Spring 2013

Forensice analysis of long term aged hot mix asphalt field cores containing reclaimed asphalt pavement

Kelly Barry

University of New Hampshire, Durham

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FORENSIC ANALYSIS OF LONG TERM AGED HOT MIX ASPHALT FIELD CORES CONTAINING RECLAIMED ASPHALT PAVEMENT
BY

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BS Civil Engineering, University of New Hampshire, 2011

Submitted to the University of New Hampshire
in Partial Fulfillment of
the Requirements for the Degree of

Master of Science
in
Civil Engineering

May, 2013
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ABSTRACT
FORENSIC ANALYSIS OF LONG TERM AGED HOT MIX ASPHALT FIELD CORES CONTAINING RECLAIMED ASPHALT PAVEMENT
by
Kelly Barry
University of New Hampshire, May, 2013

The practice of incorporating Reclaimed Asphalt Pavement (RAP) into Hot Mix Asphalt (HMA) is common within the paving industry as a cost effective source of quality paving binder and aggregate. As prices for these resources continue to rise, investigations are being made to further increase the amount of RAP in new paving projects. These mixtures incorporate already aged asphalt binder into new mixtures, which can impact the performance of the mixture in the field in terms of cracking, rutting and aging. The goal of this research project was to determine if a difference in aging between high and low RAP mixtures existed and the extent to which it effected the mixture performance. This study compared binder and mixture data from a paving project from 1987 lead by the New Hampshire Department of Transportation (NHDOT), which includes several stretches of 35% RAP mixtures along New Hampshire’s I-89 and I-93. Field cores were obtained from the travel and shoulder lanes of the pavement sections; asphalt binder was extracted and recovered from different depths in the pavement structure and cores were prepared for mixture testing in indirect tension mode. Mixture testing was inconclusive due to varying air void content and lack of low RAP specimens for comparison. Binder testing indicated high RAP mixtures age more uniformly through depth and between travel and shoulder lanes compared to low RAP mixtures.
Chapter 1: Introduction

Hot Mix Asphalt (HMA) is comprised of three main components: aggregate, asphalt binder and recycled materials. Aggregate provides the structure and strength of the mixture. Asphalt binder holds the mixture together, providing strength and recovery from loading. Recycled materials can come from several different sources, the two most common being Reclaimed Asphalt Pavement (RAP) and Reclaimed Asphalt Shingles (RAS). RAP is created by milling pavements that have reached the end of their design life and incorporating them into new mixtures. RAS can come from factory scrap or tear-off or post-consumer waste.

Asphalt binder is a byproduct of the oil refining process. As oil prices began rising, recycled materials became more popular as a source of paving quality asphalt binder, as well as paving quality aggregate. By incorporating recycled materials into new pavements, material was also kept out of landfills. Recycled materials have been already aged during their service life in the field, causing the asphalt to oxidize and increasing the stiffness of the material. Some transportation agencies mitigate the increased stiffness from RAP and RAS by “binder bumping,” or decreasing the high end of the Performance Grade (PG grade) of the binder for mixtures containing more than a specified amount of RAP or RAS. Research has shown that mixtures with RAP contents less than about 15% have little impact on the overall stiffness of the new mixtures when compared to virgin pavements. Transportation agencies have been limiting the amount of recycled product in new mixtures to a maximum of about 15-20% (4-6) before binder bumping.
There have been extensive amounts of research on the performance of asphalt mixtures containing various amounts of RAP compared to virgin mixture performance. Research has shown that unaged mixtures containing high amounts of RAP, typically greater than 20%, are stiffer than unaged, similar virgin mixtures (1, 4, 7 and 8). This stiffness increases the rutting resistance but also can decrease the fatigue resistance and increase the likelihood of low temperature cracking (1, 4, 7 and 8). The increase in stiffness is thought to be due to the oxidized asphalt binder contained in the RAP. Interestingly, research has also shown that as the mixtures age, the virgin mixtures stiffen at a faster rate than the high RAP mixtures (5, 8). Since the mixtures containing RAP have already been aged, the aging is less significant than aging that occurs in virgin or low RAP mixtures.

Due to the amount of time it takes to field age mixtures, aging protocols have been developed to simulate field aging in a laboratory setting. There are two methods to replicating field aging. One method is to age the binder use the Rolling Thin Film Oven method. This method does not take into account the aggregate structure of the mixture. Another method for aging material is to age the entire specimen in an oven over the course of several days (8). These methods significantly shorten the amount of time needed to compare unaged versus aged mixtures.

Unfortunately, asphalt mixtures are sensitive to numerous environmental conditions that may not be simulated by laboratory aging. Traffic action, sunlight, temperature changes, freeze/thaw action, depth of the mixture and changes in air voids over time can all impact the mixture's properties and are not easily replicated in the laboratory. The objective for this
The goal of this research was to determine if high RAP content had an effect on aging, and if so, what was the effect compared to low RAP pavements. In order to determine effects of aging, a full forensic analysis was completed on both binder and mixture data. The data was compared to previously determined trends regarding aging with RAP content, lane type and depth from surface.

This thesis is divided into two sections: binder testing and results and mixture testing and results. Chapter 2, Materials and Test Methods, is split into these two parts, as well as Chapter 3, Results and Discussion. Chapter 4 gives a final summary and conclusion of the research, as well as suggestions for future work.
Chapter 2: Materials and Methods

Section 1: Materials

Section 1.1: Site Locations

Road core samples were obtained using a coring drill. The specimens were extracted from two locations, one on Interstate 93 and one on Interstate 89. Maps of specimen locations are presented in Figure 1 through Figure 3. Cores were stored in the bituminous lab at UNH. The gradings for the I-93 specimens are presented in Table 1. Specimen information is presented in Table 2. The I-93 specimens were a $\frac{3}{4}$" maximum aggregate size course with AC-10 binder. Original job mix information is presented in Appendix Part F: I-93 Original Job Mix Data Sheets.
Section 1.2: Specimen Information
Table 1: Specimen Aggregate Grading

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>I-93 Surface</th>
<th>I-93 Intermediate</th>
<th>I-89 Surface</th>
<th>I-89 Intermediate</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/16&quot;</td>
<td>95-100</td>
<td>95-100</td>
<td>--</td>
<td>95-100</td>
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<tr>
<td>ac</td>
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<td>5.2%</td>
<td>6.0%</td>
<td>5.4%</td>
</tr>
</tbody>
</table>

The specimen information for those used for mixture testing is presented in Table 2.

The specimen information includes the thickness, $G_{mb}$, $G_{mm}$, air voids, VMA, VFA, and the averages for the different mixtures.

