperature \( T_{CR} \) (Bouldin et.al, 2000).
2.2 Evaluation of asphalt mixture low temperature properties

2.2.1 Indirect Tensile (IDT) test

Since the early 1990’s, IDT test (AASHTO Designation T 322-03) has been used to evaluate low temperature properties of asphalt mixtures (Rouque and Buttlar 1992, Buttlar and Rouque 1994, Zhang et al. 1997, Christensen 1998, Rouque et al. 2002). Two types of tests can be performed with the IDT: a creep test, similar to the BBR test on binder, and a strength test, similar to the DT test on binder. Four Linear Variable Differential Transducers (LVDTs) are used to measure the vertical and horizontal creep displacements for 1000 ± 2.5 seconds. Figure 2.3 depicts the experimental set up of IDT test.

![Figure 2.3 IDT experimental set up](image)

The creep compliance $J(t)$ is calculated.

\[
J(t) = \frac{H^{(t)}_m \cdot d \cdot t}{P \cdot GL} \cdot C_{compliance}
\]  

[2.7]

where

$J(t) = \text{creep compliance, } 1/\text{MPa;}$
\[ H_m^{(t)} = \text{Measured horizontal deflection at time } t, \text{ mm}; \]

\[ d = \text{Diameter of specimen (150mm);} \]

\[ t = \text{Thickness of specimen (40mm);} \]

\[ GL = \text{Gauge Length (38mm);} \]

\[ P = \text{Constant applied load, kN;} \]

\[ \varepsilon_x = \text{strain in horizontal direction, mm/mm;} \]

\[ \varepsilon_y = \text{strain in vertical direction, mm/mm;} \]

\[ C_{\text{compliance}} = 0.6354 \times \left( \frac{X}{Y} \right)^{-1} - 0.332 \quad [2.8] \]

\[ \frac{X}{Y} = \frac{\varepsilon_x \text{ in 500 seconds}}{\varepsilon_y \text{ in 500 seconds}} \quad [2.9] \]

Creep stiffness \( S(t) \) is simply calculated as:

\[ S(t) = \frac{1}{J(t)} \quad [2.10] \]

2.2.2 Bending Beam Rheometer (BBR) test for asphalt mixtures

Recently the BBR equipment was used to perform creep tests on thin beams of asphalt mixture (Marasteanu et al., 2005, 2008, see Figure 2.4). A procedure similar to the one used to test asphalt binders was followed, except that higher test loads were applied due to the higher stiffness of asphalt mixtures. Similar to IDT testing, the load was applied for 1000 seconds.
Limited comparisons were performed (Zofka et.al, 2005, Marasteanu et. al, 2008) to investigate if BBR and IDT results are similar. It was found that for some mixtures, the two test methods produced different results in particular at the lowest temperature. Figure 2.5 shows the different size of specimens used in BBR and IDT mixture testing.

2.3 Linear viscoelastic behavior of asphalt binders and mixtures

Asphalt binder and mixture experimental data is analyzed in most cases using linear viscoelasticity theory, based on which the constitutive relationship between time
dependent strain $\varepsilon(t)$ and time dependent stress $\sigma(t)$ is defined. The constitutive equation describing this relationship can be written as follows. If the strain history is known, then the stress is calculated as:

$$\sigma(t) = \int_{-\infty}^{t} \dot{\varepsilon}(t') \cdot E(t-t')dt'$$ \hspace{1cm} [2.11]

where

$$\sigma(t) = \text{time dependent stress}$$

$$\dot{\varepsilon}(t') = \frac{d\varepsilon(t')}{dt'}$$

$$E(t-t') = \text{relaxation modulus}$$

If the stress history is known, the strain is calculated as:

$$\varepsilon(t) = \int_{-\infty}^{t} \dot{\sigma}(t') \cdot J(t-t')dt'$$ \hspace{1cm} [2.12]

where

$$\varepsilon(t) = \text{time dependent strain}$$

$$\dot{\sigma}(t') = \frac{d\sigma(t')}{dt'}$$

$$J(t-t') = \text{creep compliance}$$

The two characteristic functions, creep compliance $J(t)$ and relaxation modulus $E(t)$, are not independent each other and are related as follows:

$$\int_{0}^{t} E(t') \cdot J(t-t')dt' = t$$ \hspace{1cm} [2.13]

Using Laplace transformation Equation [2.13] becomes:
\[ \bar{E}(s) \cdot \bar{J}(s) = \frac{1}{s^2} \]  

[2.14]

In many situations, the expressions for \( E(t) \) and \( J(t) \) cannot be manipulated in Laplace space. A simple numerical algorithm developed by Hopkins and Hamming (1957) has been extensively used to compute \( E(t) \) from \( J(t) \) and vice versa. This procedure was also used in the past to count BBR creep compliance to relaxation modulus (Basu, A, 2002). The steps in this procedure are as follows:

1. First, the time interval \( t_n \) is selected:
\[ t_0 = 0, t_1 = 1, t_2 = 2, \cdots t_{1000} = 1000 \]  

[2.15]

2. Creep compliance \( J(t_n) \) is calculated from creep stiffness \( S(t_n) \) as:
\[ J(t_n) = \frac{1}{S(t_n)} \]  

[2.16]

3. The integral of \( J(t) \) is defined as:
\[ f(t) = \int_0^t J(t) \, dt \]  

[2.17]

4. From equation [2.17], \( f(t) \) is calculated with trapezoidal rule for integration:
\[ f(t_{n+1}) = f(t_n) + \frac{1}{2} \cdot (J(t_{n+1}) + J(t_n)) \cdot (t_{n+1} - t_n) \]  

[2.18]

5. Equation [2.13] can be modified using equation [2.18] to obtain:
\[ t_{n+1} = \int_0^{t_{n+1}} E(t') \cdot J(t_{n+1} - t') \, dt' = \sum_{i=0}^{n} \int_{t_i}^{t_{i+1}} E(t') \cdot J(t_{n+1} - t') \, dt' \]  

[2.19]
6. From equation [2.19] each element of integral can be approximated as follows:

\[
\int_{t_i}^{t_{i+1}} E(t') \cdot J(t_{n+1} - t') dt' = -E(t_{i+1/2}) \cdot [f(t_{n+1} - t_{i+1}) - f(t_{n+1} - t_i)]
\]

[2.20]

where

\[
t_{i+1/2} = \frac{1}{2} (t_{i+1} + t_i)
\]

[2.21]

7. Equation [2.19] can be written as:

\[
t_{n+1} = -\sum_{i=0}^{n-1} E(t_{i+1/2}) \cdot [f(t_{n+1} - t_{i+1}) - f(t_{n+1} - t_i)] + E(t_{n+1/2}) \cdot f(t_{n+1} - t_n)
\]

[2.22]

8. Solving for \(E(t_{n+1/2})\), equation [2.22] becomes:

\[
E(t_{n+1/2}) = \frac{t_{n+1} - \sum_{i=0}^{n-1} E(t_{i+1/2}) \cdot [f(t_{n+1} - t_i) - f(t_{n+1} - t_{i+1})]}{f(t_{n+1} - t_n)}
\]

\[
= \frac{t_{n+1} - \sum_{i=0}^{n-1} E(t_{i+1/2}) \cdot [f(t_{i+1}) - f(t_i)]}{f(t_{n+1}) - f(t_n)}
\]

[2.23]

where, \(f(t_0) = 0;\)

\[E(t_0) = 0;\]

\[E(t_i) = \frac{t_i}{f(t_i)}\]

In this thesis, the procedure described above was used to correct BBR and IDT creep compliance to relaxation modulus.
2.4 Thermal stress calculation

Thermal stress that develops as the temperature drops in a restrained uniaxial viscoelastic beam can be calculated using Equation [2.11]. Taking into consideration that the strain is expressed as:

\[ \varepsilon = \alpha \cdot \Delta T \]  

where\[ \alpha = \text{coefficient of thermal expansion or contraction;} \]
\[ \Delta T = \text{temperature change} \]

and that the reduced time (\(\zeta\)) expressed as:

\[ \zeta = \frac{t}{a_T} \]  

where\[ t = \text{time, sec;} \]
\[ a_T = \text{shift factor} \]

is used to obtain relaxation modulus values at temperatures other than the test temperatures based on time temperature superposition, then equation [2.11] can be written as:

\[ \sigma(\zeta) = \int_{-\infty}^{\zeta} \frac{d\varepsilon(\zeta')}{d\zeta'} \cdot E(\zeta - \zeta')d\zeta' = \int_{-\infty}^{\zeta} \left( \frac{d(\alpha\Delta T)}{dt'} \right) \cdot E(\zeta(t) - \zeta'(t))dt' \]  

where

\[ E(\zeta - \zeta') = \text{relaxation modulus;} \]
\[ \varepsilon(\zeta') = \text{strain} \]
In this thesis, the following procedure was used to solve this equation and calculate thermal stresses.

1. Creep compliance is obtained from BBR and IDT experiments as previously described.

2. Relaxation modulus $E(t)$ is then calculated from BBR and IDT creep compliance $J(t)$ using Hopkins and Hamming algorithm (1957) as described by Equations [2.13] to [2.23].

3. Relaxation modulus $E(t)$ master curve is obtained using CAM model (Marasteanu and Anderson, 1996):

$$E(t) = E_g \cdot \left[1 + \left(\frac{t}{t_c}\right)^v\right]^{-w/v} \quad [2.27]$$

where

$$E_g = \text{Glassy modulus (assumed = 3GPa)};$$

$$t_c, v \text{ and } w = \text{parameters in the model}$$

The shift factor expression is:

$$a_T = 10^{C_1 + C_2 T} \quad [2.28]$$

where

$$C_1 \text{ and } C_2 = \text{parameters};$$

$$T = \text{reference temperature, } ^\circ\text{C}$$

4. The one dimensional hereditary integral equation (Equation [2.26]) is solved numerically using Gaussian quadrature with 24 Gauss points as described by Basu (2002).
5. If BBR binder creep data is used, to obtain mixture stress the values obtained from Equation [2.24] are multiplied by the empirical Pavement Constant (PC=18) prepared by Bouldin et al. (2000). If BBR mixture or IDT mixture data is used, then thermal stresses are calculated directly from Equation [2.24].

