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Performance evaluations of HMA containing reclaimed asphalt pavement and reclaimed asphalt shingles

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PERFORMANCE EVALUATIONS OF HMA CONTAINING RECLAIMED ASPHALT PAVEMENT AND RECLAIMED ASPHALT SHINGLES

BY

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Submitted to the University of New Hampshire in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering

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ABSTRACT

PERFORMANCE EVALUATIONS OF HMA CONTAINING RECLAIMED ASPHALT PAVEMENT AND RECLAIMED ASPHALT SHINGLES

By

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University of New Hampshire, May, 2011

The use of recycled materials in the form of Reclaimed Asphalt Pavement (RAP) and Reclaimed Asphalt Shingles (RAS) in Hot Mix Asphalt (HMA) has become regular practice; however, when compared to the supply of these materials their use is still conservative. Comparative studies on the performance effects are needed to propose guidelines for the handling, processing, and incorporation of RAS and high RAP into mix design procedures. Presented here are results of examining lab produced HMA containing RAS and RAP. The RAS study indicates no significant difference in the stiffness in RAS vs. RAP mixes across most temperatures, and that similar cold temperature performances can be expected. The high RAP study indicates that while RAP content affects HMA stiffness, aggregate and virgin binder selections may also have an effect on the amount that RAP content will impact the properties of a mix.
CHAPTER 1: INTRODUCTION

The use of recycled materials in the form of Reclaimed Asphalt Pavement (RAP) and Reclaimed Asphalt Shingles (RAS) in Hot Mix Asphalt (HMA) has become regular practice for much of the country. As an alternative supply of both quality aggregate and asphalt, the use of RAP and RAS effectively cuts the cost of HMA production, and as the cost of virgin materials continue to rise, much of the paving industry has begun to look more seriously at increasing the use of these materials. While many state and federal agencies do currently use RAP in the majority of their mixes, typical contents are still generally limited to about 25%, which, when compared to the supply of RAP, is actually quite conservative. Lack of experience in handling and processing high RAP and RAS materials, as well as their potential effects on HMA quality, has limited their use in the field. What is needed before these materials can be used to their full potential are comprehensive studies that examine the performance effects of HMA containing these products when compared to that of a control mix, either a virgin mix or a more common mix that contains RAP within local specifications that would actually be used in the field. From these studies, suggestions can be made for mix design procedures and product management guidelines that would enable producers to use the materials both effectively and confidently.

RAP is generated when the materials from roads that have reached the end of their service life are milled and crushed. RAS, on the other hand, is generated from scrap shingle materials that can come from either factory or post-consumer tear-off waste. Because of the difference in origins of these materials, and the fact that RAP originally contained paving grade asphalt while RAS did not, the properties of these materials can be very different, and produce different
effects when introduced to an HMA mixture. The addition of these recycled materials to an asphalt mixture changes the mechanistic properties (i.e., strength) of the mixture and affects its performance (i.e., resistance to cracking and deformation) in the field. This is a result of the aged binder being introduced to the mixture as a part of the RAP and RAS, as this binder has a different chemical composition and different properties than the virgin binder being added to the mix (1). Previous studies (2-8) have shown that the virgin and recycled binders will mix to some extent, which will change the properties of the mixture containing RAP and/or RAS when compared to one that contains only virgin material. The extent of this blending is unknown and may be different for the various RAP and RAS sources and virgin binders. The actual, or effective, properties of the binder in mixtures containing RAP and/or RAS cannot be tested directly, as the process of extracting the binder for testing results in complete blending of the virgin and RAP binder; therefore, testing must be performed on the mixtures to determine the effective binder properties (1).

Recently, efforts have been made to begin the investigation on the potential effects the inclusion of RAS has in HMA; however, at this time there are very few published reports on such studies. Research out of Oregon has shown that the inclusion of 5% RAS in a dense-graded mix results in an increase of the high temperature and low temperature performance grade when compared to the virgin binder (9). This conclusion can actually be beneficial on the high temperature end, where increased stiffness can translate into an increase in strength. On the other hand, increased stiffness can also mean increased brittleness of the binder, and therefore impacts fatigue and cracking behavior. Research out of Minnesota has shown that RAS contents greater than 5% leads to a decreased stiffness over a wide range of temperatures, but test results indicate that this has little influence on the temperature susceptibility of HMA mixes (10). These outcomes present positive results for the use of RAS in HMA mixes, as even an
increase in stiffness in the low temperature end can be accommodated for in the mix design phase if the effects are known and can be expected.

HMA research has been conducted to study mixes containing high RAP contents. A study by the Virginia DOT compared mixes containing 21 to 30 percent RAP from seven asphalt plants to mixes containing less than 20 percent RAP. Laboratory tests performed on the specimens revealed no significant difference between the higher and lower RAP content mixes for fatigue, rutting, or susceptibility to moisture (11). Also, Illinois is currently attempting to use mixes containing up to 50% RAP in HMA, and examining the effect such a content would have on structural and durability properties (13).

The remainder of this thesis is broken in to three sections; the Chapter 2 details the testing and analysis methods used in the performance evaluations of HMA mixes containing RAS or high-RAP. The Chapter 3 presents the results, discussion and conclusions of the study on the performance evaluation of HMA mixes containing RAS. This project was funded by RAS-Tech Inc. Currently, RAS to be used in HMA is generally shredded or ground to a 3/8” maximum nominal size product. RAS-Tech Inc has developed an alternative processing method for reclaimed shingles with the intent of fully optimizing their use as a recycled material. RAS-Tech's processing method first cleans the shingles of non-aggregate material (i.e., wood chips, roofing nails, tape) that is common in stockpiles of both the factory and the post-consumer scrap. The shingles are then ground to a maximum nominal size of a #16 sieve size, which is subsequently separated into an above #50 (+50) mesh and a below #50 (-50) mesh stockpile. By separating the two gradations, the +50 mesh product has reduced fines content, making it ideal for use as a recycled aggregate in HMA mixtures, while the -50 mesh shingles can be used in other applications.
The fourth chapter of this thesis discusses the results of a collaborative project examining performance comparisons between HMA mixes at various RAP contents, including virgin and high RAP mixes. This study was funded under NCHRP project 9-46, and was a collaborative effort with the University of New Hampshire being responsible for the data analysis portion of the performance evaluations.
CHAPTER 2: TESTING AND ANALYSIS METHODS

This section discusses the testing and analysis methods used in both the RAS and high-RAP performance evaluation studies.

Construction of $|G^*|$ and $\delta_{\text{binder}}$ Master Curves

Master curves for virgin binder $|G^*|$ and $\delta_{\text{binder}}$ were constructed using shift factors determined from shifting the binder storage modulus along the reduced frequency axis. The binder storage modulus is calculated using:

$$G' = |G^*| \cdot \sin(\delta_{\text{binder}})$$

The storage modulus, $G'$, master curve is constructed first and used to establish the shift factors for the mixture. This approach includes both the modulus and phase angle in the determination of the shift factor. The shift factors obtained from the storage modulus master curve are then applied to create the modulus and phase angle master curves. The generalized logistic function, also called Rowe's model throughout this report, is used to fit the binder modulus and phase angles master curves. This fit is similar to the sigmoidal function that is commonly used, but has a fifth regression coefficient that allows the curve to be non-symmetric and provides a slightly better fit than the four coefficient sigmoidal function. The equations for the dynamic modulus and phase angle master curve fits are shown below in Equations 2 and 3, respectively.

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

$$\delta_{\text{binder}}(\omega_r) = 90 \cdot b \cdot d \cdot \frac{\exp(c+d \cdot log(\omega_r))}{[1+e^{c+d \cdot log(\omega_r)}]^{1+1/e}}$$
where: a, b, c, d, e = regression coefficients

\[ \omega_r = \text{reduced angular frequency} \]

Theoretically, the regression coefficients for the binder modulus and phase angle curves should be the same. However, this does not produce the best fits for the experimental data, so individual regression coefficients are found for each master curve to provide a more accurate representation of the measured data. All master curves were shifted to a temperature of 21.1 °C. The master curves for all mixtures in the high-RAP study showing the measured data are shown in Appendix 7. Figure 1 shows an example of a \(|G^*|\) master curve for a mix from the high-RAP study, FL virgin binder #239 PG 64-22.

Figure 1: \(|G^*|\) Master Curve for FL virgin binder #239 PG 64-22

\(|G^*|\) values for the RAS study were measured by Advanced Asphalt Technologies. For the high-RAP study, \(|G^*|\) values were measured by the National Center for Asphalt Technology (NCAT). It
should be noted for the high-RAP study that during testing some equipment malfunctions occurred, and once fixed UT virgin binder #121 PG 64-34A was not retested. Therefore mixes containing this virgin binder were not analyzed any further. Data concerning the $|G^*|$ and $\delta_{\text{binder}}$ can be found in Appendix 6 for the RAS study, and Appendix 8 for the high-RAP study.