Binder testing was conducted on three layers. Mixture testing was conducted on the surface and intermediate courses. The field cores were trimmed to the appropriate thickness, which varied depending on the mixture. A schematic of the layer depths is presented in Figure 4 through Figure 7. It was noted that the surface and intermediate courses were not all the same depth for each core. Some middle binder specimens contain both surface and intermediate course material, as illustrated in the schematics.
Figure 4: Schematic of I-93 Travel Lane

Figure 5: Schematic of I-93 Shoulder Lane

Figure 6: Schematic of I-89 Travel Lane
Figure 7: Schematic of I-89 Shoulder
<table>
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<tr>
<th>Location</th>
<th>Specimen</th>
<th>Thickness (in)</th>
<th>Gmb</th>
<th>Gmm</th>
<th>Air Void</th>
<th>Average Air Void</th>
<th>VMA</th>
<th>VFA</th>
<th>Average VMA</th>
<th>Average VFA</th>
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<td>93 Travel Surface</td>
<td>C110S</td>
<td>1.402</td>
<td>2.412</td>
<td>2.457</td>
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<td>87.0</td>
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<td>15.7</td>
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<td>88.2</td>
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<td>89 Shoulder Surface</td>
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</tbody>
</table>
Section 1.3: Sources of Error

While being constructed and during its service life, pavements are subjected to numerous factors that can affect the strength, stiffness, and other characteristics of the mixture. These factors can cause changes in performance that can skew data results. Average daily traffic (ADT) is a measure of the average number of vehicles over a pavement surface in a typical day. The amount of traffic a pavement experiences can have an impact on the performance. The two pavement sections used in this research had ADT counts of approximately 20,000 vehicles per day for I-93 and 36,000 vehicles per day for I-89. Another possible difference between pavements was the type of mixing plant that was used. I-93 was mixed in a drum plant while the I-89 sections were mixed in an unknown plant type. The difference in mixing plants could also have impacted the final results. Overlay thicknesses also varied between the mixtures, which may have had an effect of the aging of the mixtures with depth when comparing the performance of surface and intermediate layers. A final known difference between the mixtures is the aggregate gradings, as shown in Table 1.

Many other factors also may have impacted the performance of the mixtures but cannot be controlled or explained. One such factor is source of RAP. It is impossible to know if the sources of RAP were the same between the different mixtures. Different sources of RAP could have different aggregate gradation, asphalt content, binder grade, or even have been in the field for different amounts of time, causing different aging of the RAP binder. Air voids have a tremendous impact on mixture performance and can also affect binder aging. Air voids are difficult to control in field conditions both from
initial lay down and as traffic increases the pavement density over time. Air void differences greater than ±0.5% create such changes in performance that direct comparisons are not valid.

Section 2: Binder Testing

Binder testing for this project included the Bending Beam Rheometer (BBR) and Direct Tension Test (DTT). The cores were cut into three sections, as shown in Figure 4 through Figure 7. The binder was extracted and recovered from three sections using a AASHTO T-164 with TCE, followed by Abson AASHTO T-170. The binder was extracted in three layers by New Hampshire Department of Transportation (NHDOT) personnel. AASHTO Specification T 313 for BBR testing, and T 314 for DTT testing were followed.

Section 2.1: Stiffness and M-Value

Stiffness is a property of the binder that is obtained from the BBR test. Stiffness, or S-value, is a measure of the binder's resistance to load. A higher stiffness increases the likelihood of low temperature cracking. Superpave has instituted a maximum of 300 MPa for the S-value. The m-value is the rate at which the stiffness of the binder changes and is also obtained from the BBR test. M-value is a measure of the binder's ability to relax without cracking after loading. The lower the m-value is, the greater its ability to relax at low temperatures. Superpave has set a minimum m-value for binder at 0.300. Figure 8 presents an example of BBR test results, where the points on the line indicate stiffness values and the slope of the line indicates m-value.
Section 2.2: Critical Cracking Temperature

Critical Cracking Temperature (CCT) was calculated by using a combination of the BBR and DTT test results. BBR data provides a measure of the thermal stresses within the specimen at increasingly colder temperatures. The DTT test causes the binder specimen to fail in pure tension at increasingly colder temperatures, which was then used to calculate the strength. The thermal stress and strength as a function of temperature was plotted on the same graph. The point of intersection of these curves was the CCT. A binder with lower CCT will have an increased resistance to thermal cracking. Figure 9 presents a schematic of strength and thermal stress data that were used to calculate CCT.
Section 2.3: Shear Modulus and Phase Angle

Shear modulus, or $|G^*|$, was obtained by a Dynamic Shear Rheometer (DSR) machine. A small specimen of binder was loaded into the DSR, which then applied a shear stress on the specimen at various frequencies. The resistance to shear stress was recorded and used to calculate $|G^*|$. The DSR was run at temperatures of 10, 21, 35, and 47°C, and frequencies of 0.016, 0.0253, 0.04, 0.0634, 0.101, 0.16, 0.253, 0.4, 0.634, 1.0, 1.59, 2.52, 4.0, 6.34, 10.0 and 15.9 Hz. The various temperatures and frequencies were used to construct a master curve. Shift factors were used to shift the data to create a smooth master curve at a reference temperature of 21°C. The equation used to fit the master curve was:

$$\log(|G^*|) = a + \frac{b}{[1 + e \cdot \exp(c + d \cdot \log(\omega_r))]^{1/\epsilon}}$$

Equation 1
Phase angle, $\delta$, was also a result of DSR testing. The phase angle of the binder is the time lag between the applied shear stress and the strain response. Shift factors were used to create a smooth master curve for the phase angle at a reference temperature of 21°C. Theoretically, the shift factors for $|G^*|$ and phase angle should be the same, however due to testing variability, separate shift factors were calculated for phase angle to obtain the best fit for each master curve. The equation used to fit the master curve for phase angle was:

$$
\delta = -90 \times b \times d \times \frac{\exp(c + d \times \log(\omega_r))}{[1 + e \times \exp(c + d \times \log(\omega_r))]^{1+1/e}}
$$

Equation 2

Where: $b, c, d, \text{ and } e = \text{ regression coefficients}$  
$\omega_r = \text{ angular frequency}$

The regression coefficients for phase angle and $|G^*|$ were not the same. They were fit individually to the data to create the best fit.