2.5 Critical cracking temperature $T_{CR}$

Thermal stresses can be further used to determine critical cracking temperature, $T_{CR}$. Two methods are commonly used.

2.5.1 Dual Instrument Method (DIM)

In this method, results from both BBR and DT tests are required. Critical temperature $T_{CR}$ is obtained at the intersection of thermal stress curve with the strength master curve as shown in Figure 2.6. In this thesis, no strength tests were performed.

![Figure 2.6 Dual Instrument Method (DIM)](image)

Figure 2.6 Dual Instrument Method (DIM)
2.5.2 Single Asymptote Procedure (SAP) method

In this method, no strength data is required (Shenoy, 2002). A line is fitted to the lowest temperature part of the thermal stress curve and the intersection with the temperature axis represents $T_{CR}$, as shown in Figure 2.7.

In this thesis, thermal stresses were calculated from 22°C to -40°C in 0.5°C temperature decrements. The single asymptote line was fitted to the two final points of the thermal stress curve:

Point 1: $(x_{i-1}, y_{i-1}) = (-39.5°C, \sigma(-39.5°C))$ and

Point 2: $(x_i, y_i) = (-40.0°C, \sigma(-40.0°C))$ [2.29]

Figure 2.7 Single Asymptote Procedure (SAP) method
2.6 Physical hardening effect

Physical aging is a time and temperature dependent, thermo reversible phenomenon which produces significant changes in physical properties of amorphous materials, especially in relaxation characteristics, at temperatures near the glass transition temperature $T_g$. Struik (1978) showed that this phenomenon also occurs in glassy materials such as bitumen, shellac and amorphous sugar.

Extensive research on physical aging effect on asphalt binder was performed during the Strategic Highway Research Program (SHRP) (Anderson et. al, 1994, Bahia, 1993). In their experiments, researchers have observed a significant increase in the BBR creep stiffness of asphalt binders with increase in the isothermal storage time at temperature above the $T_g$ of the binders. Physical aging was called physical hardening by the SHRP researchers to emphasize the thermo reversible effect (Anderson, 1994).

Basu et.al (2003) evaluated the validity of the assumption used to determine PG lower limit that 2h of loading at $T_1-10^\circ$C is equivalent to 60s of loading at $T_1$ for different storage times. They found significant differences for the test data obtained from testing specimens conditioned for 1h at the test temperature. They found less significant differences for specimens conditioned for 3 days due to physical hardening effects.
Chapter III

Experimental Work

3.1 Materials

The experimental data used in the analyses was obtained from BBR creep tests on asphalt binders and mixtures, and from IDT creep tests on asphalt mixtures. The asphalt materials tested represent materials used in the reconstruction of various experimental cells at MnRoad. Additional information is available elsewhere (Johnson, A. et al, 2009). Tables 3.1 and 3.2 describe the mixtures and binders tested.

Table 3.1 Summary of tested mixtures

<table>
<thead>
<tr>
<th>No</th>
<th>Cell Number</th>
<th>Mixture ID</th>
<th>Mixture Type</th>
<th>Binder Grade</th>
<th>RAP content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>A</td>
<td>NOVACHIP</td>
<td>PG 78-28</td>
<td>None</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>B</td>
<td>SPWEB440F</td>
<td>PG 64-34</td>
<td>None</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>D</td>
<td>SPWEB440F (S)</td>
<td>PG 64-34</td>
<td>None</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>E</td>
<td>SPWEB440C (S)</td>
<td>PG 58-34WMA*</td>
<td>Up to 20%</td>
</tr>
<tr>
<td>5</td>
<td>16</td>
<td>F</td>
<td>SPWEB430C (S)</td>
<td>PG 58-34WMA*</td>
<td>Up to 20%</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>G</td>
<td>SPNW430B</td>
<td>PG 58-28</td>
<td>30% non fractioned</td>
</tr>
<tr>
<td>7</td>
<td>21</td>
<td>H</td>
<td>SPNW430B (S)</td>
<td>PG 58-28</td>
<td>30% fractioned</td>
</tr>
<tr>
<td>8</td>
<td>22</td>
<td>I</td>
<td>SPNW430C (S1)</td>
<td>PG 58-34</td>
<td>30% fractioned</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>K</td>
<td>SPWEB400B(1)</td>
<td>PG 58-28</td>
<td>5% shingles(¨w)</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>L</td>
<td>SPWEB440C</td>
<td>PG 58-34</td>
<td>Up to 20%</td>
</tr>
<tr>
<td>11</td>
<td>15,17,21</td>
<td>M</td>
<td>SPWEB400B</td>
<td>PG 58-28</td>
<td>5% shingles(¨t)</td>
</tr>
</tbody>
</table>

WMA: Warm mix asphalt
*¨w: Manufactured wasted shingles
*¨t: Manufactured tear off shingles
Table 3.2 Summary of tested binders

<table>
<thead>
<tr>
<th>Binder ID</th>
<th>Grade</th>
<th>Mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PG 58-28</td>
<td>G, H, K, M</td>
</tr>
<tr>
<td>2</td>
<td>PG 58-34</td>
<td>I, L</td>
</tr>
<tr>
<td>3</td>
<td>PG 58-34WMA</td>
<td>E, F</td>
</tr>
<tr>
<td>4</td>
<td>PG 64-34</td>
<td>B, D, J</td>
</tr>
<tr>
<td>5</td>
<td>PG 70-28</td>
<td>A</td>
</tr>
</tbody>
</table>

3.2 Test methods

3.2.1 Bending Beam Rheometer (BBR) creep test for asphalt binders

BBR creep tests for asphalt binders were performed according to ASSHTO T 313-02 with 100g applied load and 240s of test time. Tests were performed at two temperatures: (PG+10°C) and (PG+10°C) – 6°C. All specimens were conditioned isothermally for 1 hour before testing. A summary of BBR binder testing is given in Table 3.3.

Table 3.3 Summary of BBR binder testing

<table>
<thead>
<tr>
<th>Binder ID</th>
<th>Binder Grade</th>
<th>Temperature (°C)</th>
<th>Number of Specimens at each temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PG 58-28</td>
<td>-18,-24</td>
<td>2 (-18), 1 (-24)</td>
</tr>
<tr>
<td>2</td>
<td>PG 58-34</td>
<td>-24,-30</td>
<td>1 (-24), 1 (-30)</td>
</tr>
<tr>
<td>3</td>
<td>PG 58-34WMA</td>
<td>-24,-30</td>
<td>1 (-24), 1 (-30)</td>
</tr>
<tr>
<td>4</td>
<td>PG 64-34</td>
<td>-24,-30</td>
<td>1 (-24), 3 (-30)</td>
</tr>
<tr>
<td>5</td>
<td>PG 70-28</td>
<td>-18,-24</td>
<td>3 (-18), 2 (-24)</td>
</tr>
</tbody>
</table>

3.2.2 Bending Beam Rheometer (BBR) creep test for asphalt mixture

BBR creep tests for asphalt mixtures were performed according to the method described elsewhere (Marasteanu. et al, 2008). In this test, time was 1000s rather than 240s, to match the loading time used in IDT mixture testing. The same testing equipment used in binder testing was used; however, the loads applied were higher, since mixtures are one
order of magnitude stiffer than binders, see Table 3.4.

Table 3.4 Applied constant loads for 1000 seconds in BBR mixture test

<table>
<thead>
<tr>
<th>SN (BBR mixture)</th>
<th>Temperature, °C</th>
<th>Applied load (mN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PG+10+12</td>
<td>PG+10</td>
</tr>
<tr>
<td>A, G, H, L, M</td>
<td>-6</td>
<td>-18</td>
</tr>
<tr>
<td>B, F, I</td>
<td>-12</td>
<td>-24</td>
</tr>
<tr>
<td>D, E (1&amp;24 hours)</td>
<td>-24</td>
<td>-36</td>
</tr>
<tr>
<td>K (1&amp;24 hours)</td>
<td>-18</td>
<td>-30</td>
</tr>
</tbody>
</table>

BBR mixture creep tests were performed at three temperatures: (PG+10°C) – 12°C, (PG+10°C), and (PG+10°C) + 12°C. Similar to binder testing, specimens were conditioned at the test temperature for 1 hour prior to testing. Physical hardening effects on asphalt mixture creep compliance were also considered for three mixtures: D, E and K. Six specimens were tested after 1 hour of isothermal conditioning, and nine specimens were tested after 24 hours of isothermal conditioning. A summary of BBR mixture creep testing is given in Table 3.5.

Table 3.5 Summary of BBR mixture creep tests

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Temperature (°C)</th>
<th>Number of Specimens</th>
<th>Physical Hardening</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-6,-18,-30</td>
<td>3 (-6), 3 (-18), 3 (-30)</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>-12,-24,-36</td>
<td>3 (-12), 3 (-24), 3 (-36)</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>-24,-36</td>
<td>6 (-24), 9 (-36)</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>-24,-36</td>
<td>6 (-24), 9 (-36)</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>-12,-24,-36</td>
<td>3 (-12), 3 (-24), 3 (-36)</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>-6,-18,-30</td>
<td>3 (-6), 3 (-18), 3 (-30)</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>-6,-18,-30</td>
<td>3 (-6), 3 (-18), 3 (-30)</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>-12,-24,-36</td>
<td>3 (-12), 3 (-24), 3 (-36)</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>-18,-30</td>
<td>6 (-18), 9 (-30)</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>-6,-18,-30</td>
<td>3 (-6), 3 (-18), 3 (-30)</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>-6,-18,-30</td>
<td>3 (-6), 3 (-18), 3 (-30)</td>
<td></td>
</tr>
</tbody>
</table>
3.2.3 *Indirect Tensile (IDT) creep test for asphalt mixtures*

IDT creep tests were performed according to AASHTO T 322-03. Table 3.6 summarizes the IDT mixture testing.