**Dynamic Modulus Testing**

Dynamic Modulus testing was performed in uniaxial tension, which uses a measurement of strain along the vertical axis of the specimen. The dynamic modulus, $|E^*|$ is calculated using the equation:

$$|E^*| = \frac{\sigma_{\text{amp}}}{\varepsilon_{\text{amp}}}$$  \hspace{1cm} (4)

Where $\sigma_{\text{amp}}$ is the amplitude of the applied stress waveform and $\varepsilon_{\text{amp}}$ is the amplitude of the strain response. Testing was completed for the RAS study at UNH, and was performed at frequencies of 0.1, 0.2, 0.5, 1, 2, 5, 10 and 20 Hz and at temperatures of 20, 10, 0, -10 and -20 °C. For the high-RAP project, NCAT was responsible for measuring $|E^*|$ values. It should be noted that all $|E^*|$ testing performed by NCAT was performed with a confining pressure of 25 psi. A typical set of frequency sweep curves at different temperatures is shown in Figure 2.

![Figure 2: Typical Dynamic Modulus Data](image-url)
Construction of \(|E^*|\) and \(\delta\) Master Curves

Individual isotherms from \(|E^*|\) testing are shifted horizontally along the frequency axis to create a master curve using the time-temperature superposition principle. All dynamic modulus and phase angle data master curves have been constructed using shift factors determined from shifting the storage modulus along the reduced angular frequency axis. The storage modulus is calculated using:

\[
E' = |E^*| \cdot \sin(\delta)
\]  

(5)

This method includes both the dynamic modulus and phase angle data in the master curve construction process. The generalized logistic function is used to fit the dynamic modulus and phase angles master curves. The equations for the dynamic modulus and phase angle master curve fits are shown below in Equations 6 and 7, respectively.

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

(6)

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

(7)

where:  \(a, b, c, d, e = \) regression coefficients

\(\omega_r = \) reduced angular frequency

Theoretically, the regression coefficients for the dynamic modulus and phase angle curves should be the same. However, this does not produce the best fits for the experimental data, so individual regression coefficients are found for each master curve to provide a more accurate representation of the measured data. All master curves were shifted to a temperature of 21.1 °C. The master curves for all mixtures showing the measured data for the RAS study are shown in Appendix 4, and in Appendix 8 for the high-RAP study. Figure 3 shows an example of the \(|E^*|\)
master curves from the high-RAP study for the FL mixes. It is important to note that dynamic modulus and phase angle testing was performed with a confining pressure of 25 psi placed on the specimen.

Figure 3: |E*| Master Curve comparison for FL mixes

**Back calculation of |G*| from Hirsch Model**

In both projects, back calculations of the binder |G*| from the measured mixture |E*| were completed with the Hirsch model. Originally developed in the late 1960’s by T.J. Hirsch, this model was used to calculate the modulus of elasticity of concrete. In 2003, Christensen, Pellinen, and Bonaquist refined this model to predict the dynamic modulus of HMA using the binder modulus and volumetrics of the mix. Back calculations of the binder |G*| from the measured mixture |E*| were completed with the Hirsch model using the following equations:
\[ |E^{*}\|_{\text{mix}} = P_C \cdot \left[ 4,200,000 \cdot \left( 1 - \frac{VMA}{100} \right) + 3 \cdot |G^{*}|_{\text{binder}} \cdot \left( \frac{VFA \cdot VMA}{10,000} \right) \right] + \]

\[ (1 - P_C) \cdot \left[ \frac{1 - \frac{VMA}{100}}{4,200,000} + \frac{VMA}{3 \cdot VFA \cdot |G^{*}|_{\text{binder}}} \right]^{-1} \]  

(8)

\[ P_C = \left( \frac{20 + \frac{VFA \cdot |G^{*}|_{\text{binder}}}{VMA}}{650 + \left( \frac{VFA \cdot |G^{*}|_{\text{binder}}}{VMA} \right)^{0.58}} \right)^{0.58} \]  

(9)

Where: VMA = Voids in mineral aggregate  
VFA = Voids filled with asphalt  
Pc = Contact area

The procedure evaluated for performing the back calculation is described in this section. First,  
\(|E^{*}\|_{\text{mix}}\) values were calculated using the measured master curve fits over a range of frequencies ranging from 0.1 – 500,000 Hz. The  \(|G^{*}|_{\text{binder}}\) was then determined using a point-by-point error minimization approach that would match the forward calculated  \(|E^{*}|_{\text{mix}}\) with the measured \(|E^{*}|_{\text{mix}}\). The  \(|G^{*}|_{\text{binder}}\) master curves for both the high-RAP and RAS projects were subsequently fit using the generalized logistic function (equation 10). For the high-RAP project, back-calculated \(|G^{*}|\) master curves were also fit using the Christensen-Anderson model\(^1\) (equation 11), as some curves were better fit by the different models.

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

(10)

where:  
\(a, b, c, d, e = \) regression coefficients  
\(\omega_r = \) reduced angular frequency
\[ G_0 \left( 1 + \frac{\lambda}{\omega_r} \right)^{\beta} \]  

where:  

\( G_0 = \) Glassy modulus  
\( \lambda, \beta = \) regression coefficients  
\( \omega_r = \) reduced angular frequency

Values for the back-calculated \( \delta_{\text{binder}} \) were determined for both the generalized logistic function and the Christensen-Andersen cases as the slope of the fit. It is important to note that the Hirsch model was designed based on \( |E^*| \) values measured for unconfined specimens; since in the case of the high-RAP project \( |E^*| \) values were measured on specimens that had a confining pressure of 25 psi, all values should be used for comparison purposes only and not taken as true values.

**Blending Evaluation**

Using the forward calculation of dynamic modulus from the binder, it was planned to evaluate the degree of binder blending that was taking place in the sample HMA mixes for the RAS study. This could be accomplished by developing the master curve for the forward calculated dynamic modulus of the fully extracted binders. This master curve would serve as a model of the master curve that would be expected if full blending occurred between the virgin and recycled binders within the HMA mixing process. A master curve was also constructed using the forward calculated dynamic modulus of the virgin binder, which was calculated using the volumetric parameters of each mix; this curve acted to simulate the scenario where no blending between the virgin and recycled binders occurred. By comparing the measured master curve to the calculated master curve of the fully extracted asphalt and the virgin asphalt master curves, the extent of partial blending that was actually occurring within the HMA mixing process could be assessed. It should be noted that the binder modulus was measured at 10, 22, 34 and 46 °C,
so before the master curve of the measured and calculated dynamic moduli could be directly compared both curves had to be shifted to a temperature of 21.1 °C.

**Comparison of back calculated and measured |G*| values**

For the high-RAP project, the back calculated |G*| \_binder and \_\_\_binder values were compared to the measured |G*| and \_\_\_binder master curves in order to evaluate the extent of blending that is occurring in the various RAP mixtures. These comparisons can be seen in Appendix 10. It would be expected that for mixes where there is no blend of virgin and recycled binders, there should be a negligible difference between the back-calculated |G*| master curves for a mix and the measured |G*| master curve for a virgin binder. Since recycled binders are typically much stiffer than virgin binders, it would be expected that mixes containing recycled binder as part of their effective binder content should see an increase in |G*| values. A large increase in stiffness for the back-calculated |G*| master curve over the measured |G*| master curve for the virgin binder would suggest a large amount of blending between the virgin and recycled binders. For this study, the master curve |G*| \_binder and \_\_\_binder comparisons are shown in the Appendices 9 and 10. Figure 4 shows the comparison of the back calculated |G*| master curve from the high-RAP study for FL mix 9.5 mm – 0% RAP – PG 64-22 using both the Christensen-Anderson and Rowe fits with the measured |G*| master curve for the FL virgin binder.
To determine the effective performance grade upper limit of each mixture, the $|G^*|_{\text{mix}}$ and the $\delta_{\text{binder}}$ master curves were first shifted to different temperatures using appropriate shift factors. Together, the log of the shift factors for the binder and dynamic modulus data were plotted and fit with a second order polynomial equation so that the shift factor could be determined at any particular temperature for each mix. Figure 5 shows this process. The effective high temperature PG grade of the binder in the mix is determined as the temperature that corresponds with the value of $|G^*|/\sin(\delta) = 2.2$ kPa at 1.6 Hz. The values for $|G^*|$ were determined by shifting the back calculated master curve to the appropriate temperature (dividing reduced frequency by the shift factor corresponding with the particular temperature) and then determining the $|G^*|$ value at 1.6 Hz for that temperature. The same procedure was used to determine the $\delta$ at the test temperatures. Figures 6 and 7 illustrate this process for the
example mix from the high-RAP study of FL – 9.5 mm – 0% RAP – PG 64-22 with the Christiansen-Anderson fit

\[ y = 0.0005x^2 - 0.1281x + 2.4618 \]

\[ R^2 = 0.996 \]

**Figure 5: Fitted Shift Factors for FL mix - 9.5 mm - 0% RAP - PG 64-22**

**Figure 6: \(|G^*| \) values at 1.6 Hz for FL mix - 9.5 mm - 0% RAP - PG 64-22**
Figure 7: $\delta_{\text{binder}}$ values at 1.6 Hz for FL mix - 9.5 mm - 0% RAP - PG 64-22

The values for $\log(|G^*|/\sin(\delta))$ were then calculated and plotted against temperature and fitted with a linear regression. The temperature that corresponded with the $\log(|G^*|/\sin(\delta))$ value of $\log(2.2)$ was noted as the upper limit of the effective PG of the binder. Figure 8 illustrates this process for the example mix of FL – 9.5 mm – 0% RAP – PG 64-22. For this example, the effective PG upper limit was determined to be 107.2 °C.
Figure 8: $|G^*|/\sin\delta$ value at log(2.2) Hz for FL mix - 9.5mm - 0% RAP - PG 64-22

For the high-RAP project, this procedure was performed using the both the generalized logistic and the Christensen-Anderson fits for back calculated $|G^*|$ values. Most of the mixtures required extrapolation beyond the highest test temperature (76 °C). The effective PG was also determined using virgin binder measured $|G^*|$ and $\delta_{\text{binder}}$ values instead of back calculated values. The upper limits of the effective PG were not determined for mixes containing the UT virgin binder #122 PG 64-34A, as virgin binder modulus master curves were never developed for this binder.