Section 2.4: Percent Difference and Ratio Analysis

Only one specimen was tested at each location and depth. A typical statistical analysis could not be performed with only a single replicate. In order to quantify the differences between binder results, the percent difference was taken between the specimens for Stiffness, m-value and critical cracking temperature. The equation used to calculate the percent difference was:
\[
\% \text{ Difference} = \frac{(a - b)}{a}
\]

Equation 3

Where: 
\(a\) = Control Specimen  
\(b\) = Comparison Specimen

To compare the shear modulus and phase angle master curves, a ratio of the modulus and phase angle values at various reduced frequencies were calculated and plotted on a log scale. The equation used to calculate the ratio was:

\[
\text{Ratio} = \frac{\text{Modulus or Phase Angle Value of Mix A}}{\text{Modulus or Phase Angle Value of Mix B}}
\]

Equation 4

Where: 
Modulus or Phase Angle of Mix A = Value at Frequency X  
Modulus or Phase Angle of Mix B = Value at Frequency X

Section 3: Mixture Testing

Section 3.1: Dynamic Modulus & Phase Angle

Field cores were tested using an indirect tension (IDT) method and setup. IDT testing uses Linear Variable Differential Transformers (LVDTs) in both the vertical and horizontal direction across the front and back face of the specimens. The specimens were fitted with 4 sets of metal brackets that were attached using a two-part epoxy, which was allowed to cure for a minimum of 2 hours. The specimens were loaded into the environmental chamber where 4 LVDTs, 2 horizontal and 2 vertical, were tightened into the brackets. The specimens were temperature conditioned until a dummy specimen of similar dimensions fitted with an internal thermocouple reached the testing
temperature, ±0.5°C. The ram was lowered until the loading strip came in contact with
the specimen. A sinusoidal load was applied at frequencies of 20, 10, 5, 1, 0.5, and 0.1
Hz and the specimens was tested at temperatures of 20, 10, 0, -10, and -20°C. The load
and strain were recorded using a data acquisition system from National Instruments and
LabView. The data were then post-processed using a combination of Matlab and Excel.
To create the master curve, the data were first fit with a curve using the equations:

\[
\text{Predicted Harmonic Response} = D_1 \cdot \text{Time}^n + (A \cdot \sin((\omega_t \cdot \text{Time}) - \alpha))
\]

Equation 5

\[
\omega_t = 2 \cdot \pi \cdot \text{Frequency}
\]

Equation 6

Where: \( D_1, n, A, \) and \( \alpha \) = Fitting Coefficients
Frequency = Test Frequency, Hz

Equation 5 was fit for each load and LVDT of each specimen at every frequency
and temperature. An example of this fitted predicted harmonic response and the raw
data is presented in Figure 10.
The dynamic modulus, or $|E^*|$, is the ratio of the stress amplitude to the strain response:

$$|E^*| = \frac{\sigma_{amp}}{\varepsilon_{amp}}$$

Equation 7

Where: $\sigma_{amp} =$ Amplitude of the applied stress wave

$\varepsilon_{amp} =$ Amplitude of the applied strain response

Equation 7 was used for uniaxial testing, where all the LVDTs are in the vertical direction. Since the specimens were tested in IDT mode, where both vertical and
horizontal LVDTs are used, the equation for calculating dynamic modulus using IDT data was the following:

\[
|E^*|, \text{psi} = \frac{2 \cdot \text{Load}}{\pi t \cdot 0.5} - 0.0001399 \\
* \left(0.0037 \cdot \text{Ave. Vertical LVDTs} - 0.0042 \cdot \text{Ave. Horizontal LVDTs}\right)
\]

Equation 8

Where: 
Load = Amplitude of the sinusoidal load wave, lbs
\(t\) = specimen thickness, inches
Ave. Vertical and Horizontal LVDTs = Average of the amplitude of the sinusoidal strain waves, in/in
An example of dynamic modulus values measured at different temperatures and frequencies are shown in Figure 11.

![Figure 11: |E*| Frequency Sweep for Entire Temperature Range](image)

Once all the data were fitted and each dynamic modulus value was calculated, the master curve was created. Similar to the shear modulus, the data were shifted with regards to a reference temperature of 20°C using the principle of time-temperature superposition. This was completed using shift factors until the data created a smooth curve that could be fit. An example of this is presented in Figure 12. Note that the horizontal axis is now labeled as Reduced Frequency to indicate the data has been shifted.
The final step was to fit a smooth curve to the shifted data. This was done using the generalized logistic function which is presented in Equation 9.

$$\log(|E^*|) = a + \frac{b}{[1 + e \cdot \exp(c + d \cdot \log(\omega_r))]^e}$$

Equation 9

Where: $a, b, c, d$, and $e$ = Regression Coefficients
$\omega_r$ = Angular Frequency

The regression coefficients are fit using the method of least squares, where the difference between the measured and predicted values are squared, and the sum of the error is minimized using Excel's solver function. The fitted curve was the plotted over
the shifted data to ensure the fit was representative of the data. An example of the fitted curve is presented in Figure 13.

![Figure 13: Fitted Curve vs. Shifted Data](image)

Once all replicate specimens had been tested and analyzed, the generalized logistic function was fit for all the replicates, which was then be used to compare the different mixtures. Again, the method of least squares was used to optimize the curve
to fit the data. An example of this is presented in Figure 14.

![Graph showing mixture curve fitting with various symbols and lines representing different materials or conditions.](image)

Figure 14: Mixture Curve Fitting

The phase angle, \( \delta \), was also calculated from the IDT test data. To calculate the phase angle the fitted load and strain data were used. The time at which the peak load and corresponding peak strain response for each LVDT was found using the fitted data and the difference between the two values was calculated. Phase angle calculations are not impacted by uniaxial or IDT testing, so the average was then taken from all four LVDTs. Once all the data had been fitted, they were plotted, as shown in Figure 15. Phase angle data collected from IDT mode has higher variability than uniaxial testing, which is presented in Figure 15.
Once all the data had been plotted, it was shifted using the same time-temperature superposition principal as used for fitting $|E^*|$. An example of shifted phase angle data is presented in Figure 16. Note that the horizontal axis is now labeled as Reduced Frequency to indicate the data have been shifted.
The final step was to fit a smooth curve to the raw data. The generalized power law, as shown in Equation 10, was used to fit the data.

\[
\delta = -90 \cdot b \cdot d \cdot \frac{\exp(c + d \cdot \log(\omega_r))}{[1 + e \cdot \exp(c + d \cdot \log(\omega_r))]^{1+1/e}}
\]

Equation 10

Where: \(b, c, d\) and \(e\) = Regression Coefficients

\(\omega_r\) = Angular Frequency

The regression coefficients were fit using the method of least squares, where the difference between the measured and predicted values are squared, and the sum of the error was minimized using Excel’s solver function. The fitted curve was the plotted over

Figure 16: Shifted Phase Angle
the shifted data to ensure the fit was representative of the data. An example of the fitted curve is presented in Figure 17.