**Table 3.6 Summary of IDT mixture testing**

<table>
<thead>
<tr>
<th>Mixture</th>
<th>PG Grade</th>
<th>Temperature (°C)</th>
<th>Number of Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>PG-70-28</td>
<td>-6,-18,-30</td>
<td>3 at each temperature</td>
</tr>
<tr>
<td>B</td>
<td>PG-64-34</td>
<td>-12,-24,-36</td>
<td>3 at each temperature</td>
</tr>
<tr>
<td>D</td>
<td>PG-64-34</td>
<td>-12,-24,-36</td>
<td>3 at each temperature</td>
</tr>
<tr>
<td>E</td>
<td>PG-58-34WMA</td>
<td>-12,-24,-36</td>
<td>3 at each temperature</td>
</tr>
<tr>
<td>F</td>
<td>PG-58-34WMA</td>
<td>-12,-24,-36</td>
<td>3 at each temperature</td>
</tr>
<tr>
<td>G</td>
<td>PG-58-28</td>
<td>-6,-18,-30</td>
<td>3 at each temperature</td>
</tr>
<tr>
<td>H</td>
<td>PG-58-28</td>
<td>-6,-18,-30</td>
<td>3 at each temperature</td>
</tr>
<tr>
<td>I</td>
<td>PG-58-34</td>
<td>-12,-24,-36</td>
<td>3 at each temperature</td>
</tr>
<tr>
<td>K</td>
<td>PG-58-28</td>
<td>-6,-18,-30</td>
<td>3 at each temperature</td>
</tr>
<tr>
<td>L</td>
<td>PG-58-34</td>
<td>-12,-24,-36</td>
<td>3 at each temperature</td>
</tr>
<tr>
<td>M</td>
<td>PG-58-28</td>
<td>-6,-18,-30</td>
<td>3 at each temperature</td>
</tr>
</tbody>
</table>
Chapter IV

Data Analysis and Comparison

To investigate the effect of the test method on the material parameters used to evaluate asphalt mixture low temperature behavior, the following analyses were performed on the results obtained in the experimental plan described in Chapter 3.

1. Compare creep stiffness $S(t)$ and m-value $m(t)$ obtained from BBR and IDT mixture creep tests
2. Compare relaxation modulus $E(t)$ calculated from BBR and IDT mixture creep test results
3. Compare thermal stresses $\sigma(t)$ calculated from BBR binder, BBR mixture, and IDT mixture creep test results, respectively
4. Compare thermal stress values at PG, PG+10°C, and critical cracking temperature $T_{CR}$
5. Compare thermal stress $\sigma(t)$ calculated using different combinations of test temperatures and shift factors and BBR and IDT mixture creep compliance test results, respectively
6. Evaluate physical hardening effects on thermal stresses $\sigma(t)$ for three mixtures using BBR mixture creep test results

4.1 Comparison of creep stiffness $S(t)$ and m-value $m(t)$ obtained from BBR and IDT mixture creep tests

A simple hypothesis testing method was used to check if the creep stiffness $S(t)$ values
obtained from BBR mixture testing are same with the $S(t)$ obtained from IDT mixture testing. The comparison was performed for time values $t$ from 10s to 1000s, in equal intervals of 10s. Creep stiffness $S(t)$ was obtained as described in Chapter 2. The BBR and IDT test methods are different and are independent of each other. Statistically, two assumptions were made in this hypothesis testing procedure:

1. Each result of each test method follows normal distribution.
2. Each result of each test method has the same standard deviation.

The hypothesis was set as follows:

Null hypothesis: $H_0 : \mu_{BBR,S(t)} = \mu_{IDT,S(t)}$  \[4.1\]

Alternative hypothesis: $H_a : \mu_{BBR,S(t)} \neq \mu_{IDT,S(t)}$  \[4.2\]

where

$\mu_{BBR,S(t)} = \text{Mean of creep stiffness from BBR mixture test}$

$\mu_{IDT,S(t)} = \text{Mean of creep stiffness from IDT mixture test}$

The pooled standard deviation can be computed as follows:

$$S_{P,S(t)} = \sqrt{\frac{(n_{BBR} - 1) \cdot S_{BBR,S(t)}^2 + (n_{IDT} - 1) \cdot S_{IDT,S(t)}^2}{n_{BBR} - n_{IDT} - 2}}$$  \[4.3\]

where

$S_{BBR,S(t)} = \text{Standard deviation of creep stiffness } S(t) \text{ from BBR mixture test}$

$S_{IDT,S(t)} = \text{Standard deviation of creep stiffness } S(t) \text{ from IDT mixture test}$

$n_{BBR} = \text{Number of specimens used in BBR mixture test}$

$n_{IDT} = \text{Number of specimens used in IDT mixture test}$
Using Equation [4.3], t-statistic at any time \( t \) can be computed as:

\[
t_{S(t)} = \frac{\mu_{BBR,S(t)} - \mu_{IDT,S(t)}}{S_{P,S(t)} \sqrt{\frac{1}{n_{BBR}} + \frac{1}{n_{IDT}}}}
\]  

[4.4]

The degrees of freedom in this hypothesis test are calculated as follows:

\[
df = n_{BBR} + n_{IDT} - 2
\]  

[4.5]

A similar approach is taken to compare the m-value \( m(t) \) from BBR mixture and IDT mixture tests. The hypothesis test was set as follows:

**Null hypothesis:** \( H_0 : \mu_{BBR,m(t)} = \mu_{IDT,m(t)} \)  

[4.6]

**Alternative hypothesis:** \( H_a : \mu_{BBR,m(t)} \neq \mu_{IDT,m(t)} \)  

[4.7]

where

\[
\mu_{BBR,m(t)} = \text{Mean of } m(t) \text{ from BBR mixture test}
\]

\[
\mu_{IDT,m(t)} = \text{Mean of } m(t) \text{ from IDT mixture test}
\]

\[
S_{P} = \sqrt{\frac{(n_{BBR} - 1) \cdot S_{BBR,m(t)}^2 + (n_{IDT} - 1) \cdot S_{IDT,m(t)}^2}{n_{BBR} - n_{IDT} - 2}}
\]  

[4.8]

where

\[
S_{BBR,m(t)} = \text{Standard deviation of } m(t) \text{ from BBR mixture test}
\]

\[
S_{IDT,m(t)} = \text{Standard deviation of } m(t) \text{ from IDT mixture test}
\]

\[
n_{BBR} = \text{Number of specimens used in BBR mixture test}
\]

\[
n_{IDT} = \text{Number of specimens used in IDT mixture test}
\]
\[ t_{m(t)} = \frac{\mu_{BBR,m(t)} - \mu_{IDT,m(t)}}{S_p \cdot \sqrt{\frac{1}{n_{BBR}} + \frac{1}{n_{IDT}}}} \]  
\[ df = n_{BBR} + n_{IDT} - 2 \]

T-statistic of creep stiffness \( S(t) \) and \( m \)-value \( m(t) \) were calculated every 10 seconds for 1000 seconds.

In generating \( t \)-critical for \( \alpha = 0.05 \) (5\% of error), three specimens were used for each test temperature condition (PG+10, PG+10-12 and PG+10+12) in BBR mixture and IDT mixture testing. Therefore, \( t \)-critical can be computed as:

\[ t_{df=3+3-2=4,0.025,\text{two-tails}} = \pm 2.77645 \approx \pm 2.7 \]

For some mixtures, \( S(t) \) and \( m \)-values \( m(t) \) obtained at the lowest test temperature (PG+10-12) showed abnormal variation with loading time \( t \) and were not considered in the analysis. Therefore, \( t \)-critical in these cases were computed using Equation [4.11] and lower degrees of freedom. For mixtures D, E and K, a larger number of specimens were tested which resulted higher degrees of freedom. For the same mixtures, BBR testing was performed only at two temperatures. Therefore, no hypothesis test was performed at PG+10+12. Table 4.1 summarizes \( t \)-critical values for each mixture used in the hypothesis test. The creep stiffness \( S(t) \) and \( m \)-value \( m(t) \) t-static plots for each mixture are shown in Figure 4.1 to 4.11. If the t-statistic plot is located in \( t \)-critical range, the null hypothesis is accepted (Equation [4.1] and [4.6], respectively); otherwise, the null hypothesis is rejected.
Table 4.1 T-critical values used in hypothesis test

<table>
<thead>
<tr>
<th>Mixture</th>
<th>t-critical, $\alpha = 0.05$ (5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PG+10+12</td>
</tr>
<tr>
<td></td>
<td>df</td>
</tr>
<tr>
<td>A</td>
<td>4</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
</tr>
<tr>
<td>D</td>
<td>7</td>
</tr>
<tr>
<td>E</td>
<td>7</td>
</tr>
<tr>
<td>F</td>
<td>4</td>
</tr>
<tr>
<td>G</td>
<td>4</td>
</tr>
<tr>
<td>H</td>
<td>4</td>
</tr>
<tr>
<td>I</td>
<td>4</td>
</tr>
<tr>
<td>K</td>
<td>7</td>
</tr>
<tr>
<td>L</td>
<td>4</td>
</tr>
<tr>
<td>M</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 4.1 Hypothesis test results for $S(t)$ and $m(t)$, mixture A
**Figure 4.2 Hypothesis test results for S(t) and m(t), mixture B**

**Figure 4.3 Hypothesis test results for S(t) and m(t), mixture D**

**Figure 4.4 Hypothesis test results for S(t) and m(t), mixture E**
Figure 4.5 Hypothesis test results for S(t) and m(t), mixture F

Figure 4.6 Hypothesis test results for S(t) and m(t), mixture G

Figure 4.7 Hypothesis test results for S(t) and m(t), mixture H

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Figure 4.8 Hypothesis test results for \(S(t)\) and \(m(t)\), mixture I

Figure 4.9 Hypothesis test results for \(S(t)\) and \(m(t)\), mixture K

Figure 4.10 Hypothesis test results for \(S(t)\) and \(m(t)\), mixture L
The summary of the results of hypothesis testing is given in Table 4.2 and Table 4.3. At PG+10+12, significant $S(t)$ differences were found for mixtures A, H and I. At PG+10, significant $S(t)$ differences were found for mixtures B, D and I. At PG+10-12, mixtures D, E, F and L were found with significant differences. For $m(t)$, the findings are very different and a clear dependence on the test temperature is observed. At the lowest test temperature PG+10-12, significant differences were found for all mixtures. At the intermediate temperature PG+10, significant differences were found for six of the eleven mixtures, while for the highest test temperatures, differences were found for only two mixtures.
Table 4.2 Summary of hypothesis test for creep stiffness $S(t)$

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Time (sec), $S(t)$, PG+10+12</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td>A</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Time (sec), $S(t)$, PG+10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td>A</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td></td>
</tr>
<tr>
<td>L</td>
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Gray box: significant difference, White box: no significant difference
Table 4.3 Summary of hypothesis test for m-value m(t)

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<td>M</td>
<td></td>
</tr>
</tbody>
</table>

Gray box: significant difference, White box: no significant difference

32
4.2 Comparison of relaxation modulus $E(t)$ calculated from BBR and IDT mixture creep compliance data

Relaxation modulus $E(t)$ was calculated from the creep compliance $J(t)$ experimental data using the method described in the literature review. In the CAM model, the glassy modulus $E_g$, was assumed equal to 30 GPa. The three parameters, cross over time $t_c$ and shape parameters $v$ and $w$, were obtained as part of the fitting procedure. The Time Temperature Superposition (TTS) principle was used with the data obtained at the three test temperatures and relaxation modulus $E(t)$ master curves were generated by shifting the lowest temperature data, and the highest temperature data, respectively to the intermediate temperature data kept as reference. Note that for this particular analysis, the shifting was done on the average relaxation modulus $E(t)$ values.