**Thermal Stress Restrained Specimen Tensile Strength (TSRST) Test**

For the RAS study, the TSRST test was performed to assess the low temperature performance of each of the four HMA mixes. The test followed AASHTO procedure TP 10-93, with slightly different testing apparatus and specimen dimensions due to dimensions of gyratory
compactor used during specimen fabrication, as well as initial temperature of the specimen.

The test began once the specimen reached an internal temperature of -5 °C, as measured by the internal temperature of a dummy specimen with a thermocouple inserted that was placed in the environmental chamber of the Instron at the same time as the test sample. Once this occurred, the specimen was restrained by screwing the end plates of the specimen into place on the uniaxial testing jig. The specimen was then cooled at a rate of -6 °C per hour. The load that was experienced by the specimen by the material contraction was measured and recorded using LabView until fracture of the specimen occurred. The temperature as well as the load measured from the Instron at the point of fracture was noted. A typical temperature-strain load plot from a TSRST test can be seen in Figure 9. All data pertaining to the TSRST analysis for this study can be found in Appendix 7.

![Figure 9: Typical Temperature - Strain Load Plot from TSRST Test](image)
CHAPTER 3: PERFORMANCE EVALUATION OF HMA CONTAINING RAS

Introduction

This section discusses the use of RAS in HMA (15). Presented here are materials and mix designs, results from the performance evaluations and conclusions from this study. Funded by RAS-Tech, this study compared three test mixture containing different RAS products to one control mixture that contains RAP as the only alternative binder source. The laboratory mixes were tested and evaluated for their performance based on the critical cracking temperatures and PG grades for the recovered binders, as well as their $|E^*|$, $\delta$, $|G^*|$, and $\delta_{\text{binder}}$ master curves, TSRST performance, and effective PG upper limit as back-calculated from the $|E^*|$ values for the mix.

Materials

Virgin Aggregates

Virgin aggregates used in this project were donated from Pike Industries, Inc. and obtained from their Portsmouth, NH plant. The 12.5 mm, 9.5 mm and primary dust stockpiles came from Pike’s Eliot, ME quarry, while the washed sand and washed manufactured sand came from the Madbury, NH quarry. The gradations for each stockpile are shown in Table 1.
Table 1: Virgin Aggregate Gradations

<table>
<thead>
<tr>
<th>% Passing</th>
<th>Madbury Washed Sand</th>
<th>Madbury Washed Manufactured Sand</th>
<th>Eliot Primary Dust</th>
<th>9.5</th>
<th>12.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sieve size</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>37.5 (1 1/2&quot;)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>25.0 (1&quot;)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>19.0 (3/4&quot;)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>12.5 (1/2&quot;)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>94</td>
</tr>
<tr>
<td>9.5 (3.8&quot;)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>99</td>
<td>47</td>
</tr>
<tr>
<td>4.75 (#4)</td>
<td>96</td>
<td>99</td>
<td>98</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>2.36 (#8)</td>
<td>85</td>
<td>77</td>
<td>79</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>1.18 (#16)</td>
<td>69</td>
<td>53</td>
<td>58</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>0.6 (#30)</td>
<td>48</td>
<td>34</td>
<td>42</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>0.3 (#50)</td>
<td>24</td>
<td>19</td>
<td>28</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>0.15 (#100)</td>
<td>6</td>
<td>7</td>
<td>17</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>0.075 (#200)</td>
<td>1.5</td>
<td>2.6</td>
<td>9.8</td>
<td>1.3</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Virgin Asphalt Binder**

Virgin asphalt binder used in this project was donated from Pike Industries and obtained from their Portsmouth, NH plant. The binder was a PG 64 – 28, and contained a PPA (polyphosphoric acid) modifier. The mixing temperature was 165 °C and the compaction temperature was 145 °C. The continuous grade of the virgin binder can be seen in Table 4. Dynamic Shear values for the recovered binder are shown in Table 5, and creep stiffness and slope values are shown in Table 6.

**Reclaimed Asphalt Pavement (RAP)**

The RAP used in this project was donated from Pike Industries and obtained from their Portsmouth, NH plant. The the extracted PG grade of the RAP binder was 88 – 22. The actual and continuous PG grade of the RAP binder is shown in Table 4. The asphalt content and gradation of the RAP stockpile is shown in Table 2. Dynamic Shear values for the recovered binder are shown in table 5, creep stiffness and slope values are shown in Table 6. Critical cracking data for binder recovered from test mixes can be found in Appendix 3.
### Table 2: RAP Aggregate Gradation, Asphalt Content

<table>
<thead>
<tr>
<th>Sieve size mm</th>
<th>% Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>37.5 (1 1/2&quot;)</td>
<td>100</td>
</tr>
<tr>
<td>25.0 (1&quot;)</td>
<td>100</td>
</tr>
<tr>
<td>19.0 (3/4&quot;)</td>
<td>100</td>
</tr>
<tr>
<td>12.5 (1/2&quot;)</td>
<td>100</td>
</tr>
<tr>
<td>9.5 (3.8&quot;)</td>
<td>98</td>
</tr>
<tr>
<td>4.75 (#4)</td>
<td>75</td>
</tr>
<tr>
<td>2.36 (#8)</td>
<td>58</td>
</tr>
<tr>
<td>1.18 (#16)</td>
<td>46</td>
</tr>
<tr>
<td>0.6 (#30)</td>
<td>34</td>
</tr>
<tr>
<td>0.3 (#50)</td>
<td>22</td>
</tr>
<tr>
<td>0.15 (#100)</td>
<td>13</td>
</tr>
<tr>
<td>0.075 (#200)</td>
<td>7.6</td>
</tr>
<tr>
<td>Measured ac</td>
<td>4.37%</td>
</tr>
</tbody>
</table>

**Reclaimed Asphalt Shingles (RAS)**

There were three sources of RAS used in this project. All three sources were post-consumer materials. The normally ground shingles were donated from ERRCO in Epping, NH. RAS-Tech Inc. provided the +50 mesh and -50 mesh shingles. The asphalt contents as well as the gradations of the shingles were measured and are shown in Table 3. The recovered binder from the RAS was too stiff to be graded. Dynamic shear values for the recovered binder are shown in Table 5, creep stiffness and slope values are shown in Table 6. Critical cracking data for binder recovered from test mixes can be found in Appendix 3.
### Table 3: RAS Aggregate Gradation, Asphalt Content

<table>
<thead>
<tr>
<th>Sieve size</th>
<th>% Passing</th>
<th>Sieve size</th>
<th>% Passing</th>
<th>Sieve size</th>
<th>% Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm</td>
<td></td>
<td>mm</td>
<td></td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>37.5 (1 1/2&quot;)</td>
<td>ERRCO</td>
<td>RAS-Tech</td>
<td>RAS-Tech</td>
<td>+50 Mesh</td>
<td>-50 Mesh</td>
</tr>
<tr>
<td>25.0 (1&quot;)</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>19.0 (3/4&quot;)</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>12.5 (1/2&quot;)</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>9.5 (3.8&quot;)</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>4.75 (#4)</td>
<td>97.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>2.36 (#8)</td>
<td>94.3</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>1.18 (#16)</td>
<td>67.5</td>
<td>77.1</td>
<td>100.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6 (#30)</td>
<td>42.6</td>
<td>39.1</td>
<td>94.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3 (#50)</td>
<td>36.2</td>
<td>26.8</td>
<td>90.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.15 (#100)</td>
<td>30.2</td>
<td>21.2</td>
<td>74.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.075 (#200)</td>
<td>23.6</td>
<td>17.4</td>
<td>57.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured AC</td>
<td>23.62%</td>
<td>12.1%</td>
<td>28.0%</td>
<td></td>
<td></td>
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</tbody>
</table>

### Table 4: Asphalt Grades from Each Source of Binder

<table>
<thead>
<tr>
<th>Source</th>
<th>PG Grade</th>
<th>Continuous PG Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP</td>
<td>88 — 22</td>
<td>89.3 — 22.0</td>
</tr>
<tr>
<td>Normal Ground Shingles</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>+50 Mesh Shingles</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>-50 Mesh Shingles</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Virgin Binder</td>
<td>64 — 28</td>
<td>65.1 — 29.8</td>
</tr>
</tbody>
</table>