![Figure 17: Fitted Phase Angle vs. Shifted Data](image)

Section 3.2: Creep Compliance

Creep compliance, $D(t)$, testing was completed with the same setup as the dynamic modulus and phase angle. An instantaneous load was applied and held for 200 seconds while the data acquisition program recorded the load and strain in all 4 LVDTs. Test temperatures included 0, -10 and -20°C. Total strain in each of the LVDTs was targeted between 100-300$\mu$e. The horizontal and vertical LVDT data were averaged at each time interval. A ratio of the horizontal and vertical deformation at 100 seconds after the start of testing was used, as shown in Equation 11.
\[
\frac{X}{Y} = \frac{\Delta X_t}{\Delta Y_t}
\]

Equation 11

Where:  
\(\Delta X_t\) = Average horizontal deformation at time \(t\)  
\(\Delta Y_t\) = Average horizontal deformation at time \(t\)

Creep compliance was calculated using Equation 12 and Equation 13. The plotted \(D(t)\) curves is presented in Figure 18.

\[
D(t) = \frac{\Delta X \times D \times b}{P \times GL} \times C_{cmlt}
\]

Equation 12

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

Equation 13

Where:  
\(D(t)\) = Creep Compliance at time \(t\), \(1/kPa\)  
GL = Gage length, meters  
D = Diameter of specimen, meters  
b = Average thickness of specimen, meters  
P = Creep load, kN
The creep compliance for each temperature was shifted to a reference temperature of -20°C using shift factors. The data were filtered and fit with a power law function as shown in Equation 14 and Excel’s Solver function was used to minimize the sum of error of all the temperatures. An example of the shifted and fitted predicted curve is presented in Figure 19.

\[ \text{Predicted } D(t) = D_0 + D_1 \ast (t^M) \]

Equation 14

Where: \( D_0, D_1 \) and \( M \) = Regression Coefficients
\( t \) = Time, second
Section 3.3: Strength Testing

Once the data from the creep and dynamic modulus testing had been analyzed, the specimen was moved back into the environmental chamber. It was cooled until it reached a temperature of -10°C ±0.5, which was monitored using a dummy specimen of similar dimensions fitted with an internal thermocouple. Once the test temperature had been reached, the specimen was loaded at a constant rate of 0.0082 in/sec until failure. The data were analyzed using the LTStress spreadsheet, April 2012 version, created by Don Christensen. The LTStress spreadsheet requires a user input of specimen dimensions, gage length of LVDTS, creep data from 3 replicate specimens at 0°C, -10°C and -20°C, and the load at failure from the same 3 specimens. The LTStress sheet was sensitive to noisy data, so data obtained from the creep test had to be pre-
smoothed before running the analysis. This was done by fitting an exponential curve to the data, and using the predicted exponential curve at the time increments used in the LTStress sheet. An example of the smoothed data is presented in Figure 20.

Section 3.4 Percent Difference and Ratio Analysis

Similar to the analysis performed for the binder results, the percent difference was taken between the specimens for strength values. The equation used to calculate the percent difference was:

\[
\% \text{ Difference} = \frac{(a - b)}{a}
\]

Equation 15

Where: \( a = \text{Control Specimen} \)
To compare the dynamic modulus and phase angle master curves, a ratio of the modulus and phase angle values at various reduced frequencies were calculated and plotted on a log scale. The equation used to calculate the ratio was:

\[
\text{Ratio} = \frac{\text{Modulus or Phase Angle Value of Mix A}}{\text{Modulus or Phase Angle Value of Mix B}}
\]

Equation 16

Where:
- \(\text{Modulus or Phase Angle of Mix A} = \text{Value at Frequency X}\)
- \(\text{Modulus or Phase Angle of Mix B} = \text{Value at Frequency X}\)
Chapter 3: Results and Discussion

Section 1: Naming Scheme for Binder Data

The name of the specimen started with the route number from which the sample was cored, followed by a “T” or “S” for travel lane or shoulder lane, respectively, followed by a number which indicates the %RAP in the mixture, followed by a “t”, “m”, or “b” for the top 0.5”, middle 1”, and bottom 1” respectively. Refer to Figure 4 through Figure 7 for depths of layers and binder extraction. Binder specimens that contained a mixture of surface and intermediate course binder were noted with a “*” at the end of the name.

Section 2: Binder Results

Only one binder extraction was taken at each depth for each mixture. Due to only having a single replicate, a typical statistical analysis could not be completed. Instead, a comparison of percent difference between the layer depths, travel and shoulder lanes, and RAP contents was used to determine the differences between the specimens. The control specimens for percent differences are displayed as the numerator in the legend of each graph. All comparisons were calculated at a reference temperature of -18°C.

It was expected that the high RAP mixtures would have higher stiffness and CCT, and lower m-value due to the already aged binder. Increased exposure to oxidation at the surface was expected to cause higher stiffness and CCT at the surface and decrease through the middle and bottom layers. The m-value was expected to decrease through
the middle and bottom layers. Traffic action has been shown to decrease the effects of aging at the surface, so it was probable that there would be lower stiffness and CCT values in the travel lane compared to the shoulder lane, and higher m-values in the travel lane.

High air voids can affect binder aging by allowing more air to flow through the mixture and increasing the rate of oxidation. High air voids extending into the lower layers can also allow oxidation to occur at deeper layers. Available air void data is displayed in Table 2. The high RAP intermediate course had much higher air voids than the surface course. This may have impacted the amount of aging in the intermediate course, if the oxygen was able to flow through the surface course. Only the I-89 shoulder surface had available air void data. The low RAP mixture had the highest air voids of any mixtures which could have affected the amount of aging the specimen experienced, particularly since it was at the surface.

Section 2.1: Stiffness

Superpave specifications required the creep stiffness values measured from BBR testing to be less than 300 MPa, as previously stated. A comparison of all stiffness results is shown in Figure 21. The BBR test was run at increasingly negative temperatures until the specimen failed to meet the Superpave specifications. For example, 93T35t was tested at -12 and -18°C because it had a stiffness value greater than 300 MPa at -18°C. The comparison of stiffness values show a decrease in stiffness with depth, lower stiffness in the travel lane compared to the shoulder lane and a
decrease in stiffness with lower RAP content. The stiffness trends followed the predicted behaviors, indicating these specimens are good candidates for determining if RAP has an impact on aging as there were no unexpected trends.

Figure 22 through Figure 24 present the percent differences between the different lane types, RAP contents and depths. Figure 22 presents the percent difference between the travel and shoulder lanes with depth between the high and low RAP mixtures. The graph presented a very interesting trend of behavior between the high and low RAP mixes. The high RAP mixes had decreasing difference in stiffness further away from the surface, the low RAP mixes had increasing difference in stiffness.

Figure 23 presents the percent difference between the depths and lanes. It can be assumed that the bottom layers are most similar in performance to the original mixture, as the rate of aging is slower further from the surface. Using this assumption, it was presented that the high RAP mixtures had less difference in aging with depth, or the high RAP mixtures were more similar in performance to the original mixture than the low RAP mixtures. This trend was demonstrated in both the travel and shoulder lanes.