Two shift factors were obtained:

$$\log(a_{c1}) = c_1 + c_2 \cdot T$$ : shift factor between high (PG+10+12) and intermediate (reference, PG+10) temperature \[4.12\]

$$\log(a_{c2}) = c_3 + c_4 \cdot T$$ : shift factor between low (PG+10+12) and intermediate (reference, PG+10) temperature \[4.13\]

The shift factor values are shown in Table 4.4.

Because of the different time values for the $E(t)$ master curve generated from BBR and IDT test, respectively, only simple graphical comparisons were done. These comparisons are shown in Figures 4.12 to 4.17. For mixtures D, E and K, only two different temperature conditions were tested in BBR, which explains the shorter time range of the BBR master curves.
<table>
<thead>
<tr>
<th>Mixture ID</th>
<th>Reference Temperature</th>
<th>BBR mixture</th>
<th>IDT mixture</th>
</tr>
</thead>
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<tr>
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<td>-18</td>
<td>2.342</td>
<td>-2.138</td>
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<tr>
<td>B</td>
<td>-24</td>
<td>2.098</td>
<td>-1.461</td>
</tr>
<tr>
<td>D</td>
<td>-24</td>
<td>1.948</td>
<td>2.064</td>
</tr>
<tr>
<td>E</td>
<td>-24</td>
<td>1.156</td>
<td>2.463</td>
</tr>
<tr>
<td>F</td>
<td>-24</td>
<td>2.412</td>
<td>-1.158</td>
</tr>
<tr>
<td>G</td>
<td>-18</td>
<td>1.828</td>
<td>-1.973</td>
</tr>
<tr>
<td>H</td>
<td>-18</td>
<td>1.914</td>
<td>-1.618</td>
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<tr>
<td>I</td>
<td>-24</td>
<td>1.520</td>
<td>-1.424</td>
</tr>
<tr>
<td>K</td>
<td>-18</td>
<td>1.586</td>
<td>2.032</td>
</tr>
<tr>
<td>L</td>
<td>-18</td>
<td>1.822</td>
<td>-2.073</td>
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<tr>
<td>M</td>
<td>-18</td>
<td>1.857</td>
<td>-2.240</td>
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</tbody>
</table>

Figure 4.12 Relaxation modulus $E(t)$ master curves, mixture A and mixture B
Figure 4.13 Relaxation modulus $E(t)$ master curves, mixture D and mixture E

Figure 4.14 Relaxation modulus $E(t)$ master curves, mixture F and mixture G

Figure 4.15 Relaxation modulus $E(t)$ master curves, mixture H and mixture I
It is observed that for mixtures F, G, H, I and M almost identical master curves are observed from BBR and IDT data. Differences are observed for mixtures A, B, E and L and significant differences are observed for mixtures D and K.

4.3 Comparison of thermal stresses $\sigma(t)$ calculated from BBR binder, BBR mixture and IDT mixture creep tests, respectively

Using the relaxation modulus $E(t)$ data obtained in section 4.2, thermal stresses $\sigma(t)$ were calculated using the approach described in Chapter 2. Two cooling rates, 1°C/hour (1d/h) and 10°C/hour 10(d/h) were used. A constant coefficient of thermal contraction
\( \alpha = 30.28 \times 10^{-6} \) was assumed for all mixtures (Marasrteanu et. al, 2007). First, a graphical comparison was performed. Since for practical reason, tests are performed at only two temperatures, it was decided to generate two different thermal stresses: one based on the data obtained at low and intermediate temperature, and one based on the data obtained at intermediate and high temperature. First, thermal stresses obtained from averaged from BBR mixture and IDT mixture testing were compared. Then thermal stresses obtained from mixture IDT data were compared to thermal stresses obtained from BBR binder data and the empirical “pavement constant” or PC described in Chapter 2 and 3. A statistical comparison then performed between the thermal stresses obtained from BBR mixture and IDT mixture data based on the individual test results for each replicate rather than the average of the test replicates.

4.3.1 Graphical comparison of thermal stresses obtained from BBR mixture and IDT mixture test

For the graphical comparison method, thermal stresses \( \sigma(t) \) were computed from averaged relaxation modulus \( E(t) \) at each temperature (PG+10-12, PG+10 and PG+10+12). Figure 4.18 shows a schematic of the computation process of thermal stresses \( \sigma(t) \). For three mixtures, D, E and K, tests were performed at two temperatures, and only thermal stresses \( \sigma(t) \) with second shift factor \( (a_t^2) \) were compared. Plots of the thermal stresses are show in Figures 4.19 to 4.29.
Figure 4.18 Thermal stress comparison process for graphical comparison

Figure 4.19 Thermal stress comparison, mixture A
Figure 4.20. Thermal stress comparison, mixture B

Figure 4.21. Thermal stress comparison, mixture D

Figure 4.22 Thermal stress comparison, mixture E
Figure 4.23 Thermal stress comparison, mixture F

Figure 4.24 Thermal stress comparison, mixture G

Figure 4.25 Thermal stress comparison, mixture H
Figure 4.26 Thermal stress comparison, mixture I

Figure 4.27 Thermal stress comparison, mixture K

Figure 4.28 Thermal stress comparison, mixture L
For mixtures A, F, L and M, almost identical results of thermal stresses were found from BBR and IDT mixture test. For mixtures B and G and shift factor $a_{T1}$, similar results of thermal stresses were found; however, for shift factor $a_{T2}$, some differences were found between BBR and IDT thermal stresses. Significant differences of thermal stresses were found in mixtures H and I even though no significant differences were found when comparing relaxation modulus master curves. For mixture D, E and K partial differences were found. Similar to the comparison for relaxation modulus master curve, similar BBR and IDT thermal stresses were obtained for mixtures A, B, D, E, F, G, K, L and M. However, different results were observed when comparing relaxation modulus master curves and thermals stresses for mixtures H and I.

### 4.3.2 Graphical comparison of thermal stresses obtained from BBR binder and IDT mixture creep tests

In a recent AASHTO specification (MP1a), asphalt mixture thermal stresses were calculated from asphalt binder thermal stresses multiplied by an empirical Pavement
Constant (PC) equal to 18. A significant drawback of using the PC method is the fact that it cannot explain the difference in thermal stresses for mixtures that contain the same type of asphalt binder but different type of aggregates. Figures 4.32 to 4.37 show the plots for the thermal stresses from IDT mixture and BBR binder data. Significant differences are observed between the thermal stresses obtained with the two methods, which suggests that the PC method (BBR binder test) should not be used to predict thermal stresses $\sigma(t)$ of asphalt mixtures.

**Figure 4.30 Thermal stress plots for mixtures A and B**

**Figure 4.31 Thermal stress plots for mixtures D and E**
Figure 4.32 Thermal stress plots for mixtures F and G

Figure 4.33 Thermal stress plots for mixtures H and I

Figure 4.34 Thermal stress plots for mixtures K and L
4.3.3 Statistical analysis

To better evaluate the difference between the thermal stresses $\sigma(t)$ calculated from the mixture BBR and mixture IDT experiments, hypothesis testing was performed in this section. The computation process of thermal stresses is shown in Figure 4.36. The process is similar to the computation process shown in Section 4.1. However, in this procedure, relaxation modulus $E(t)$ at each temperature condition was not averaged but combined randomly into three different relaxation moduli $E(t)$ to generate six different thermal stress $\sigma(t)$ data sets. Six different shift factors $a_t$ were calculated from relaxation modulus $E(t)$ master curves and, finally, six thermal stresses were generated (three thermal stress curves using shift factor $a_{t1}$ and three thermal stress curves using shift factor $a_{t2}$). For example, in Figure 4.36 thermal stress 1 and thermal stresses 4 were calculated from the same combination of relaxation moduli but using different shift factors, $a_{t1}$ and $a_{t2}$, respectively. Also thermal stress 2 and 5, and thermal stress 3 and 6, were calculated from the same combination of relaxation moduli but using different shift factors, $a_{t1}$ and $a_{t2}$, respectively.
Figure 4.36 Process of generating thermal stresses $\sigma(t)$ for hypothesis testing
The hypothesis test was constructed similarly to the previous section:

Null hypothesis: \[ H_0 : \mu_{BBR}(t) = \mu_{IDT}(t) \] [4.14]