### Table 5: Dynamic Shear Values for Recovered Binder from Each Source

<table>
<thead>
<tr>
<th>Source</th>
<th>Temp</th>
<th>Dynamic Shear G*/sinδ (kPa)</th>
<th>Temp</th>
<th>Dynamic Shear G*/sinδ (kPa)</th>
<th>Temp</th>
<th>Dynamic Shear G*/sinδ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Recovered Binder</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RAP</td>
<td>88 °C</td>
<td>1.17</td>
<td>88 °C</td>
<td>2.53</td>
<td>28 °C</td>
<td>4098</td>
</tr>
<tr>
<td></td>
<td>94 °C</td>
<td>0.94</td>
<td>94 °C</td>
<td>1.33</td>
<td>25 °C</td>
<td>5696</td>
</tr>
<tr>
<td>Normal Ground Shingles</td>
<td>112 °C</td>
<td>89.90</td>
<td>112 °C</td>
<td>99.82</td>
<td>34 °C</td>
<td>5268</td>
</tr>
<tr>
<td>Shingles</td>
<td>118 °C</td>
<td>151.8</td>
<td>118 °C</td>
<td>171.03</td>
<td>37 °C</td>
<td>4681</td>
</tr>
<tr>
<td>+50 Mesh Shingles</td>
<td>112 °C</td>
<td>15.49</td>
<td>112 °C</td>
<td>31.56</td>
<td>28 °C</td>
<td>4990</td>
</tr>
<tr>
<td>Shingles</td>
<td>118 °C</td>
<td>8.28</td>
<td>118 °C</td>
<td>20.95</td>
<td>25 °C</td>
<td>5903</td>
</tr>
<tr>
<td>-50 Mesh Shingles</td>
<td>112 °C</td>
<td>8.85</td>
<td>112 °C</td>
<td>19.96</td>
<td>25 °C</td>
<td>4930</td>
</tr>
<tr>
<td>Shingles</td>
<td>118 °C</td>
<td>5.43</td>
<td>118 °C</td>
<td>4930</td>
<td>22 °C</td>
<td>5846</td>
</tr>
</tbody>
</table>

**Table 3:** RAS Aggregate Gradation, Asphalt Content

**Table 4:** Asphalt Grades from Each Source of Binder

**Table 5:** Dynamic Shear Values for Recovered Binder from Each Source
Table 6: Creep Stiffness and Slope Values at 60 s for Recovered Binder from Each Source

<table>
<thead>
<tr>
<th>Source</th>
<th>Temp</th>
<th>S</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP</td>
<td>-12 °C</td>
<td>218</td>
<td>0.300</td>
</tr>
<tr>
<td></td>
<td>-18 °C</td>
<td>419</td>
<td>0.240</td>
</tr>
<tr>
<td>Normal Ground Shingles</td>
<td>0 °C</td>
<td>109</td>
<td>0.206</td>
</tr>
<tr>
<td></td>
<td>-30 °C</td>
<td>690</td>
<td>0.155</td>
</tr>
<tr>
<td>+50 Mesh Shingles</td>
<td>0 °C</td>
<td>62</td>
<td>0.266</td>
</tr>
<tr>
<td></td>
<td>-30 °C</td>
<td>612</td>
<td>0.177</td>
</tr>
<tr>
<td>-50 Mesh Shingles</td>
<td>0 °C</td>
<td>32.6</td>
<td>0.277</td>
</tr>
<tr>
<td></td>
<td>-30 °C</td>
<td>655</td>
<td>0.177</td>
</tr>
</tbody>
</table>

Mix Design

In the scope of this project, four mix designs were developed; one with the recycled binder from RAP only, and one each with the recycled binder from RAP as well as a RAS product. It was initially proposed to use mixtures that contained different proportions of the shingle products from RAS-Tech, however, it was later decided to use either the +50 mesh or -50 mesh material only in a mix in order to examine the extremes of any effects the different products would have on the HMA properties. A NH DOT mix Type E, 12.5 mm (1/2") Superpave Surface Course mix design was used as a template in designing these mixtures. The specifics of this mix design can be seen in Appendix 1. Each mixture used the same gradation to allow a more direct evaluation of the effects the different RAP/RAS contents on the material properties.

The asphalt content coming from recycled binder was changed from the original Pike mix design in order to achieve the maximum allowed recycled materials as specified in the 2009 NHDOT specifications, which permits recycled binder in mix designs of up to 0.8%, with 0.6% of which can come from shingles (12). All mixes followed Superpave and were designed for the conditions of light traffic, with less than 0.3 million ESALs. In order to follow Superpave specifications of 4% air voids using a gyratory compactive effort of \( N_{des} = 50 \), the total asphalt content of the RAP only mixture was increased from 5.4% as Pike specified to 5.7% by adding
additional virgin binder. Likewise, the total asphalt content was adjusted by adding additional virgin binder for each of the mixtures containing RAS in order to reach this target of 4% air voids at $N_{des} = 50$. The gradations for each mixture are shown in Table 7 and Figure 10; the asphalt content coming from recycled sources as well as the total asphalt content for each mix can be seen in Table 4 as well. Volumetrics for the four mixes are shown in Table 8.

Table 7: Mixture Gradations, Asphalt Contents

<table>
<thead>
<tr>
<th>Sieve size</th>
<th>RAP Only Mix</th>
<th>Mix with Normal Ground Shingles</th>
<th>Mix with +50 Mesh Shingles</th>
<th>Mix with -50 Mesh Shingles</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm</td>
<td>% Passing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>37.5 (1 1/2&quot;)</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>25.0 (1&quot;)</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>19.0 (3/4&quot;)</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>12.5 (1/2&quot;)</td>
<td>98.7</td>
<td>98.7</td>
<td>98.7</td>
<td>98.7</td>
</tr>
<tr>
<td>9.5 (3.8&quot;)</td>
<td>86.0</td>
<td>86.0</td>
<td>86.0</td>
<td>86.0</td>
</tr>
<tr>
<td>4.75 (#4)</td>
<td>57.9</td>
<td>57.9</td>
<td>57.9</td>
<td>57.9</td>
</tr>
<tr>
<td>2.36 (#8)</td>
<td>43.0</td>
<td>43.0</td>
<td>43.0</td>
<td>43.0</td>
</tr>
<tr>
<td>1.18 (#16)</td>
<td>32.4</td>
<td>32.4</td>
<td>32.4</td>
<td>32.4</td>
</tr>
<tr>
<td>0.6 (#30)</td>
<td>22.6</td>
<td>22.6</td>
<td>22.6</td>
<td>22.6</td>
</tr>
<tr>
<td>0.3 (#50)</td>
<td>13.2</td>
<td>13.2</td>
<td>13.2</td>
<td>13.2</td>
</tr>
<tr>
<td>0.15 (#100)</td>
<td>5.8</td>
<td>5.8</td>
<td>5.8</td>
<td>5.8</td>
</tr>
<tr>
<td>0.075 (#200)</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>ac from RAP</td>
<td>0.8%</td>
<td>0.2%</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>ac from RAS</td>
<td>0.0%</td>
<td>0.6%</td>
<td>0.6%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Virgin ac</td>
<td>4.9%</td>
<td>5.7%</td>
<td>5.2%</td>
<td>5.3%</td>
</tr>
<tr>
<td>Total ac</td>
<td>5.7%</td>
<td>6.5%</td>
<td>6.0%</td>
<td>6.1%</td>
</tr>
</tbody>
</table>
Figure 10: Mixture Gradation Curves

Table 8: Mixture Volumetrics

<table>
<thead>
<tr>
<th></th>
<th>Voids-in-the Mineral Aggregate (VMA, %)</th>
<th>Voids Filled With Asphalt (VFA, %)</th>
<th>Dust-to-Binder Ratio</th>
<th>%Gmm @ N_{ini}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superpave Criteria</td>
<td>≥ 14.0</td>
<td>70 - 80</td>
<td>0.6 – 1.2</td>
<td>≤ 91.5</td>
</tr>
<tr>
<td>RAP Only Mix</td>
<td>15.8</td>
<td>76.9</td>
<td>0.61</td>
<td>90.2</td>
</tr>
<tr>
<td>Mix with Normal Ground Shingles</td>
<td>17.2</td>
<td>77.0</td>
<td>0.54</td>
<td>90.0</td>
</tr>
<tr>
<td>Mix with +50 Mesh Shingles</td>
<td>16.1</td>
<td>75.7</td>
<td>0.59</td>
<td>91.1</td>
</tr>
<tr>
<td>Mix with -50 Mesh Shingles</td>
<td>16.6</td>
<td>75.4</td>
<td>0.56</td>
<td>90.2</td>
</tr>
</tbody>
</table>
**Specimen Fabrication**

All virgin aggregate was sieved and stored in separate stockpiles by sieve size. The RAP and RAS was stored as individual stockpiles, unsieved. Virgin aggregate for each specimen was batched by sieve size, while the RAP and RAS was batched as a stockpile, assuming that a representative sample was taken from each stockpile. Virgin aggregates, RAP, and RAS were cold blended prior to any heating to aid in mixing. If pre-blending was not done, agglomerations of the materials would occur due to their high asphalt contents. These mixtures were heated along with the virgin binder for the period of time required for the asphalt to come to proper mixing temperature (165 °C), generally 1.5 to 2 hours. Once combined in a bucket mixer, the HMA was short term aged for two hours at the compaction temperature. The specimens were then compacted to a specified height using a Superpave Gyratory Compactor (SGC). After compaction, the specimens were allowed to cool to room temperature overnight, and cut using diamond wet saws to testing dimensions (75 mm diameter, 150 mm height). The G\(m_b\) of all specimens were measured using a Corelok Vacuum Sealing system. The air void content, VMA, and VFA values were calculated for each specimen.