Figure 24 presents the percent difference between RAP contents within lane types. The figure presents increasing difference with depth between the RAP contents. From Figure 21 and Figure 22, it has been demonstrated that there was higher variability between the stiffness of the low RAP mixtures with depth. Using this trend, along with those presented in Figure 24, the argument can be made that there was a difference in aging between high and low RAP mixtures. The high RAP mixtures were
stiffening at a much more uniform rate than the low RAP mixtures. If the previously
discussed assumption of the bottom layer being most similar to the original mixture was
used within the context of Figure 24, it would appear that the high RAP mixtures were
aging differently than the low RAP mixtures. The low RAP mixtures had more variability
between lanes which was highlighted in this figure, particularly in the travel lane.

Figure 21: Stiffness of All Binder Specimens
Figure 22: Percent Difference between Stiffness of Travel and Shoulder Lanes with Depth

Figure 23: Percent Difference between Stiffness of Lanes with Depth
Section 2.2: M-Value

Superpave specifications require the m-value measured from BBR testing to be greater than or equal to 0.300 at the testing temperature corresponding to the low PG grade. A comparison of all m-value results is presented in Figure 25. The comparison of m-values presented an increase in values with depth, higher m-values in the travel lane compared to the shoulder lane, and an increase in m-value with lower RAP content. The m-value trends also followed the predicted behaviors, further indicating the specimens are good candidates for investigating effects of RAP on aging.

Figure 26 through Figure 28 present the percent differences between the different lane types, RAP contents and depths. Figure 26 presents the percent difference between the travel and shoulder lanes with depth between the high and low RAP mixtures. Similar to the stiffness results, there was a larger difference among the low RAP mixtures compared to the high RAP mixtures between lane types. The same
trend observed in the stiffness results, where the difference was decreasing with depth in the high RAP mixtures while the difference increased in the low RAP mixtures, was also observed here. The previous assumption of the bottom layer being closest to original condition may explain why the high RAP mixtures are showing less difference in m-value at the bottom compared to the top. The low RAP mixtures have a much higher percent difference throughout lane types, indicating that they may be aging differently than the high RAP mixes.

Figure 27 presents the percent difference between the depths and lanes. The low RAP mixes had higher variability between depths in all lanes when compared to the high RAP mixes, with the exception of I-93 and I-89 travel middle/bottom. These results were demonstrating a more uniform aging with depth in the high RAP specimens, a much different behavior than the low RAP mixes. Also, using the assumption of the bottom being similar to the original mix, it appeared the high RAP mixes were aging less than the low RAP mixes.

Figure 28 presents the percent difference between RAP contents within lane types. The figure presented an increasing difference with depth between the RAP contents. Again similar to the stiffness results and discussion, it has been presented that there was a much greater variability in the low RAP mixtures, especially with depth from the surface. The low RAP mixtures had more variability between them which was highlighted in this figure, particularly in the travel lane.
Figure 25: M-Value of All Binder Specimens

Figure 26: Percent Difference between M-Value of Travel and Shoulder Lanes with Depth
Section 2.3: Critical Cracking Temperature

A comparison of all Critical Cracking Temperature (CCT) samples is presented in Figure 29. The comparison of CCT values presented a general decrease in CCT with depth, lower CCT in the travel lane compared to the shoulder lane, and a decrease in
CCT with lower RAP content. CCT values followed predicted trends based on previous research. As all the material followed expected trends, they were candidates for examining the effects of RAP on aging.

Figure 30 through Figure 32 presents the percent differences between the different lane types, RAP contents and depths. Figure 30 presents the percent difference between the travel and shoulder lanes with depth between the high and low RAP mixtures. Similar to data shown in previous comparisons, the high RAP mixtures had more similar performance with depth between layers while the low RAP mixtures had increasingly different performance with depth between layers. This trend was indicating a difference in aging between the high and low RAP mixtures.

Figure 31 presents the percent difference between the depths and lanes. Interestingly, the previous trends observed with the high RAP mixtures being less different with depth and lane type was not observed here, particularly between the top and middle specimens. Examining Figure 29, the high RAP travel and shoulder data had an unusual middle CCT. This may partially explain the change in trends for CCT between high and low RAP data. It is also important to point out that there is very little difference between the top and bottom of the high RAP travel lane, while the low RAP travel lane had the biggest difference between top and bottom specimens, which was also observed in previous data and does hint at difference in aging between high and low RAP mixtures.
Figure 32 presents the percent difference between RAP contents within lane types. The figure presented an overall increase difference with depth between the RAP contents in the travel lane and an overall decrease in difference with depth in the shoulder lane. The increase in difference with depth was observed in the previous two data sets. From Figure 30 and Figure 31, it has been demonstrated that there is higher variability between the stiffness of the low RAP mixtures with depth, especially in the travel lane. Using this trend, along with those presented in Figure 32, it was suggested that there was a difference in aging between high and low RAP mixtures and the high RAP mixes were aging at a slower rate than the low RAP mixes.

Figure 29: Critical Cracking Temperature of All Binder Specimens
Figure 30: Percent Difference between CCT of Travel and Shoulder Lanes with Depth

Figure 31: Percent Difference CCT Stiffness of Lanes with Depth
Section 2.4: Shear Modulus and Phase Angle

The dynamic shear modulus, $|G^*|$, master curves for all of the samples is presented in Figure 33. In general, the top sections had the highest (stiffest) master curves and the stiffness decreased with depth and RAP content. The shoulder lanes also had stiffer master curves than the travel lanes. These trends were further illustrated in Figure 34 through Figure 40, which presented a comparison of each lane and RAP content with depth, as well as all the lanes and RAP contents at each depth.

Figure 41 through Figure 44 present ratios of the different master curves by depth, lane type and RAP content. The ratio graphs indicated the relative stiffness between the mixtures, where the legend indicated which specimen was the numerator in the ratio. For example, Figure 41 presents the blue line as ratio of the shear modulus of the I-93 shoulder top specimen to the shear modulus of the I-93 shoulder middle.
specimen where a value larger than 1.0 would indicate the top specimen is larger, or stiffer, than the middle specimen.

With few exceptions, the low RAP mixtures showed larger ratios, indicating a larger difference in performance. Figure 41 and Figure 42 in particular demonstrated the difference between the low RAP and high RAP ratio differences. At all depths and frequencies the ratio of high RAP specimens were close to 1, indicating very similar performance while the low RAP travel lane ratio was close to 12 times greater between the top and bottom specimens and close to 5 times greater for the shoulder lane at low frequencies. This greater difference suggested the low RAP mixtures were not aging uniformly with depth, while the high RAP mixtures were aging at a more similar rate between the depths. Figure 43 also presented a more uniform aging between shoulder and travel lane for the high RAP mixtures, when compared with the low RAP mixtures.