Alternative hypothesis: \[ H_a : \mu_{BBR}(t) \neq \mu_{IDT}(t) \] [4.15]

where

\[ \mu_{BBR}(t) = \text{Mean of thermal stress from BBR mixture test at time } t \]

\[ \mu_{IDT}(t) = \text{Mean of thermal stress from IDT test at time } t \]

\[ S_p(t) = \sqrt{\frac{(n_{BBR}-1) \cdot S_{BBR}^2(t) + (n_{IDT}-1) \cdot S_{IDT}^2(t)}{n_{BBR} - n_{IDT} - 2}} \] [4.16]

where

\[ S_{BBR}(t) = \text{Standard deviation of thermal stress from BBR mixture test at time } t \]

\[ S_{IDT}(t) = \text{Standard deviation of thermal stress from IDT test at time } t \]

\[ n_{BBR} = \text{Number of specimen used in BBR mixture test} \]

\[ n_{IDT} = \text{Number of specimen used in IDT test} \]

\[ t = \frac{\mu_{BBR}(t) - \mu_{IDT}(t)}{S_p(t) \cdot \sqrt{\frac{1}{n_{BBR}} + \frac{1}{n_{IDT}}}} \] [4.17]

\[ df = n_{BBR} + n_{IDT} - 2 \] [4.18]

T-statistic values were calculated every 0.5°C from 22°C to -40°C. Except mixtures D, E and K, three specimens were used at each temperature, and therefore, a total of nine specimens were used for one mixture test. For \( \alpha = 0.05 \) (5% of error), t-critical was calculated as follows:

\[ t(df_{n_1+n_2-2} = df_{3+3-2}, p = \pm 0.025) = \pm 2.77645 \leq \pm 2.7 \] [4.19]
For mixture D, E and K, only two temperature conditions were used for BBR testing: PG+10°C-12 and PG+10°C. Therefore, the analysis was performed only for shift factor \( a_2 \). Values of t-critical and degrees of freedom were calculated as:

\[
 df = n_{BBR} + n_{IDT} - 2 = 6 + 3 - 2 = 7 \tag{4.20}
\]

\[
 t(df_{n1+n2-2} = df_{6+3-2}, p = \pm 0.025) = \pm 2.362 \cong \pm 2.4 \tag{4.21}
\]

The results are plotted in Figures 4.37 to 4.47. If the t-statistic plot is positioned in the range of t-critical, the null hypothesis (Equation 4.14) is accepted. If t-statistic is outside of t-critical, the null hypothesis is rejected.

**Figure 4.37 Hypothesis test for mix BBR and mix IDT thermal stress, mixture A**

**Figure 4.38 Hypothesis test for mix BBR and mix IDT thermal stress, mixture B**
Figure 4.39 Hypothesis test for mix BBR and mix IDT thermal stress, mixture D

Figure 4.40 Hypothesis test for mix BBR and mix IDT thermal stress, mixture E

Figure 4.41 Hypothesis test for mix BBR and mix IDT thermal stress, mixture F
Figure 4.42 Hypothesis test for mix BBR and mix IDT thermal stress, mixture G

Figure 4.43 Hypothesis test for mix BBR and mix IDT thermal stress, mixture H

Figure 4.44 Hypothesis test for mix BBR and mix IDT thermal stress, mixture I
Figure 4.45 Hypothesis test for mix BBR and mix IDT thermal stress, mixture K

Figure 4.46 Hypothesis test for mix BBR and mix IDT thermal stress, mixture L

Figure 4.47 Hypothesis test for mix BBR and mix IDT thermal stress, mixture M

Similar to section 4.1, the summary of the results of hypothesis testing is given in Tables 4.5 and 4.6.
Table 4.5 Summary of hypothesis test for thermal stress comparison (1d/h)

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<th>Thermal stress $\sigma(t)$, shift factor $a_{11}$, 1d/h</th>
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<td>Temp 22 18 14 10 6 2 -2 -6 -10 -14 -18 -22 -26 -30 -34 -36 -38 -40</td>
</tr>
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</tr>
<tr>
<td>B</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>Gray box</td>
</tr>
<tr>
<td>I</td>
<td></td>
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<td>L</td>
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Gray box: significant difference, White box: no significant difference
Table 4.6 Summary of hypothesis test for thermal stress comparison (10d/h)

<table>
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<th>Mixture</th>
<th>Thermal stress $\sigma(t)$, shift factor $a_{t1}$, 10d/h</th>
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<td>Temp 22 18 14 10 6 2 -2 -6 -10 -14 -18 -22 -26 -30 -34 -36 -38 -40</td>
</tr>
<tr>
<td>A</td>
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</table>

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Thermal stress $\sigma(t)$, Shift factor $a_{t2}$, 10d/h</th>
</tr>
</thead>
<tbody>
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<tr>
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</table>

Gray box: significant difference, White box: no significant difference

The results indicate that, at low temperature thermal stresses generated with shift factor $a_{t1}$ are similar for the two test methods, except for mixture I, for both cooling rates. If shift factor $a_{t2}$ is used, significant differences are observed for six of the eleven mixtures tested. Hypothesis testing for BBR binder and IDT test was not performed in this thesis because in graphical comparison results all of mixture cases showed significant differences.
4.4 Comparison of thermal stresses $\sigma(t)$ at PG, PG+10 °C, and $T_{CR}$

In this section, graphical and statistical comparisons of thermal stresses obtained from mixture IDT, mixture BBR, and binder BBR testing were performed at three specific temperatures: PG+10, PG and critical cracking temperature $T_{CR}$. The Single Asymptote Procedure (Shenoy, 2002) described in Chapter 2, was used to obtain $T_{CR}$.

4.4.1 Comparison of thermal stresses at PG and PG+10°C

Bar charts of the thermal stresses at PG and PG+10°C from BBR binder (PC=18), BRR mixture (BBR) and IDT mixture tests (IDT) are shown in Figures 4.48 to 4.51. Two different shift factors, $a_{t1}$ and $a_{t2}$, and two temperature cooling rates, 1d/h and 10d/h, were used in thermal stress calculations.

![Figure 4.48 Comparison of thermal stress data at PG°C temperature (1d/h)]](image)
In general, the BBR mix and IDT mix thermal stresses are similar except for mixtures E, H and I. The BBR binder thermal stresses were different however, in particular at
Hypothesis tests were performed between BBR mixture and IDT mixture thermal stresses. The same statistical analysis procedure, t-critical, and degrees of freedom defined by equations [4.14] to [4.18] were used. Critical level was set as $\alpha = 0.05$. T-critical was set as $\pm 2.7$ for all mixtures except mixtures D, E and K, for which the t-critical was set as $\pm 2.4$. The results are listed in Tables 4.7 to 4.10.

### Table 4.7 Summary results of thermal stress comparison at PG (1d/h)

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Thermal stress (MPa)</th>
<th>t-statistic, $a_{T1}$</th>
<th>t-statistic, $a_{T2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IDT mix</td>
<td>BBR mix</td>
<td>$(\sigma_{\text{IDT}} - \sigma_{\text{BBR}})/\sigma_{\text{BBR}}$</td>
</tr>
<tr>
<td></td>
<td>$a_{T1}$</td>
<td>$a_{T2}$</td>
<td>$a_{T1}$</td>
</tr>
<tr>
<td>A</td>
<td>1.97</td>
<td>2.15</td>
<td>1.67</td>
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<tr>
<td>B</td>
<td>2.52</td>
<td>2.44</td>
<td>2.39</td>
</tr>
<tr>
<td>D</td>
<td>1.47</td>
<td>1.96</td>
<td>24.80%</td>
</tr>
<tr>
<td>E</td>
<td>4.42</td>
<td>3.88</td>
<td>13.97%</td>
</tr>
<tr>
<td>F</td>
<td>3.09</td>
<td>2.59</td>
<td>3.08</td>
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<td>2.18</td>
<td>2.64</td>
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<td>H</td>
<td>3.17</td>
<td>2.82</td>
<td>2.34</td>
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<td>3.75</td>
<td>3.77</td>
<td>2.36</td>
</tr>
<tr>
<td>K</td>
<td>2.25</td>
<td>2.42</td>
<td>7.02%</td>
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<tr>
<td>L</td>
<td>2.44</td>
<td>2.64</td>
<td>2.61</td>
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<tr>
<td>M</td>
<td>3.83</td>
<td>3.86</td>
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Gray box: significant difference, White box: no significant difference
### Table 4.8 Summary results of thermal stress comparison at PG (10d/h)

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Thermal stress (MPa)</th>
<th>t-statistic, $a_{T1}$</th>
<th>t-statistic, $a_{T2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IDT mix</td>
<td>BBR mix</td>
<td>$(\sigma_{IDT} - \sigma_{BBR})/\sigma_{BBR}$</td>
</tr>
<tr>
<td>A</td>
<td>$a_{T1}$ 3.64</td>
<td>$a_{T2}$ 3.64</td>
<td>$a_{T1}$ 3.34</td>
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<tr>
<td>B</td>
<td>$a_{T1}$ 4.17</td>
<td>$a_{T2}$ 4.08</td>
<td>$a_{T1}$ 4.54</td>
</tr>
<tr>
<td>D</td>
<td>$a_{T1}$ 2.47</td>
<td>$a_{T2}$ 2.47</td>
<td>$a_{T1}$ 3.50</td>
</tr>
<tr>
<td>E</td>
<td>$a_{T1}$ 7.37</td>
<td>$a_{T2}$ 6.67</td>
<td>$a_{T1}$ 10.53%</td>
</tr>
<tr>
<td>F</td>
<td>$a_{T1}$ 5.09</td>
<td>$a_{T2}$ 5.04</td>
<td>$a_{T1}$ 5.16</td>
</tr>
<tr>
<td>G</td>
<td>$a_{T1}$ 4.35</td>
<td>$a_{T2}$ 4.83</td>
<td>$a_{T1}$ 4.06</td>
</tr>
<tr>
<td>H</td>
<td>$a_{T1}$ 6.01</td>
<td>$a_{T2}$ 5.82</td>
<td>$a_{T1}$ 4.59</td>
</tr>
<tr>
<td>I</td>
<td>$a_{T1}$ 6.27</td>
<td>$a_{T2}$ 6.28</td>
<td>$a_{T1}$ 4.80</td>
</tr>
<tr>
<td>K</td>
<td>$a_{T1}$ 3.92</td>
<td>$a_{T2}$ 4.34</td>
<td>$a_{T1}$ 9.59%</td>
</tr>
<tr>
<td>L</td>
<td>$a_{T1}$ 4.51</td>
<td>$a_{T2}$ 4.72</td>
<td>$a_{T1}$ 5.03</td>
</tr>
<tr>
<td>M</td>
<td>$a_{T1}$ 6.38</td>
<td>$a_{T2}$ 6.37</td>
<td>$a_{T1}$ 6.33</td>
</tr>
</tbody>
</table>