The G\(s_b\) for the shingles aggregate was not directly measured, instead, a range of possible VMA and VFAs were calculated for each specimen; in the end, it was determined that this range of G\(s_b\) for the RAS aggregate did not have a large enough impact on the VMA and VFA of a specimen to be considered significant. Therefore, in all subsequent calculations involving the VMA and VFA, the average value of G\(s_b\) was used. All specimens used in this study matched the target air void content of 4%, ± 0.5%. Individual values for the volumetric properties of each specimens can be found in Appendix 2. A naming scheme was developed that had all specimens containing the RAP only mixture begin with the letter R; all specimens containing both RAP and the Normal Ground Shingles product began with the letter N; all specimens containing both the
RAP and the +50 mesh shingles product began with the letter G; and all specimens containing both the RAP and -50 mesh shingles product began with the letter L. This letter was then followed by the mix’s total asphalt content, and the batch ID. Individual test specimen volumetrics can be found in Appendix 2.

**Testing Setup and Equipment**

The strength and dynamic modulus testing performed in this study were conducted using a closed-loop servo-hydraulic system, manufactured by Instron®. The testing apparatus included the loading frame (model 8800), a 20k kip hydraulic load actuator (model IST 3690 Series 100kN Pedestal Mounted Actuator), a 5 kip load cell, a 20 kip load cell, control tower (model 8500), a control panel (model 8500 Plus), an environmental chamber (model 3119-407), and personal computers Instron’s Fast Track 2 Software (actuator control), Labview 7.1 (data acquisition), Microsoft® Excel and MATLAB (data and statistical analysis) (1). The set up for the TSRST test also required a National Instruments Hi-Speed USB Carrier (NI USB-9162).

The Envirotherm® environmental chamber was used to set the testing environment desired using low pressure nitrogen. The chamber controlled the temperature within ±0.1 °C with a Eurotherm® thermostat (model 2408); the range of testing was performed between -20 and 20 °C. Figure 11 shows the environmental chamber with the nitrogen hose in the lab; Figure 12 shows the thermostat. During testing, a dummy sample of the same dimensions of the test specimens with a thermocouple permanently inserted was placed within the environmental chamber in order to monitor the internal temperature of the test specimen.
Specimens were prepped for dynamic modulus and TSRST test simultaneously. All specimens were cored and cut to have a 75 mm diameter and a height of 150 mm. Once specimens were surface dry, metal end plates were attached and the epoxy was allowed to cure a minimum of 12 hours. In order to measure the uniaxial strain placed on the specimen during.
dynamic modulus testing, four sets Linearly Variable Differential Transducers (LVDTs) were attached to the specimen using L-shaped brackets that were attached with screws to brass targets that had been set with epoxy on the specimen. Each set of LVDTs had a length of 4” along the vertical axis of the specimen, and each set was oriented at 90° from each other. The length of the LVDTs was measured several times with calipers throughout the gluing process to ensure that this 4” length was precisely maintained. Figure 13 shows a specimen completely prepped for dynamic modulus mounted within the uniaxial testing jig in the environmental chamber.

Figure 13: Fully Prepared and Mounted Specimen Ready for Dynamic Modulus Testing
Once dynamic modulus testing was completed for each specimen it was prepped for a TSRST test. For this, the specimen remained in the environmental chamber (unrestrained) and was cooled to the testing temperature. LVDTs were removed from the surface and replaced with three thermocouples connected to the NI hi-speed USB carrier at the top, middle and bottom of the specimen which measured surface temperature. These thermocouples were held in place simply with clay putty. It should be noted that if this procedure is duplicated, it is not recommended to use tape to fasten the thermocouples to the specimen, as they will instead record a measurement that is a combination of the surface and chamber temperatures. By using clay there is a small barrier between the chamber and the thermocouple so that recorded temperatures are more representative of the surface of the specimen.

**Results and Discussion**

This section presents binder testing performed on the extracted and recovered binder from each mixture. Additionally, the results of the complex modulus testing with the Hirsch model comparison, the TSRST tests, and the fatigue tests, are presented within this section.

**Recovered Binder Test Results**

**Asphalt Grades, Creep Stiffness and Slope**

The PG grades were determined for the recovered binder from the four HMA mixes and are summarized in Table 9. The addition of RAP and RAS cause a change in both the high and low PG grades from the virgin PG 64-28 binder that was used. The continuous high and low PG temperatures are greater for the RAS mixtures, although the normal ground shingle mixture is not quite high enough to cause an increase in the high PG grade above the RAP mixture. The increase in temperature on the low side is not significant enough to cause a difference in the low PG grade between the RAP and RAS mixtures.
G*/sinδ values measured using recovered binder from each mixture are presented in Table 10. The G*/sinδ values indicate that the binder extracted from the normal ground shingles mix was stiffer than that which was extracted from the RAP, +50 mesh shingle, or -50 mesh shingle mix, which were comparable to each other. However, the G*sinδ values indicate that at 19 °C, the extracted binder from all four mixes are comparable, and at 16 °C the RAP mixture is stiffer. Creep stiffness and m-values measured using the recovered binder from each mixture are given in Table 11. The creep stiffness values show that those containing RAS were comparable to the mix that contained RAP only at -12 °C, and were less stiff at -18 °C. Superpave mix design requirements put a restriction on binder test results for the Bending Beam Rheometer tests, requiring binder to have a maximum stiffness of 300 MPa and a minimum m-value of 0.300 at -24 °C. The S and m-values for binder recovered from the mixes can be seen in Table 11. For the fully recovered mix binder, all binders fail to meet this requirement, however it is important to keep in mind that the fully recovered mix binder represents the case of 100% blending which is most likely not the case for the actual mix binder. The RAS mixtures generally have lower m-values than the RAP mixture; so the low temperature PG grade of the RAP mixture would tend to be limited by the S value whereas the m-value would tend to control the low PG grade of the RAS mixtures.
Table 10: G*/sinδ Values for Recovered Binder from Mixtures

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Temp (°C)</th>
<th>G*/sinδ (kPa)</th>
<th>Temp (°C)</th>
<th>G*sinδ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP Only</td>
<td>70</td>
<td>2.48</td>
<td>19</td>
<td>4831</td>
</tr>
<tr>
<td></td>
<td>76</td>
<td>1.21</td>
<td>16</td>
<td>9271</td>
</tr>
<tr>
<td>Normal Ground Shingles</td>
<td>70</td>
<td>4.20</td>
<td>19</td>
<td>4637</td>
</tr>
<tr>
<td></td>
<td>76</td>
<td>2.03</td>
<td>16</td>
<td>6363</td>
</tr>
<tr>
<td>+50 Mesh Shingles</td>
<td>76</td>
<td>2.47</td>
<td>19</td>
<td>4873</td>
</tr>
<tr>
<td></td>
<td>82</td>
<td>1.3</td>
<td>16</td>
<td>6730</td>
</tr>
<tr>
<td>-50 Mesh Shingles</td>
<td>76</td>
<td>2.28</td>
<td>19</td>
<td>4473</td>
</tr>
<tr>
<td></td>
<td>82</td>
<td>1.2</td>
<td>16</td>
<td>6567</td>
</tr>
</tbody>
</table>

Table 11: Creep Stiffness and m-Values at 60 s for Recovered Binder from Mixtures

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Temperature (°C)</th>
<th>S (MPa)</th>
<th>m-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP Only</td>
<td>-12 °C</td>
<td>117</td>
<td>0.332</td>
</tr>
<tr>
<td></td>
<td>-18 °C</td>
<td>259</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>-24 °C</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Normal Ground Shingles</td>
<td>-12 °C</td>
<td>118</td>
<td>0.333</td>
</tr>
<tr>
<td></td>
<td>-18 °C</td>
<td>244</td>
<td>0.281</td>
</tr>
<tr>
<td></td>
<td>-24 °C</td>
<td>478</td>
<td>0.239</td>
</tr>
<tr>
<td>+50 Mesh Shingles</td>
<td>-12 °C</td>
<td>117</td>
<td>0.322</td>
</tr>
<tr>
<td></td>
<td>-18 °C</td>
<td>246</td>
<td>0.284</td>
</tr>
<tr>
<td></td>
<td>-24 °C</td>
<td>455</td>
<td>0.256</td>
</tr>
<tr>
<td>-50 Mesh Shingles</td>
<td>-12 °C</td>
<td>121</td>
<td>0.328</td>
</tr>
<tr>
<td></td>
<td>-18 °C</td>
<td>248</td>
<td>0.284</td>
</tr>
<tr>
<td></td>
<td>-24 °C</td>
<td>452</td>
<td>0.223</td>
</tr>
</tbody>
</table>

Critical Cracking Temperature

The critical cracking temperature was determined for the recovered binder from each of the HMA mixes as well as for the virgin binder, as shown in Figure 14. The addition of recycled materials increases the critical cracking temperature, with the RAP only mixture showing the largest increase. The + 50 mesh and -50 mesh mixtures are similar, with the normal ground shingles showing a higher value. Higher critical cracking temperatures lead to worse low temperature performance; based on these results, the RAP only mix is indicated as the mix with the worse low temperature performance.
This section provides a summary of the binder shear modulus and binder phase angle data measured on recovered binder from the four HMA mixes. Figure 15 shows the comparison of all $|G^*|$ master curves and Figure 16 shows the comparison of all binder phase angle ($\delta_b$) master curves. The recovered binders from the mixes containing RAS are stiffer than the RAP mix and the virgin binder at low reduced frequencies (high temperature). The RAS mixes are nearly indistinguishable from each other. At the higher frequencies (lower temperatures), all of the recovered binder from the HMA mixes have similar values for $|G^*|$, which are stiffer than the virgin binder.