![Figure 33: Summary of All Binder's |G*| Master Curves](image)
Figure 34: I-93 Travel $|G^*|$ Master Curves

Figure 35: I-93 Shoulder $|G^*|$ Master Curves
Figure 36: I-89 Travel $|G^*|$ Master Curves

Figure 37: I-89 Shoulder $|G^*|$ Master Curves
Figure 38: Top 0.5" |G∗| Master Curves

Figure 39: Middle 1.0" |G∗| Master Curves
Figure 40: Bottom 1.0" $|G^*|$ Master Curves

Figure 41: Ratio of $|G^*|$ by Depth from Surface for Travel Lanes
**Figure 42:** Ratio of $|G^*|$ by Depth from Surface for Shoulder Lanes

**Figure 43:** Ratio of $|G^*|$ of Lane by Depth
The phase angle master curves for samples are presented in Figure 45. In general, the elastic behavior increased with depth and the shoulder lanes had less elastic behavior than the travel lanes which were expected trends. RAP content seemed to have little impact on the elastic behavior of the mixtures. Figure 47 through Figure 52 present the master curves for each mixture and at each depth.

Figure 53 through Figure 56 present ratios of the different master curves by depth, lane type and RAP content. The differences among the phase angle ratio graphs were much smaller than those observed in the $|G^*|$ ratio graphs. There was an increase in ratio values at the high frequencies, but this trend was observed in all lane types and RAP contents. In general, there was no significant difference between phase angle values of high or low RAP mixtures. Figure 55 presented one trend that was observable, which was an increase in the difference between the high and low RAP mixtures with depth in the travel and shoulder lanes, although it was more noticeable in
the travel lane. This could indicate difference in aging, as the high RAP aged more uniformly, causing a greater difference between the depths further from the surface specimens.

Figure 45: Summary of All Binder's Phase Angle Master Curves

Figure 46: I-93 Travel Phase Angle Master Curves
Figure 47: I-93 Shoulder Phase Angle Master Curves

Figure 48: I-89 Travel Phase Angle Master Curves
Figure 49: I-89 Shoulder Phase Angle Master Curves

Figure 50: Top 0.5" Phase Angle Master Curves
Figure 51: Middle 1.0" Phase Angle Master Curves

Figure 52: Bottom 1.0" Phase Angle Master Curves
Figure 53: Ratio of Phase Angle by Depth from Surface for Travel Lanes

Figure 54: Ratio of Phase Angle by Depth from Surface for Shoulder Lanes
Section 3: Mixture results

The mixture dynamic modulus and phase angle data were difficult to compare.

Air voids that varied more than ±0.5% between mixtures were not able to be compared as air voids caused changes in performance that affected modulus and phase angle data.
As presented in Table 2, only two mixtures had air voids within the allowable range, the high RAP travel and shoulder intermediate layers. Further complicating data collection, IDT dynamic modulus and phase angle testing was extremely sensitive and testing specimens thinner than 1.0" was not practicable. The high RAP mixtures had surface and intermediate courses 1.0" or greater, but only the low RAP shoulder surface had a thickness greater than 1.0" and was able to be tested. Lack of low RAP data and varying air voids meant conclusions could not be drawn regarding aging effects of high RAP mixtures.

It was expected that the low RAP mixtures would be less stiff than the high RAP mixtures, that stiffness would decrease with depth and the travel lane would be less stiff than the shoulder lane. It was also expected that the low RAP mixtures would be more elastic than the high RAP mixtures, that an increase in depth would cause an increase in elastic behavior and the travel lane would be more elastic that the shoulder lane.

Section 3.1: Dynamic Modulus and Phase Angle

A dynamic modulus, $|E^*|$, master curve for each mixture is presented in Figure 57. In general, the shoulder surface courses had stiffer behavior than the other courses tested. The high RAP surfaces were less stiff than the low RAP surfaces and stiffness increased with depth. These results are not consistent with what was found with the binder testing nor are they expected based on previous research. It was likely a function of high varying air voids and other factors that are not able to be controlled in field conditions that caused these unusual results.
A two-tailed T-Test with confidence interval of 0.95 was conducted on the
dynamic modulus results at specific frequencies that covered the range of data tested.
The results of this statistical analysis can be found in Appendix Part C.3: in Table 3. 1-93
shoulder surface course was statistically different from the 1-93 shoulder Intermediate
course, 1-93 travel intermediate course and 1-89 shoulder surface course at low
frequencies. With a few exceptions at various frequencies, the other mixes all had no
significant statistical difference in dynamic modulus values.

Figure 58 through Figure 60 present ratio comparisons of the different mixtures.
As discussed previously, comparisons are not recommended for mixtures with air voids
varying more than ±0.5%.

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![Graph](image_url)

**Figure 57**: Summary of All |E*| Master Curves
Figure 58: Ratio of I-93 $|E^*|$ Master Curves by Lane

Figure 59: Ratio of I-93 $|E^*|$ Master Curves by Depth
A phase angle master curve for each mixture is presented in Figure 61. In general, the surface mixtures had similar low temperature (high frequency) performance. The intermediate course had the largest change in behavior from high temperature (low frequency) to low temperature (high frequency), as it went from most elastic to least elastic when compared to the surface mixtures. It is also interesting to note that at the surface, the travel lane had the more elastic behavior, but at the intermediate layer the shoulder lanes had more elastic behavior. As stated before, varying air voids most likely caused the varying trends that were not consistent with previous research and expected behavior. Phase angle data is particularly sensitive when tested in IDT mode, which also may have impacted the results.

Again, a two-tailed T-Test with a 0.95 confidence interval was conducted on the phase angle values of the mixtures. The results of this statistical analysis can be found in Appendix Part D.3: Phase Angle Statistical Analysis in Table 4. The I-93 shoulder
surface was again statistically different than the I-93 shoulder intermediate course, over nearly the entire frequency range, with the exception being at the lowest frequency. The I-93 shoulder surface was also statistically different from the I-89 shoulder surface at the lower and upper frequencies, but had no significant difference at the middle frequencies, and from the I-93 travel intermediate course at low frequencies. The I-93 shoulder intermediate course was statistically different from the I-89 shoulder surface at the middle frequencies. The remaining mixtures, with a few exceptions, showed no statistical difference.

Figure 62 through Figure 64 present ratio comparisons of the different mixtures. As discussed previously, comparisons are not recommended for mixtures with air voids varying more than ±0.5%. depth.