Gray box: significant difference, White box: no significant difference

### Table 4.9 Summary results of thermal stress comparison at PG+10°C (1d/h)

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Thermal stress (MPa)</th>
<th>t-statistic, $a_{T1}$</th>
<th>t-statistic, $a_{T2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IDT mix</td>
<td>BBR mix</td>
<td>$(\sigma_{IDT} - \sigma_{BBR})/\sigma_{BBR}$</td>
</tr>
<tr>
<td>A</td>
<td>$a_{T1}$ 0.42</td>
<td>$a_{T2}$ 0.37</td>
<td>$a_{T1}$ 0.26</td>
</tr>
<tr>
<td>B</td>
<td>$a_{T1}$ 0.64</td>
<td>$a_{T2}$ 0.67</td>
<td>$a_{T1}$ 0.54</td>
</tr>
<tr>
<td>D</td>
<td>$a_{T1}$ 0.39</td>
<td>$a_{T2}$ 0.66</td>
<td>$a_{T1}$ 40.91%</td>
</tr>
<tr>
<td>E</td>
<td>$a_{T1}$ 1.80</td>
<td>$a_{T2}$ 2.12</td>
<td>$a_{T1}$ 15.09%</td>
</tr>
<tr>
<td>F</td>
<td>$a_{T1}$ 0.71</td>
<td>$a_{T2}$ 1.10</td>
<td>$a_{T1}$ 0.73</td>
</tr>
<tr>
<td>G</td>
<td>$a_{T1}$ 0.60</td>
<td>$a_{T2}$ 0.67</td>
<td>$a_{T1}$ 0.48</td>
</tr>
<tr>
<td>H</td>
<td>$a_{T1}$ 0.73</td>
<td>$a_{T2}$ 0.84</td>
<td>$a_{T1}$ 0.46</td>
</tr>
<tr>
<td>I</td>
<td>$a_{T1}$ 0.95</td>
<td>$a_{T2}$ 0.94</td>
<td>$a_{T1}$ 0.75</td>
</tr>
<tr>
<td>K</td>
<td>$a_{T1}$ 0.54</td>
<td>$a_{T2}$ 1.03</td>
<td>$a_{T1}$ 47.57%</td>
</tr>
<tr>
<td>L</td>
<td>$a_{T1}$ 0.60</td>
<td>$a_{T2}$ 0.55</td>
<td>$a_{T1}$ 0.71</td>
</tr>
<tr>
<td>M</td>
<td>$a_{T1}$ 1.36</td>
<td>$a_{T2}$ 1.32</td>
<td>$a_{T1}$ 1.34</td>
</tr>
</tbody>
</table>

Gray box: significant difference, White box: no significant difference
Table 4.10 Summary results of thermal stress comparison at PG+10°C (10d/h)

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Thermal stress (MPa)</th>
<th>t-statistic, $a_{T1}$</th>
<th>t-statistic, $a_{T2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IDT mix</td>
<td>BBR mix</td>
<td>($\sigma_{IDT} - \sigma_{BBR}$)/$\sigma_{BBR}$</td>
</tr>
<tr>
<td>A</td>
<td>0.98</td>
<td>0.87</td>
<td>0.73</td>
</tr>
<tr>
<td>B</td>
<td>1.15</td>
<td>1.21</td>
<td>1.34</td>
</tr>
<tr>
<td>D</td>
<td>0.73</td>
<td>3.34</td>
<td>1.32</td>
</tr>
<tr>
<td>E</td>
<td>1.55</td>
<td>2.51</td>
<td>1.62</td>
</tr>
<tr>
<td>G</td>
<td>1.40</td>
<td>1.14</td>
<td>1.29</td>
</tr>
<tr>
<td>H</td>
<td>1.90</td>
<td>2.22</td>
<td>1.45</td>
</tr>
<tr>
<td>I</td>
<td>2.06</td>
<td>2.04</td>
<td>1.90</td>
</tr>
<tr>
<td>K</td>
<td>3.34</td>
<td>3.87</td>
<td>13.70%</td>
</tr>
<tr>
<td>L</td>
<td>1.31</td>
<td>1.19</td>
<td>1.75</td>
</tr>
<tr>
<td>M</td>
<td>2.63</td>
<td>2.55</td>
<td>2.64</td>
</tr>
</tbody>
</table>

Gray box: significant difference, White box: no significant difference

At PG temperature and both cooling rates, significant differences in thermal stresses were found for mixtures D, H and I. For mixture H and shift factor $a_{T1}$, no significant differences were found at PG temperature. At PG+10°C, mixtures B, D, E, H, I and K showed significant differences that were found. Mixture H and B showed difference for 10 d/h of cooling rate but not for 1 d/h of cooling rate. Mixture I showed difference for 1 d/h but not for 10 d/h. Mixtures D, E and K showed differences for both cooling rates.

4.4.2 $T_{CR}$ from BBR binder, BBR mixture, and IDT mixture tests

Before comparing thermal stresses at $T_{CR}$, the $T_{CR}$ values obtained with SAP method were compared graphically and statistically by hypothesis testing. Bar charts are shown in Figures 4.52 and 4.53.
It is observed that $T_{\text{CR}}$ values determined from BBR binder data using PC=18 are significantly different than the $T_{\text{CR}}$ values determined from BBR mix and IDT mix data, respectively.

A statistical comparison was performed for $T_{\text{CR}}$ obtained from mixture IDT and mixture BBR data. Critical level was set as $\alpha = 0.05$ and t-critical values calculated at PG and PG+10°C are listed in Tables 4.11 and 4.12. Similar results were observed in $T_{\text{CR}}$ values calculated using 1d/h and 10d/h cooling rates. For mixtures D, E, H and L, significant differences were found in comparison of $T_{\text{CR}}$ values. For mixture H, a difference was
found for shift factor $a_{T1}$ only. No significant differences were found for mixture L at PG and PG+10°C and shift factor $a_{T2}$. However, significant differences were found for shift factor $a_{T1}$.

Table 4.11 Summary results of critical cracking temperature $T_{CR}$ (1 d/h)

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Critical Temperature (°C)</th>
<th>t-statistic, $a_{T1}$</th>
<th>t-statistic, $a_{T2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IDT mix</td>
<td>BBR mix</td>
<td>$T_{CR(IDT)} - T_{CR(BBR)}$</td>
</tr>
<tr>
<td>A</td>
<td>-27.81</td>
<td>-27.07</td>
<td>-28.46</td>
</tr>
<tr>
<td>B</td>
<td>-30.57</td>
<td>-30.43</td>
<td>-29.71</td>
</tr>
<tr>
<td>D</td>
<td>-30.35</td>
<td></td>
<td>-28.40</td>
</tr>
<tr>
<td>E</td>
<td>-25.83</td>
<td></td>
<td>-20.94</td>
</tr>
<tr>
<td>F</td>
<td>-28.72</td>
<td>-25.04</td>
<td>-28.63</td>
</tr>
<tr>
<td>G</td>
<td>-27.59</td>
<td>-27.24</td>
<td>-27.22</td>
</tr>
<tr>
<td>H</td>
<td>-25.88</td>
<td>-25.72</td>
<td>-26.79</td>
</tr>
<tr>
<td>I</td>
<td>-28.21</td>
<td>-28.24</td>
<td>-28.03</td>
</tr>
<tr>
<td>K</td>
<td>-26.90</td>
<td></td>
<td>-25.24</td>
</tr>
<tr>
<td>L</td>
<td>-30.13</td>
<td>-30.45</td>
<td>-28.77</td>
</tr>
<tr>
<td>M</td>
<td>-24.03</td>
<td>-24.18</td>
<td>-24.30</td>
</tr>
</tbody>
</table>

Gray box: significant difference, White box: no significant difference

Table 4.12 Summary results of critical cracking temperature $T_{CR}$ with 10 d/h

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Critical Temperature (°C)</th>
<th>t-statistic, $a_{T1}$</th>
<th>t-statistic, $a_{T2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IDT</td>
<td>BBR mixture</td>
<td>$T_{CR(IDT)} - T_{CR(BBR)}$</td>
</tr>
<tr>
<td>A</td>
<td>-25.03</td>
<td>-24.59</td>
<td>-25.33</td>
</tr>
<tr>
<td>B</td>
<td>-26.99</td>
<td>-28.68</td>
<td>-27.08</td>
</tr>
<tr>
<td>D</td>
<td>-28.93</td>
<td></td>
<td>-26.50</td>
</tr>
<tr>
<td>E</td>
<td>-23.02</td>
<td></td>
<td>-18.21</td>
</tr>
<tr>
<td>F</td>
<td>-26.25</td>
<td>-21.60</td>
<td>-26.08</td>
</tr>
<tr>
<td>G</td>
<td>-24.26</td>
<td>-23.86</td>
<td>-23.87</td>
</tr>
<tr>
<td>H</td>
<td>-21.88</td>
<td>-21.47</td>
<td>-23.32</td>
</tr>
<tr>
<td>I</td>
<td>-25.36</td>
<td>-25.40</td>
<td>-24.95</td>
</tr>
<tr>
<td>K</td>
<td>-24.30</td>
<td></td>
<td>-22.79</td>
</tr>
<tr>
<td>L</td>
<td>-27.84</td>
<td>-28.11</td>
<td>-25.86</td>
</tr>
<tr>
<td>M</td>
<td>-20.65</td>
<td>-20.83</td>
<td>-20.83</td>
</tr>
</tbody>
</table>

Gray box: significant difference, White box: no significant difference
4.5 Comparison of thermal stresses calculated using different shift factors from BBR and IDT mixture creep tests, respectively

In section 4.3, thermal stresses calculated from BBR mixture data were compared to thermal stresses calculated from IDT mixture data. In this section, thermal stresses are calculated using different shift factors for BBR mixture data and for IDT mixture data, respectively, as shown in Figure 4.54.