The recovered binder phase angle master curves for the RAS mixes are similar and less viscous than the virgin binder and the recovered RAP mix binder. The slope of the RAS mix binder curves match the slope of the virgin binder phase angle master curve, but the recovered RAP mix binder has a steeper slope.
Figure 15: Binder Modulus Master Curves for Recovered and Virgin Binders

Figure 16: Binder Phase Angle Master Curves for Recovered and Virgin Binders
Mixture Test Results

Dynamic Modulus and Phase Angle

This section provides a summary of the dynamic modulus and phase angle data measured for the four mixtures. Figures 17 and 18 show the comparison of the average dynamic modulus and phase angle master curves for each mixture, respectively.

Figure 17: Average Dynamic Modulus Master Curve Comparison of all Mixes

Figure 18: Average Phase Angle Master Curve Comparison of all HMA Mixes
From Figure 17, it is clear that the RAP only mixture has a higher mean dynamic modulus than the RAS mixtures at the higher reduced frequencies (i.e. at some test temperatures). It also appears that the RAS mixtures are all similar. The dynamic modulus values at specific frequencies along the master curve were compared using the t-test with a 95% confidence interval to determine if there is a significant difference between mixtures. The analysis showed that the RAP mix is significantly different than +50 mesh and -50 mesh mixes, but not different than the normal ground shingles mixture. The normal ground shingles mix was significantly different than the -50 mesh and RAP mixtures only at higher reduced frequencies (>1x10^5 Hz).

Similarly, the t-test was conducted using phase angle mastercurve data. Over most of the reduced frequency range, the mean values of phase angles were statistically comparable. However, the normal ground shingles values were significantly different than the -50 mesh mix at frequencies greater than 1x10^5 Hz. The RAP mixture has a higher percent binder replacement and lower asphalt content than the RAS mixtures, which could explain the stiffer dynamic modulus. This may also be an indication of the amount of blending occurring between the recycled and virgin binder in each mix; if the RAP binder blends more than the RAS binder (i.e. the RAS is acting more like a black rock), the RAP mixture would have a stiffer effective binder modulus, resulting in a stiffer measured dynamic modulus for the mixture.

**Hirsch Model Comparison of Dynamic Modulus**

The forward calculations of the dynamic modulus from the recovered and virgin binders using the Hirsch model are compared to the measured mixture dynamic modulus values to evaluate the degree of blending that occurred within the HMA mixing procedure. All master curves were shifted to 20 °C. Figures 19 – 22 show the results of these comparisons. The process of recovering binder from the mixture results in full blending of the virgin and recycled binders, so it was expected that this master curve would represent the stiffest possible dynamic modulus values. The virgin binder modulus was used to represent the case where no blending
occurs, providing the lower bound dynamic modulus curve. However, for all four mixtures, the measured mixture master curves are stiffer than the predicted master curves from the recovered (fully blended) binder. This phenomenon is not completely understood at this time and is likely due to some other mixture properties. This has been noted by other researchers (16) and will be investigated in the future.

Figure 19: Master Curve Comparison for HMA Mix Containing RAP Only
Figure 20: Master Curve Comparison for HMA Mix Containing Normal Ground Shingles

Figure 21: Master Curve Comparison for HMA Mix Containing +50 Mesh Shingles
Effective PG Determination

To complete the determination of the effective PG grade for each mixture, the binder shear modulus was back calculated using the Hirsch model and the measured mixture the dynamic modulus curves. The back calculated (from mix) and measured (from recovered binder) $|G^*|$ master curves are shown in Figure 23. All master curves are shifted to 20 °C.
The effective high PG temperature for each mixture determined using the back calculated $|G^*|$ (partial blending) and the measured $|G^*|$ (full blending) curves are summarized in Table 12. Using the recovered binder analysis, the RAS mixtures all have similar high PG temperatures that are greater than that for the RAP mixture. The RAP mixture shows a high PG temperature below the virgin binder grade, which is likely an artifact of extrapolating the shift factors. The effective high PG temperatures based on the back calculated values are greater than those for the measured values, as expected. However, the trend among the mixtures is different. The normal ground shingles have the highest value, and the RAP and +50 mesh mixtures are more similar.
Table 12: Comparison of Effective PG for HMA Mixes from Measured Extracted (Fully Blended) and Back Calculated $|G^*|$.

| Mixture          | High PG Temperature: Measured $|G^*|$ | High PG Temperature: Back Calculated $|G^*|$ |
|------------------|--------------------------------------|------------------------------------------|
| RAP Only         | 61.5                                 | 88.0                                     |
| Normal Ground Shingles +50 Mesh Shingles | 78.5 | 93.0 |
| -50 Mesh Shingles          | 76.0                                 | 74.4                                     |
|                   | 80.0                                 | 77.1                                     |

**Thermal Stress Restrained Specimen Tensile Strength Test**

The average temperature and load at failure in the TSRST test for each mix are shown in Figures 24 and 25, respectively. Standard t-tests indicate that the mean values for load and temperature at failure are not significantly different for any of the four mixes. The standard deviations for each are represented as error bars.
Figure 24: Comparison of Average Temperature at Failure for Each Mix

Figure 25: Comparison of the Average Load at Failure for Each Mix
Summary and Conclusions

This study compared the use of RAP and RAS as a recycled aggregate and binder source in HMA pavement. One RAP and three RAS mixtures were evaluated based on the PG grade, DSR, creep stiffness and slope values, critical cracking temperature, and |G*| and δ₀ master curves of extracted binder from each mix. The potential performance of the mixtures were also evaluated by developing the |E*| and δ master curves, the comparison of the back calculated |G*| values as determined by the Hirsch model and the effective high temperature PG grade of the mix. The mixes were also evaluated for low temperature and fatigue performance.

Conclusions based on the results of the laboratory tests performed in this study are:

Recovered Binder Testing

- The continuous PG grade shows that RAS mixtures are stiffer at the high temperature end, and that RAP and RAS have comparable stiffness at the low temperature end. This is expected because the RAS binder is much stiffer than the RAP binder.

- Creep stiffness and m-value trends with temperature for the recovered binders show that the low PG grade of the RAP tends to be controlled by the S values while the m-value controls the low PG grade of the RAS mixtures.

- Critical cracking temperatures for the recovered RAS mixture binder were lower than the RAP mixture binder, indicating that the RAS mixtures would have better low temperature performance.

- |G*| master curves for the three recovered RAS mixture binders were very similar. The recovered binder from the RAP mixture was softer than the RAS mixtures at low reduced frequencies, but was comparable to the RAS mixture binders at the higher reduced frequencies. The recovered binder from the RAP mixture had a higher phase angle and steeper rate of change than the RAS mixture binders.
• The effective high temperature PG grade for the mixtures determined from the measured \(|G^*|\) values on recovered binders show that RAP has the lowest value, and that the RAS mixes are very similar to each other.

**Mixture Testing**

• \(|E^*|\) master curves for the three RAS mixtures are statistically the same over most of the reduced frequency range. The RAP mix shows a stiffer average response, but is only statistically different than the +50 and -50 mesh RAS mixtures. The phase angle curves for all mixtures were statistically similar.

• The effective high temperature PG grade for the mixtures determined using the back calculated \(|G^*|\) values (from measured mix \(|E^*|\)) show the +50 and -50 mesh mixtures to have comparable effective PG grades, which were lower than the effective PG grades for RAP and Normal Ground Shingle mixes.

• TSRST tests showed that the load and temperature at failure for the four mixtures were not significantly different, indicating similar low temperature performance.

The comparison of the RAS and RAP mixtures is different based on the recovered binder and mixture testing. The binder testing indicates that the RAS mixtures are stiffer than the RAP mix at high temperatures and would perform better with respect to low temperature cracking. The mixture testing shows that the RAP mix has a stiffer response than the RAS mixtures; this is likely due to a combination of effects that include binder content, source material properties, and blending. The low temperature evaluation of these mixtures indicates the RAP and RAS mixtures will have similar performance. As agencies make the decision whether to use RAS or RAP in a mixture, the performance as well as the cost of the materials and amounts of virgin materials required (RAS mixtures require more virgin ac) need to be considered.


**Recommendations for Future Work**

Future research should be performed to repeat these tests with plant produced mixtures, as plant mixes tend to differ from lab mixes in their physical and mechanical properties. Additionally, these tests should be repeated to include mixtures that contain higher RAS percentages than what the NHDOT currently allows in order to determine the maximum amount of RAS material could be used in HMA mixes. Long term field performance of RAS mixtures also needs to be evaluated.
CHAPTER 4: PERFORMANCE EVALUATION OF HMA CONTAINING HIGH RAP

Introduction

This section discusses the performance evaluation of HMA mixes containing high RAP contents, meaning mixes that contain from 20 to 50+\% RAP. Funded under NCHRP project 9-46, this study compared mixes with various RAP contents to virgin mixes. While most highway agencies opt to use mixes that contain some portion of RAP to control costs, the amount of RAP that is generally incorporated into a mix is still relatively low based on its supply. This is largely due to a lack of guidance when it comes to both mix design of HMA containing large amounts of RAP, as well as RAP management. The overall scope of this project had three main objectives, which were (16):

1. Develop a feasible mix design and analysis procedure for high RAP mixes that will result in long-lasting quality pavements.
2. Recommend changes to the current AASHTO specification for designing HMA that will allow for the development of mixes containing as much or greater than 50\% RAP.
3. Determine appropriate RAP management practices and develop a best practices guideline.