Figure 61: Summary of All Mixture's Phase Angle Master Curves
Figure 62: Ratio of I-93 Phase Angle Master Curves by Lane

Figure 63: Ratio of I-93 Phase Angle Master Curves by Depth
Section 3.2: Creep

A creep compliance, D(t), master curve for each mixture is presented in Figure 65. It was expected that the compliance would increase depth and RAP content. In general, there was a decrease in compliance with depth and the high RAP sections had more compliant behavior than the low RAP section, which was not expected behavior. This is likely attributed to the varying air voids as discussed previously. Figure 66 through Figure 68 present ratio comparisons of the different mixtures. As discussed previously, comparisons are not recommended for mixtures with air voids varying more than ±0.5% depth.
Figure 65: Summary of All Mixture D(t) Master Curves

Figure 66: Ratio of I-93 D(t) Master Curves by Lane
Section 3.3 Strength Testing

The estimated strength values for the mixtures are shown in Figure 69. It was expected that strength would decrease with depth from surface, the high RAP mixtures would have higher strength values than low RAP mixtures and the travel lane would
have a lower strength value than the shoulder lane. In general, there was a decrease in strength with depth and the high RAP sections at the intermediate layer had higher strength than the low RAP section. The 93 shoulder surface course (high RAP) had a much higher strength value than the other mixtures. These trends are consistent with expected results. It was unclear why the strength values followed expected trends while dynamic modulus, phase angle and creep compliance did not. Despite the expected behavior, there were not enough low RAP mixtures to investigate differences in aging behavior with RAP content.

The critical cracking temperature values for the mixtures are shown in Figure 70. It was expected that the CCT would decrease with depth from surface, the high RAP mixtures would have higher CCT than low RAP mixtures and the travel lane would have a lower CCT than the shoulder lane. In general, CCT decreased with depth and decreased with RAP content. These results follow some expected trends, but are still affected by varying air voids and do not have enough low RAP mixtures to draw any useful insights into effects of RAP on aging.
Section 4: Binder and Mixture Comparison

Comparing the results from the binder testing and the mixture testing, some conflicting trends emerge, particularly with respect to effects of depth and RAP content.

While the binder testing consistently presented decreasing stiffness with depth and
decreasing stiffness with RAP content, the mixture results presented increasing stiffness with depth and decreasing stiffness with higher RAP content. The different results can be partially explained by air voids. The intermediate layers and low RAP mixtures had significantly higher air voids, which may have increased the air flow throughout the mixture, increasing oxidation and speeding up the aging process.

When examining at the binder results, observed trends followed predicted results based on previous research. Stiffness testing, Critical Cracking Temperature and Shear Modulus testing all indicated that the travel lanes were less stiff than shoulder lanes, stiffness decreased with depth from the surface, and the RAP mixtures were stiffer than the low RAP mixtures. However, by comparing differences and ratios, another interesting trend emerged. The low RAP mixtures had much more variability in stiffness between layers, particularly between the top and middle layers at low frequencies. This trend was observed in both the travel and shoulder lanes results. While the high RAP mixtures were stiffer overall, there was more uniform aging between layers. Previous research has demonstrated that binder ages rapidly in the beginning of its service life and then begins to slow down. The RAP binder has already been aged and is likely causing the binder to age at more uniform rate with depth and between layers.

Trends were not as consistent for the mixture results. There was an increase in stiffness with depth in the shoulder high RAP mixture but a decrease in stiffness with depth in the travel high RAP mixture. The high RAP surface mixture was less stiff than
the low RAP surface mixture, which was not consistent with binder results. One trend
that was consistent with binder results was the travel lane was less stiff than the
shoulder.

Critical Cracking Temperature was tested for both the binder and mixture
specimens. While mixture trends CCT were not as unexpected as the other mixture
testing results, they were significantly higher temperatures than the binder CCT values.
This was most likely a result of the LTStress spreadsheet that was used for calculating
mixture CCT. The LTStress spreadsheet was extremely sensitive and may have been
affected by unknown factors or noisy data.

It is unclear what caused differences in results between the mixture and the
binder results. Air voids varied between mixtures, which likely caused changes in
performance of the mixture specimens. Other factors such as ADT, aggregate gradation,
mixing plant type, RAP source and layer thickness may have had an effect on the
mixture specimens that is unknown and unable to be controlled.
Chapter 4: Summary and Conclusions

The research goal for this project was to determine if high RAP mixes age differently than low RAP mixes. Field cores that had been in service for 23 years with varying amounts of RAP were obtained. Both binder and mixtures were tested from the surface and intermediate courses. Differences between high and low RAP performance were calculated and compared to determine if a difference in aging behavior existed.

The binder was extracted, recovered and tested for shear modulus, phase angle, stiffness, m-value and critical cracking temperature. The mixture was tested for dynamic modulus, phase angle, creep compliance, strength and critical cracking temperature.

The binder testing, in general, yielded trends among RAP contents, lane types and depths that were consistent with previous research. By quantifying the difference between the high and low RAP performance the following conclusions were drawn regarding the effects of RAP content on aging:

- High RAP binder had more uniform performance results between depths than low RAP binder
- High RAP binder had more uniform performance result with depth between shoulder and travel lanes than low RAP binder

The mixture testing, in general, yielded conflicting trends among RAP contents, lane types and depth that were not consistent with expected results. These unexpected trends may have been caused by varying air voids, which was unexpected but not
unusual as air voids change over the service life of the pavement, and other uncontrollable differences in the mixtures. Low air voids can increase the stiffness of the mixture, while extremely high air voids can have a similar effect over time by increasing the air flow through the pavement. Only one low RAP mixture could be tested. Lack of low RAP comparison mixtures and varying air voids meant mixture test results were inconclusive in answering the research objective. It was not possible to determine if the trends between the mixture performances were a result of RAP content or other factors that occurred within mixtures over time.

The research goal was answered by the evaluated the difference between high and low RAP binder and the observed trend of high RAP aging more uniformly between lanes and depths compared to the low RAP mixtures.
Recommendations for Future Work

The following items are recommendations to for future work to evaluate the effect of high RAP on asphalt pavement performance in field aged mixtures:

- Include test sections of wider range of RAP contents;
- Evaluate initial mixture and binder performance;
- Evaluate mixture and binder performance at regular time intervals throughout pavement service life; and
- Eliminate as many sources of error between test sections possible by selecting roadways with similar ADT and consistent aggregate gradation, layer thickness and air void content.
References