Section 4.3

- \( \sigma(t) \) from BBR mix, shift factor \( a_{t1} \)
- \( \sigma(t) \) from IDT mix, shift factor \( a_{t1} \)
- \( \sigma(t) \) from BBR mix, shift factor \( a_{t2} \)
- \( \sigma(t) \) from IDT mix, shift factor \( a_{t2} \)

Section 4.5

- \( \sigma(t) \) from BBR mix, shift factor \( a_{t1} \)
- \( \sigma(t) \) from BBR mix, shift factor \( a_{t2} \)
- \( \sigma(t) \) from IDT mix, shift factor \( a_{t1} \)
- \( \sigma(t) \) from IDT mix, shift factor \( a_{t2} \)

Figure 4.54 Section 4.3 and section 4.5 comparisons

The same approach used in section 4.3 was taken in this section. Plots of the thermal stresses calculated with different shift factors, \( a_{t1} \) and \( a_{t2} \), are shown in Figures 4.55 to
Figure 4.55 Comparison of thermal stresses, mixture A

Figure 4.56 Comparison of thermal stresses, mixture B

Figure 4.57 Comparison of thermal stresses, mixture D
Figure 4.58 Comparison of thermal stresses, mixture E

Figure 4.59 Comparison of thermal stresses, mixture F

Figure 4.60 Comparison of thermal stresses, mixture G
Figure 4.61 Comparison of thermal stresses, mixture H

Figure 4.62 Comparison of thermal stresses, mixture I

Figure 4.63 Comparison of thermal stresses, mixture K
It is observed that in general, the two shift factors result in similar thermal stresses.

There are a few cases in which the stresses are different: for mixture B, different results were found in BBR test but not in IDT test. For mixture D, E and G differences were found in IDT testing. In mixture F both tests showed significance differences in generating thermal stresses with different shift factors.

To further investigate these differences, t-statistic analysis was also used similar to section 4.3.2. The hypothesis test plots are shown in Figures 4.66 to Figure 4.76.
Figure 4.66 T-statistic results for $\sigma(t)$ using $a_{T1}$ and $a_{T2}$ respectively, mixture A.

Figure 4.67 T-statistic results for $\sigma(t)$ using $a_{T1}$ and $a_{T2}$ respectively, mixture B.

Figure 4.68 T-statistic results for $\sigma(t)$ using $a_{T1}$ and $a_{T2}$ respectively, mixture D.
Figure 4.69 T-statistic results for $\sigma(t)$ using $a_{T1}$ and $a_{T2}$ respectively, mixture E

Figure 4.70 T-statistic results for $\sigma(t)$ using $a_{T1}$ and $a_{T2}$ respectively, mixture F

Figure 4.71 T-statistic results for $\sigma(t)$ using $a_{T1}$ and $a_{T2}$ respectively, mixture G
Figure 4.72. T-statistic results for \( \sigma(t) \) using \( a_{T1} \) and \( a_{T2} \) respectively, mixture H

Figure 4.73. T-statistic results for \( \sigma(t) \) using \( a_{T1} \) and \( a_{T2} \) respectively, mixture I

Figure 4.74. T-statistic results for \( \sigma(t) \) using \( a_{T1} \) and \( a_{T2} \) respectively, mixture K
Figure 4.75 T-statistic results for $\sigma(t)$ using $a_{T1}$ and $a_{T2}$ respectively, mixture L

Figure 4.76 T-statistic results for $\sigma(t)$ using $a_{T1}$ and $a_{T2}$ respectively, mixture M

Only mixture F showed significant difference in thermal stress calculated using different shift factors for both BBR mix and IDT mix data.

4.6 Physical hardening effects on thermal stress $\sigma(t)$ calculation

The BBR creep data from asphalt mixtures, D, E and K were used in the analysis. The creep data was obtained as follows: each mixture was conditioned for 1 hour and tested. Then, the specimen was stored at the same temperature for an additional 23 hours and
tested again. Thermal stress plots of mixtures D, E and K calculated from 1h and 24h are shown in Figures 4.77 and 4.78.

Figure 4.77 Thermal stress for mixture D and E for different conditioning times

Figure 4.78 Thermal stress for mixture K for different conditioning times

The two conditioning times resulted in different thermal stresses for all mixtures. The differences were higher for 1 d/h rate than the 10 d/h rate. A statistical analysis, similar to section 4.5 was also performed. Since different number of specimens was used, nine specimens at PG+10 and six specimens at PG+10-12, t-critical was set as ±2.2~2.4 with significant level of α = 0.05. The results are shown in Figures 4.79 and 4.80.
It can be seen that for mixtures D and E, thermal stresses are different. Even though for mixture K, the stresses were not different down to -20°C, differences became significant below that temperature. Similar to previous research (Basu and Marasteanu, 2001), physical hardening effect was found to be significant in computing thermal stresses for asphalt mixture. Thermal stress values at PG, PG+10°C and $T_{CR}$ were further compared, and the results are shown in Tables 4.13 and 4.14 and Figures 4.81 and 4.82.
Table 4.13 Summary of thermal stresses for different storage times

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Thermal stress (MPa), 1d/h</th>
<th>t-statistic, PG+10</th>
<th>t-statistic, PG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 hour 24 hours</td>
<td>( \sigma_{24h} - \sigma_{1h} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PG+10  PG</td>
<td>PG+10  PG</td>
<td>PG+10  PG</td>
</tr>
<tr>
<td>D</td>
<td>0.43  1.60</td>
<td>1.26  3.21</td>
<td>0.83  1.61</td>
</tr>
<tr>
<td>E</td>
<td>2.12  3.88</td>
<td>4.13  7.14</td>
<td>2.01  3.26</td>
</tr>
<tr>
<td>K</td>
<td>1.03  2.42</td>
<td>1.79  4.00</td>
<td>0.76  1.58</td>
</tr>
</tbody>
</table>

Gray box: significant difference, White box: no significant difference

Table 4.14 Summary of critical cracking temperatures for different storage times

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Critical Temperature (°C)</th>
<th>t-static</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 hour 24 hours</td>
<td>( \sigma_{24h} - \sigma_{1h} )</td>
</tr>
<tr>
<td></td>
<td>PG+10  PG</td>
<td>PG+10  PG</td>
</tr>
<tr>
<td>D</td>
<td>-29.32 -26.91</td>
<td>-28.67 -27.17</td>
</tr>
<tr>
<td>E</td>
<td>-20.94 -18.21</td>
<td>-19.88 -18.81</td>
</tr>
<tr>
<td>K</td>
<td>-25.24 -22.79</td>
<td>-25.04 -22.89</td>
</tr>
</tbody>
</table>

Figure 4.81 Comparison of thermal stresses \( \sigma(t) \) with different storage times
As expected, significant differences in thermal stresses at PG and PG+10°C were found for mixtures D and E. For mixture K, no differences were found at PG+10°C (t-statistic=1.36), however, differences were found at PG. No significant differences of critical cracking temperature were found. It appears that although physical hardening affected thermal stresses, it did not significantly affect $T_{CR}$. 

Figure 4.82 Critical cracking temperature, $T_{CR}$ with different storage times
Chapter V

Summary and Conclusions

In this thesis, thermal stresses calculated using binder BBR data, mixture BBR data, and mixture IDT data, respectively, were compared to determine if mixture BBR test is a viable option to calculate thermal stresses. The BBR test is much easier to perform and the equipment is substantially cheaper than the traditional IDT equipment. In addition, the effect of isothermal physical hardening on thermal stress calculations was evaluated and discussed.

5.1 Summary

Eleven different asphalt mixtures and four different asphalt binders from MnROAD were tested and analyzed in this thesis. BBR binder, BBR mixture, and IDT mixture creep tests were performed at different temperatures and the creep compliance $J(t)$ was obtained. Then, using Hopkins and Hamming algorithm, the relaxation modulus $E(t)$ was computed, from which thermal stresses $\sigma(t)$ and critical cracking temperature $T_{CR}$ of asphalt binders and mixtures were predicted.

The analysis of the experimental data consisted of the following comparisons:

1. Creep stiffness $S(t)$ and m-value $m(t)$ obtained from BBR and IDT mixture creep tests
2. Relaxation modulus $E(t)$ calculated from BBR and IDT mixture creep test results
3. Thermal stresses $\sigma(t)$ calculated from BBR binder, BBR mixture, and IDT mixture creep test results, respectively
4. Thermal stress values at PG, PG+10°C, and critical cracking temperature $T_{CR}$

5. Thermal stress $\sigma(t)$ calculated using different combinations of test temperatures and shift factors and BBR and IDT mixture creep compliance test results, respectively

In addition, physical hardening effects on thermal stresses $\sigma(t)$ for three mixtures using BBR mixture creep test results was investigated.

### 5.2 Conclusions

The main findings of this thesis can be summarized as follows:

1. When comparing BBR mixture creep stiffness to IDT mixture creep stiffness, significant differences were found for 3 to 4 mixtures at each of the three temperatures. Only mixture I had significant differences at two temperatures; the rest of the mixtures had differences at only one temperature. Note that mixtures D, E, and K, were not tested at PG+10°C+12°C.

2. When comparing the m-value $m(t)$, the results were clearly dependent on test temperature. At PG+10°C-12°C, all mixtures had significant differences. At PG+10°C, six mixtures out of the set of eleven had significant differences, and at PG+10°C+12°C only two mixtures had significant differences. This result seems to indicate that at the lowest test temperatures, where the slope of the creep stiffness curve is very small, the two test methods give different results. Most likely, this is due to reaching the sensitivity limits of the displacement transducers in the two instruments.

3. In the case of comparing relaxation modulus $E(t)$ master curve between BBR
mixture and IDT mixture tests, almost identical master curves are observed for mixtures F, G, H, I and M. Differences are observed for mixtures A, B, E and L and significant differences are observed for mixtures D and K.

4. When comparing thermal stresses from BBR mixture and IDT mixture test, almost identical results of thermal stresses were obtained for mixtures A, F, L and M. For mixtures B and G and shift factor $a_{T1}$, similar thermal stresses were obtained; however, for shift factor $a_{T2}$, differences were found between BBR and IDT thermal stresses. Significant differences of thermal stresses were found in mixtures H and I even though no significant differences were found when comparing relaxation modulus master curves. For mixture D, E and K partial differences were found.