For this project, the University of New Hampshire’s involvement was to evaluate the performance of test mixes that were designed to be representative of HMA typically used in four different areas of the country: North Atlantic, Western, North Central, and Southeastern. Mixes design variables included Nominal Maximum Size Aggregate, Virgin Binder PG, and RAP levels commonly used in the four different regions. A summary of the mix designs can be found in Table 13.
Table 13: Mix designs variables for NCHRP Project 9-46

<table>
<thead>
<tr>
<th></th>
<th>North Atlantic</th>
<th>Western</th>
<th>North Central</th>
<th>Southeastern</th>
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<tr>
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<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
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<tr>
<td></td>
<td>25%</td>
<td>25%</td>
<td>40%</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>55%</td>
<td>55%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Virgin Binder PG</td>
<td>58-28 (2)</td>
<td>58-34 (2)</td>
<td>58-28</td>
<td>64-22</td>
</tr>
<tr>
<td></td>
<td>70-28 (2)</td>
<td>64-34 (2)</td>
<td></td>
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</tr>
<tr>
<td>Nominal Max. Size</td>
<td>12.5 mm</td>
<td>12.5 mm</td>
<td>9.5 mm</td>
<td>9.5 mm</td>
</tr>
<tr>
<td>Aggregate</td>
<td></td>
<td></td>
<td>19.0 mm</td>
<td>19.0 mm</td>
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The performance of the test mixes were evaluated by the comparison of the $|G^*|$ and $\delta_{binder}$ master curves for the virgin binders, as well as the $|E^*|$ and $\delta$ master curves for the mixes. Dynamic modulus values were used with the Hirsch model to back-calculate $|G^*|$ values for the mix, which were then used to determine the effective PG upper limit of the mix binder. Details on these analyses can be found in the chapter 2. Again, it is important to note that the effective PG limits determined by this study should be used for comparison purposes only as the dynamic modulus testing was performed with a confining pressure of 25 psi. This is because back calculated values for $|G^*|$ were determined using the Hirsch model, which was designed for unconfined specimens only. The mix design for all mixes was completed by NCAT, as well as all $|E^*|$ and $|G^*|$ testing was completed, while the University of New Hampshire was responsible for the data analysis portion. Results from the $|G^*|$, and $\delta_{binder}$ master curve comparisons can be found in Appendices 8 – 10.
Results and Discussion

The results from the $|E^*|$ and $\delta$ master curve comparisons can be seen below.

![Graph showing $|E^*|$ master curve comparisons for different mixes and RAP percentages.](image)

**Figure 26: FL Mixes $|E^*|$ Master Curve Comparison**
Figure 27: MN Mixes $|E^*|$ Master Curve Comparison

Figure 28: NH Mixes $|E^*|$ Master Curve Comparison - 0% RAP
Figure 29: NH Mixes |E*| Master Curve Comparison - 25% RAP

Figure 30: NH Mixes |E*| Master Curve Comparison - 55% RAP
Figure 31: NH Mixes |E*| Master Curve Comparison - PG 58-28A

Figure 32: NH Mixes |E*| Master Curve Comparison - PG 58-28B
Figure 33: NH Mixes $|E^*|$ Master Curve Comparison - PG 70-28A

Figure 34: NH Mixes $|E^*|$ Master Curve Comparison - PG 70-28B
Figure 35: UT Mixes $|E^*|$ Master Curve Comparison - 0% RAP

Figure 36: UT Mixes $|E^*|$ Master Curve Comparison - 25% RAP
Figure 37: UT Mixes $|E^*|$ Master Curve Comparison - 55% RAP

Figure 38: UT Mixes $|E^*|$ Master Curve Comparison - PG 58-34A
Figure 39: UT Mixes $|E^*|$ Master Curve Comparison - PG 58-34B

Figure 40: UT Mixes $|E^*|$ Master Curve Comparison - PG 64-34B
Figure 41: FL Mixes δ Master Curve Comparison

Figure 42: MN Mixes δ Master Curve Comparison
Figure 43: NH Mixes δ Master Curve Comparison – 0% RAP

Figure 44: NH Mixes δ Master Curve Comparison - 25% RAP
Figure 45: NH Mixes δ Master Curve Comparison - 55% RAP

Figure 46: NH Mixes δ Master Curve Comparison - PG 58-28A
Figure 47: NH Mixes $\delta$ Master Curve Comparison - PG 58-28B

Figure 48: NH Mixes $\delta$ Master Curve Comparison - PG 70-28A
Figure 49: NH Mixes $\delta$ Master Curve Comparison - PG 70-28B

Figure 50: UT Mixes $\delta$ Master Curve Comparison - 0% RAP
Figure 51: UT Mixes δ Master Curve Comparison - 25% RAP

Figure 52: UT Mixes δ Master Curve Comparison – RAP 55% RAP
Figure 53: UT Mixes $\delta$ Master Curve Comparison - PG 58-34A

Figure 54: UT Mixes $\delta$ Master Curve Comparison - PG 58-34B
The comparisons of the $|E^*|$ master curves indicate that mixes that vary only by RAP content have an increase in stiffness, although this increase is not necessarily proportional to the amount of RAP the mix contains, and in some cases can even be considered negligible, particularly in the case of the NH and some UT mixes. These results indicate that the effect of RAP in a mix not only depends on its content, but on the virgin binder and aggregate selections as well. Additionally, the master curve comparisons for the phase angle show that in many cases, the mixes which exhibited stiffer $|E^*|$ values tended to have peak phase angle values at the lower reduced frequencies.

Determined effective PG limits for the test mixtures ranged from 75 – 126 °C. In most cases, the effective PG upper limit saw an increase as the RAP content of a mix increased, although the extent to which RAP content affected the effective PG was dependent on the mix.
The use of either the Christiansen Andersen or Rowe’s model as a $|G^*|$ fit also had a significant effect on the effective PG upper limits. Generally, Rowe’s model produced a higher effective PG than the Christiansen-Andersen model did. This occurrence can be traced back to the difference the two models had on the back calculated $\delta_{\text{binder}}$ master curves. A summary of these results can be seen in Table 14, as well as in Appendix 11. The effective PG upper limit calculated using the $|G^*|$ measured for the virgin binder is also shown in Table 14 to demonstrate the difference that using a $|G^*|$ value calculated with a $|E^*|$ value for a specimen under a confining pressure imparts. Again, the values for effective PG upper limits calculated for this project should only be used for comparison purposes, and not taken as true values. Charts comparing the effective PG upper limits for each state based on NMSA, virgin binder and RAP content can also be seen below, as well as in Appendix 11.
Table 14: Effective PG Upper Limits

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<th>Mix</th>
<th>CA Model</th>
<th>Rowe Model</th>
<th>Virgin Binder</th>
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<td>FL - 9.5 mm - 40% RAP - 64-22</td>
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<td>137.1</td>
<td>73.2</td>
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<tr>
<td>FL - 19.0 mm - 0% RAP - 64-22</td>
<td>108.3</td>
<td>97.5</td>
<td>73.0</td>
</tr>
<tr>
<td>FL - 19.0 mm - 40% RAP - 64-22</td>
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<td>MN - 9.5 mm - 0% RAP - 58-28B</td>
<td>80.1</td>
<td>88.8</td>
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<td>MN - 9.5 mm - 40% RAP - 58-28B</td>
<td>89.9</td>
<td>95.0</td>
<td>64.8</td>
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<td>MN - 19.0 mm - 40% RAP - 58-28B</td>
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<tr>
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<tr>
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<td>NH - 12.5 mm - 55% RAP - 58-28B</td>
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<tr>
<td>NH - 12.5 mm - 0% RAP - 70-28A</td>
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<td>122.5</td>
<td>74.2</td>
</tr>
<tr>
<td>NH - 12.5 mm - 25% RAP - 70-28A</td>
<td>91.1</td>
<td>136.3</td>
<td>71.1</td>
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<tr>
<td>NH - 12.5 mm - 55% RAP - 70-28A</td>
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<td>127.5</td>
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<td>133.1</td>
<td>73.1</td>
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<td>75.2</td>
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<td>UT - 12.5 mm - 25% RAP - 58-34A</td>
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<tr>
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<td>122.0</td>
<td>62.9</td>
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<td>126.0</td>
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<td>99.2</td>
<td>59.0</td>
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<td>UT - 12.5 mm - 0% RAP - 64-34B</td>
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<td>78.3</td>
<td>73.8</td>
</tr>
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<td>UT - 12.5 mm - 55% RAP - 64-34B</td>
<td>83.1</td>
<td>118.0</td>
<td>73.8</td>
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</table>
Figure 56: Effective PG Upper Limit of MN mixes Based on Christensen-Anderson Fits

Figure 57: Effective PG Upper Limit of MN mixes Based on Christensen-Anderson Fits
Figure 58: Effective PG Upper Limit of NH mixes Based on Christensen-Anderson Fits

Figure 59: Effective PG Upper Limit of UT mixes Based on Christensen-Anderson Fits
Figure 60: Effective PG Upper Limit of FL mixes Based on Rowe's Fits

Figure 61: Effective PG Upper Limit of MN mixes Based on Rowe's Fits
Figure 62: Effective PG Upper Limit of NH mixes Based on Rowe's Fits

Figure 63: Effective PG Upper Limit of UT mixes Based on Rowe's Fits
Summary and Conclusions

This study compared mixes containing various RAP contents, ranging from virgin mixes to high RAP mixes. Potential performance of the mixes were evaluated based on $|E^*|$ and $\delta$ master curves, $|G^*|$ and $\delta_b$ master curves, and Hirsch model back-calculated $|G^*|$ and $\delta_b$ master curves. Additionally, the effective high temperature PG of the mix was calculated as used as a measure to evaluate the effects of RAP content on a mix.