8. Tarbox, S., & Daniel, J. S. "Effects of Long Term Oven Aging on RAP Mixtures."

Appendix

Part A: Binder $|G^*|$ Results

Part A.1: Individual Specimen $|G^*|$ Master Curves

Figure 71: 93535t $|G^*|$ Master Curve

Figure 72: 93535m $|G^*|$ Master Curve
Figure 73: 95S35b $|G^*|$ Master Curve

Figure 74: 93T35t $|G^*|$ Master Curve
Figure 75: 93T35m $|G^*|$ Master Curve

Figure 76: 93T35b $|G^*|$ Master Curve
Figure 77: 8950t \(|G^*|\) Master Curve

Figure 78: 8950m \(|G^*|\) Master Curve
Figure 79: 8950b $|G^*|$ Master Curve

Figure 80: 89T0t $|G^*|$ Master Curve
Figure 81: 89T0m $|G^*|$ Master Curve

Figure 82: 89T0b $|G^*|$ Master Curve
Figure 83: Laf0t $|G^*|$ Master Curve

Figure 84: Lafo0m $|G^*|$ Master Curve
Figure 85: Lafob |G*| Master Curve

Part B: Binder Phase Angle Results

Part B.1: Individual Specimen Phase Angle Master Curves

Figure 86: 9353St Phase Angle Master Curve
Figure 87: 93S35m Phase Angle Master Curve

Figure 88: 93S35b Phase Angle Master Curve
Figure 89: 93T35t Phase Angle Master Curve

Figure 90: 93T35m Phase Angle Master Curve
Figure 91: 93T35b Phase Angle Master Curve

Figure 92: 89S0t Phase Angle Master Curve
Figure 93: 8950m Phase Angle Master Curve

Figure 94: 8950b Phase Angle Master Curve
Figure 95: 89T0t Phase Angle Master Curve

Figure 96: 89T0m Phase Angle Master Curve
Figure 97: 89T0b Phase Angle Master Curve

Figure 98: Laf0t Phase Angle Master Curve
Figure 99: Laf0m Phase Angle Master Curve

Figure 100: Laf0b Phase Angle Master Curve
Part C: Mixture $|E^*|$ Results

Part C.1: Individual Specimen $|E^*|$ Master Curves

Figure 101: C107AB $|E^*|$ Master Curve

Figure 102: C107AS $|E^*|$ Master Curve
Figure 103: C108AB $|E^*|$ Master Curve

Figure 104: C108AS $|E^*|$ Master Curve
Figure 105: C110B \( |E^*| \) Master Curve

Figure 106: C110S \( |E^*| \) Master Curve
Figure 107: C112B $|E^*|$ Master Curve

Figure 108: C112S $|E^*|$ Master Curve
Figure 109: C121AB $|E^*|$ Master Curve

Figure 110: C121AS $|E^*|$ Master Curve
Figure 111: C122B $|E^*|$ Master Curve

Figure 112: C122S $|E^*|$ Master Curve
Figure 113: C304AS $|E^*|$ Master Curve

Figure 114: C306AS $|E^*|$ Master Curve
Figure 115: C315AS |E*| Master Curve

Figure 116: C318AS |E*| Master Curve
Part C.2: Mixture $|E^*|$ Master Curves

Figure 117: I-93 Shoulder Surface Mixtures $|E^*|$ Master Curves

Figure 118: I-93 Shoulder Intermediate Mixtures $|E^*|$ Master Curves
**Figure 119: I-93 Travel Surface Mixture \(|E^*|\) Master Curves**

**Figure 120: I-93 Travel Intermediate Mixtures \(|E^*|\) Master Curves**
Part C.3: Mixture Dynamic Modulus Statistical Analysis

Table 3: Mixture Dynamic Modulus Statistical Analysis

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Part D: Mixture Phase Angle Results

Part D.1: Individual Specimen Phase Angle Master Curves

Figure 122: C107AB Phase Angle Master Curve

Figure 123: C107AS Phase Angle Master Curve
Figure 124: C108AB Phase Angle Master Curve

Figure 125: C108AS Phase Angle Master Curve
Figure 126: C110B Phase Angle Master Curve

Figure 127: C110S Phase Angle Master Curve
Figure 128: C112B Phase Angle Master Curve

Figure 129: C112S Phase Angle Master Curve
Figure 130: C121AB Phase Angle Master Curve

Figure 131: C121AS Phase Angle Master Curve
Figure 132: C122B Phase Angle Master Curve

Figure 133: C122S Phase Angle Master Curve
Figure 134: C304AS Phase Angle Master Curve

Figure 135: C306AS Phase Angle Master Curve
Figure 136: C315AS Phase Angle Master Curve

Figure 137: C318S Phase Angle Master Curve
Part D.2: Mixture Phase Angle Master Curves

Figure 138: I-93 Shoulder Surface Mixture Phase Angle Master Curves

Figure 139: I-93 Shoulder Intermediate Mixture Phase Angle Master Curves
Figure 140: I-93 Travel Surface Mixture Phase Angle Master Curve

Figure 141: I-93 Travel Intermediate Mixture Phase Angle Master Curve
**Figure 142:** I-89 Shoulder Surface Mixture Phase Angle Master Curve

**Part D.3: Phase Angle Statistical Analysis**

**Table 4: Mixture Phase Angle Statistical Analysis**

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112
### Part E: Mixture Creep Results

#### Part E.1: Individual Specimen D(t) Master Curves

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Figure 143: C107AB D(t) Master Curve

Figure 144: C107AS D(t) Master Curve
Figure 145: C108AB D(t) Master Curve

Figure 146: C108AS D(t) Master Curve
Figure 147: C110B D(t) Master Curve

Figure 148: C110S D(t) Master Curve
Figure 149: C112B D(t) Master Curve

Figure 150: C112S D(t) Master Curve
Figure 151: C121AB D(t) Master Curve

Figure 152: C121AS D(t) Master Curve
Figure 153: C122B D(t) Master Curve

Figure 154: C122S D(t) Master Curve
Figure 155: C304AS D(t) Master Curve

Figure 156: C306AS D(t) Master Curve
Figure 157: C306AS D(t) Master Curve

Figure 158: C315AS D(t) Master Curve
Part E.2: Mixture Creep Master Curves

Figure 159: C318AS D(t) Master Curve

Figure 160: I-93 Shoulder Surface Mixture D(t) Master Curve
Figure 161: I-93 Shoulder Intermediate Mixture D(t) Master Curve

Figure 162: I-93 Travel Surface Mixture D(t) Master Curve
Figure 163: I-93 Travel Intermediate Mixture D(t) Master Curve

Figure 164: I-89 Shoulder Surface Mixture D(t) Master Curve
### Part F: I-93 Original Job Mix Data Sheets

**NEW HAMPTONS HISTORICAL TESTING LABORATORY**

**Limestone Concrete Mix Information**

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<th>Hamilton Ave.</th>
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- **Plant Contractor**: *Campion*
- **Type Plant**: CAT PUM. *125 T.
- **Paving Contractor**: *P. WHITTING* 
- **Type Paver**: *N/A*

**Blend Specific Gravity**: 2.67

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**Cold Materials**

**Remarks:**