5. When further comparing thermal stresses from BBR mixture and IDT mixture tests obtained based on each of the two shift factors, it was found that thermal stresses generated with shift factor $a_{t1}$ are similar, except for mixture I, for both cooling rates. If shift factor $a_{t2}$ is used, significant differences are observed for six of the eleven mixtures.

6. When comparing thermal stresses from BBR binder and IDT mixture tests, significant differences were observed for all mixtures, which suggests that the PC method (BBR binder test) should not be used to predict thermal stresses $\sigma(t)$ of asphalt mixtures.

7. No significant differences were found for critical cracking temperature $T_{CR}$ computed with SAP method from BBR mixture and IDT mixture data. However, significant differences were found when BBR binder data was used.
8. The analysis performed on BBR mixture data for mixtures D, E, and K, clearly shows that physical hardening significantly affects thermal stress calculations. No effects were found when calculating $T_{CR}$.

5.3 Recommendations

Based on these findings, the following recommendations are made:

1. For thermal stress calculations, experimental data obtained at intermediate (PG+10°C) and high (PG+10°C+12°C) temperature is sufficient to obtain reasonable results. Experimental data obtained at the lowest temperature (PG+10°C-12°C) may be less accurate due to difficulties in measuring very small displacements.

2. The use of BBR binder data to estimate thermal stresses in mixtures is not recommended due to significant differences observed between the mixture data and the binder data adjusted with the PC factor.
References


5. American Association of State Highway and Transportation Officials (AASHTO) Designation T322-03 (2003), "Standard Method of Test for Determining the


36. William G. Buttlar and Reynaldo Roque: “Development and evaluation of the strategic highway research program measurement and analysis system for Indirect Tensile Testing at low temperatures”, Transportation Research Record no 1454, pp 163-171


Appendix

Thermal stress computation procedure
The thermal stress computation procedure used in this thesis consists of two main steps: First step is generating relaxation modulus \( E(t) \) master curve, and second step is computing thermal stress with Gaussian quadrature approximation method (Basu, 2002). Creep stiffness \( S(t) \) and creep compliance \( J(t) \) are calculated as follows:

1. **BBR mixture test**

\[
S(t) = \frac{\sigma}{\varepsilon(t)} = \frac{P \cdot t^3}{4 \cdot b \cdot h^3 \cdot \delta(t)} \quad [1]
\]

and creep compliance \( J(t) \) is:

\[
J(t) = \frac{1}{S(t)} \quad [2]
\]

2. **IDT mixture test**

\[
J(t) = \frac{H^{(t)}_{m} \cdot d \cdot t \cdot C_{compliance}}{P \cdot GL} \quad [3]
\]

and creep stiffness \( S(t) \) is:

\[
S(t) = \frac{1}{J(t)} \quad [4]
\]

Relaxation modulus \( E(t) \) is obtained from \( J(t) \) using Hopkins and Hamming algorithm (1957), as mentioned in Chapter 2. Then, relaxation modulus \( E(t) \) master curves are generated using CAM model.

\[
E(t) = E_y \cdot \left[ 1 + \left( \frac{t}{t_c} \right)^w \right]^{\frac{w}{v}} \quad [5]
\]

In this thesis, three different temperature conditions with two different shift factors were used in generating relaxation modulus \( E(t) \) master curve. Figure A1 shows generated
Figure A1 Two different shift factors in relaxation modulus master curve

Two shift factors are calculated as follows:

\[ a_{T1} = 10^{C_1 + C_2 T} \]  

[6]
\[ a_{T2} = 10^{C_1+C_2 T} \]  

[7]

Shift factor \( a_{T1} \) is between reference temperature and lower temperature. Shift factor \( a_{T2} \) is between reference temperature and higher temperature. The shift factors can be changed to log scales as follows:

\[
\log a_{T1} = C_1 + C_2 \cdot T
\]  

[8]

\[
\log a_{T1} = C_3 + C_4 \cdot T
\]  

[9]

The CAM model (Equation [5]), can be changed to log scale with shift factor \( a_{T1} \):

\[
\log E(t) = \log E_g - \frac{w}{v} \left[ 1 + \left(10^{\log a_{T1} + \log a_{T2}}\right)^{T - T_i} \right]
\]  

[10]

Glassy modulus \( E_g \) equal to 30GPa for all asphalt mixtures is assumed.

By fitting Equation [10] to relaxation modulus \( E(t) \), five constants were determined \( (t_c, v, w, a_{T1} \) and \( a_{T2} \)): Least square error method was used with residual (error) level of 0.03~10. In Equations [8] and [9], temperature \( T \) can be written like:

\[
T = T_i - C_0 \cdot t
\]  

[11]

In Equation [12], \( T_i \) means initial temperature \((22^\circ C \text{ in this thesis})\) and \( C_0 \) means constant temperature drop rate. Therefore, Equation [6] can be written as:

\[
a_{T1} = 10^{C_1+C_2 T} = 10^{C_1+C_2 (T_i-T)} = 10^{(C_1+C_2 T_i-C_2 T_i)} = 10^{C_1+C_2 T_i - C_2 T_i}
\]  

[12]

Equation [13] can be changed to:

\[
a_{T1} = 10^{C_1+C_1} = 10^{C_2} \times 10^{C_2} = A_0 \cdot 10^{C_2}
\]  

[13]

Assuming that time temperature superposition principle is valid, then one can write:

\[
E(T,t) = E(T_0,t)
\]  

[14]
where

\[ \xi = \frac{t}{a_T(T)} \]  \hspace{1cm} [15] 

Where \( T_0 \) is the reference temperature and \( \xi \) is the “reduced time”. From Equation [15], reduced time can be also as follows:

\[ \xi = \frac{t}{a_T[T]} = \int_0^t \frac{dt'}{a_T[T(t')]} \]  \hspace{1cm} [16] 

In Equation [16], value \( t' \) means an arbitrary time prior to \( t \).

Equation [16] can be rewritten by substituting Equation [13]:

\[ \xi = \int_0^t \frac{dt'}{a_T[T(t')]} = \int_0^t \frac{dt'}{A_0 \cdot 10^{C_4 \cdot t'}} = \frac{1}{A_0} \int_0^t 10^{-C_4 \cdot t'} \, dt' = \frac{1}{A_0} \left[ -\frac{10^{-C_4 \cdot t'}}{C_4 \cdot \ln 10} \right]_0^t = \]

\[ = \frac{1}{A_0} \left[ \frac{1}{C_4 \cdot \ln 10} \cdot \left( 1 - 10^{-C_4 \cdot t} \right) \right] = \frac{1}{A_0 \cdot C_4 \cdot \ln 10} \left[ 1 - 10^{-C_4 \cdot t} \right] = A_i \cdot \left[ 1 - 10^{-C_4 \cdot t} \right] \]  \hspace{1cm} [17] 

where

\[ A_i = \frac{1}{A_0 \cdot C_4 \cdot \ln 10} = \frac{1}{10^{C_4 c_T} \cdot C_2 \cdot C_0 \cdot \ln 10} \]  \hspace{1cm} [18] 

Stress is calculated as:

\[ \sigma(t) = \int_{-\infty}^t E(\xi - \xi') \frac{\partial \varepsilon(\xi')}{\partial \xi'} \, d\xi' \]  \hspace{1cm} [19] 

where

\[ t = \frac{\Delta T}{C_0} \]  \hspace{1cm} [20] 

Strain can be written as:

\[ \varepsilon = -\alpha \cdot \Delta T \]  \hspace{1cm} [21]
Therefore, Equation [22] can be changed to:

\[
\sigma(\xi) = \int_{-\infty}^{t} E(\xi - \xi') \frac{\partial \varepsilon(\xi')}{\partial \xi'} d\xi' = -\alpha \int_{0}^{t} E(\xi - \xi') \frac{\partial (\Delta T)}{\partial \xi'} d\xi' [22]
\]

where

\(\xi'\) : An arbitrary reduced time prior to \(\xi\)

From Equation [22], \(\frac{\partial (\Delta T)}{\partial \xi}\) can be substituted like:

\[
\frac{\partial (\Delta T)}{\partial \xi} = C_0, \text{ since } \Delta T = C_0 \cdot t [23]
\]

Then:

Equation [22] becomes:

\[
\sigma(\xi) = -\alpha \int_{0}^{t} E(\xi - \xi') \frac{\partial (\Delta T)}{\partial \xi'} d\xi' = -\alpha \cdot C_0 \cdot \int_{0}^{t} E(\xi - \xi') d\xi' [24]
\]

Finally, introducing CAM model, Equation [24] can be written as:

\[
\sigma(\xi) = -\alpha \cdot C_0 \cdot \int_{0}^{t} E(\xi - \xi') \left[ 1 + \left( \frac{\xi - \xi'}{t_c} \right)^\gamma \right] \frac{w}{v} d\xi' [25]
\]

Equation [25] cannot be integrated analytically, therefore, Gaussian quadrature with 24 Gauss points approximate numerical computation method, is used. Equation [24] becomes:

\[
\sigma(\xi) = -\alpha \cdot C_0 \cdot \int_{0}^{t} E(\xi - \xi') d\xi' = -\alpha \cdot C_0 \cdot \int_{-\frac{t}{2}}^{\frac{t}{2}} E(\xi - \xi') d\xi' = -\alpha \cdot C_0 \cdot \sum_{i=1}^{24} \frac{t}{2} \cdot E(\xi - \xi_i') [26]
\]

\[
= -\alpha \cdot C_0 \cdot \frac{t}{2} \sum_{i=1}^{24} w_i \cdot E(\xi - \xi_i') [26]
\]
where

\[
\xi = \frac{1}{10^{C_1 + C_2 T_i} \cdot C_2 \cdot C_0 \cdot \ln 10} \cdot [1 - 10^{-C_4 \xi'}]
\]  \hspace{1cm} [27]

\[
\xi' = \frac{1}{10^{C_1 + C_2 T_i} \cdot C_2 \cdot C_0 \cdot \ln 10} \cdot [1 - 10^{-C_4 \xi'}]
\]  \hspace{1cm} [28]

\[
t' = \frac{t}{2} \cdot x_i + \frac{t}{2}
\]  \hspace{1cm} [29]

\[x_i: \text{Gauss point (from 1 to 24)}\]