Conclusions based on the results of the laboratory tests performed in this study are:

- $|E^*|$ master curve comparisons show that mixes that vary only in RAP contents will generally increase stiffness with the RAP content, although in some mixes any difference in stiffness can be considered negligible.
- In many cases, stiffer mixes have peak phase angle values at lower reduced frequencies.
- When fitting back-calculated $|G^*|$ master curves, some curves are better fit by the Christensen-Anderson model, while others are better fit using Rowe’s Generalized Logistic function. The determination of which is the best fit must be made on a case-by-case basis.
- In most cases, the back-calculated $|G^*|$ master curves are comparable with the master curve for the measured $|G^*|$ master curves for the virgin binders used in a particular mix, particularly as the reduced frequency increases (or temperature decreases).
- RAP content does not appear to have a significant effect on back-calculated $|G^*|$ master curves, which generally remain comparable with virgin binder master curves as RAP content is varied.
- Choice of using the Christiansen-Anderson model vs. Rowe’s Generalized Logistic function for fitting $|G^*|$ master curves has more of an effect on subsequent $\delta_b$ master...
curves. In different cases, either the Christiansen-Anderson or the Rowe’s fit may provide a master curve closer to measured $\delta_b$ master curves for virgin binders.

- Back-calculated $\delta_b$ master curves generally have a shallower slope than the measured $\delta_b$ master curves for virgin binders.
- In most cases, use of Rowe’s model to fit back-calculated $|G^*|$ master curves lead to a higher determined value for effective PG upper limit.
- The use of a confining pressure during $|E^*|$ measurements has a significant effect on the effective PG upper limit. This is most likely due to the fact that the Hirsch model has no way of correcting for this confining pressure. Because of this, values determined for the effective PG upper limit calculated using the back-calculated values for $|G^*|$ should only be used as a comparison between the different mixes, and not considered as an actual effective PG.
- In most cases, effective PG upper limit increased with RAP content, although in some cases the difference was limited to less than 6 °C using the Christensen-Anderson model for RAP contents of 0% to 55% (see NH and UT mixes). This suggests that aggregate and virgin binder selections may also have an effect of the amount that RAP content will impact the properties of a mix.

**Recommendations for Future Work**

Dynamic modulus testing should be repeated for unconfined specimen so that actual values can be determined for the effective performance grade upper limits.
REFERENCES


<table>
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<th>Design Type</th>
<th>Superpave</th>
<th>Type E, 12.5 mm (1/2&quot;&quot;)</th>
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<th>Date: 5/26/2009</th>
<th>Mix Code: 153</th>
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<td>E</td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>Surface Course</td>
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<td></td>
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<table>
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<th>Sieve mm</th>
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<th>25.0 (1&quot;)</th>
<th>19.0 (3/4&quot;)</th>
<th>12.5 (1/2&quot;)</th>
<th>9.5 (3/8&quot;)</th>
<th>4.75 (#4)</th>
<th>2.56 (#8)</th>
<th>1.18 (#16)</th>
<th>0.6 (#30)</th>
<th>0.3 (#50)</th>
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<tr>
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<td>11.8</td>
<td>5.0</td>
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| % Sand: | 57.4 | 30.0 | 12.6 |}

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**APPENDIXES**

Appendix 1: Pike Industries Mix Design Type E, 12.5 mm, 15% RAP

Figure 64: Pike Industries, In. Mix Design
### Appendix 2: HMA with RAS - Test Sample Volumetrics

#### Table 15: Air Voids, VMA, VFA

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<tr>
<th>Sample ID</th>
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<th>Gmb</th>
<th>Gmm</th>
<th>Ps</th>
<th>Gsb, blend</th>
<th>Gsb, blend max</th>
<th>Gsb, blend min</th>
<th>Air Voids %</th>
<th>VMA</th>
<th>VMA max</th>
<th>VMA min</th>
<th>VMA Average</th>
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Appendix 3: HMA with RAS - Critical Cracking Temperature Data

Table 16: BBR Stiffness (MPa) for HMA Containing RAP

<table>
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<tr>
<th>Time</th>
<th>Beam 1</th>
<th>Beam 2</th>
<th>Average</th>
<th>Beam 1</th>
<th>Beam 2</th>
<th>Average</th>
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<td>8</td>
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<td>179</td>
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<td>383</td>
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<td>549</td>
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<td>264</td>
<td>259</td>
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<td>91.3</td>
<td>92</td>
<td>206</td>
<td>214</td>
<td>210</td>
<td>407</td>
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<td>71.4</td>
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<td>171</td>
<td>168</td>
<td>359</td>
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Table 17: DTT Strength (MPa) and Strain (%) for HMA Containing RAP

<table>
<thead>
<tr>
<th>Temp, C</th>
<th>Strength</th>
<th>Strain</th>
</tr>
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<tbody>
<tr>
<td>-12</td>
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<tr>
<td>-18</td>
<td>4.214</td>
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<td>-24</td>
<td>4.768</td>
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</table>

Sample ID: RC1881

PAV Fracture Strength & Thermal Stress, MPa
Critical Temperature -24 2 C

Figure 65: Critical Cracking Temperature for HMA Containing RAP
Table 18: BBR Stiffness (MPa) for HMA Containing Normal Ground Shingles

<table>
<thead>
<tr>
<th>Time</th>
<th>Beam 1</th>
<th>Beam 2</th>
<th>Average</th>
<th>Beam 1</th>
<th>Beam 2</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
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<td>407</td>
<td>403</td>
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<td>728</td>
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<td>351</td>
<td>350</td>
<td>668</td>
<td>625</td>
<td>647</td>
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<td>295</td>
<td>295</td>
<td>578</td>
<td>541</td>
<td>560</td>
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<tr>
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<td>243</td>
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<td>463</td>
<td>478</td>
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<td>201</td>
<td>198</td>
<td>200</td>
<td>413</td>
<td>390</td>
<td>402</td>
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<tr>
<td>240</td>
<td>162</td>
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<td>161</td>
<td>341</td>
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Table 19: DTT Strength (MPa) and Strain (%) for HMA Containing Normal Ground Shingles

<table>
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<th>Strain</th>
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<tr>
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Sample ID: RC1903

PAV Fracture Strength & Thermal Stress, MPa

Critical Cracking Temperature -26.8 C

Figure 66: Critical Cracking Temperature for HMA Containing Normal Ground Shingles
Table 20: BBR Stiffness (MPa) for HMA Mix Containing +50 Mesh Shingles

<table>
<thead>
<tr>
<th>Time</th>
<th>-18 C</th>
<th>-24 C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beam 1</td>
<td>Beam 2</td>
</tr>
<tr>
<td>8</td>
<td>428</td>
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<td>15</td>
<td>369</td>
<td>346</td>
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<td>30</td>
<td>309</td>
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<tr>
<td>60</td>
<td>255</td>
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<td>120</td>
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<tr>
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<td>166</td>
<td>159</td>
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Table 21: DTT Strength (MPa) and Strain (%) for HMA Mix Containing +50 Mesh Shingles

<table>
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<th>Strength</th>
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</thead>
<tbody>
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Sample ID: RC1901

Figure 67: Critical Cracking Temperature for HMA Containing +50 Mesh Shingles
Table 22: BBR Stiffness (MPa) for HMA Containing -50 Mesh Shingles

<table>
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<tr>
<th>Time</th>
<th>-18 C</th>
<th>-24 C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beam 1</td>
<td>Beam 2</td>
</tr>
<tr>
<td>8</td>
<td>417</td>
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<tr>
<td>15</td>
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<td>355</td>
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<tr>
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<td>161</td>
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Table 23: DTT Strength (MPa) and Strain (%) for HMA Containing -50 Mesh Shingles

<table>
<thead>
<tr>
<th>Temp, C</th>
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<th>Strain</th>
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Sample ID: RC1902

PAV Fracture Strength & Thermal Stress, MPa

Critical Cracking Temperature -27.9 C

Figure 68: Critical Cracking Temperature for HMA Containing -50 Mesh Shingles
## Appendix 4: HMA with RAS: Dynamic Modulus Data

### Table 24: Dynamic Modulus Data for HMA Mix Containing RAP Only

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Temperature (°C)</th>
<th>R5.7D3</th>
<th>R5.7D4a</th>
<th>R5.7D4b</th>
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</thead>
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<td>3517.3825</td>
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<td>9402.92</td>
<td>9667.264</td>
<td>8524.0703</td>
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</table>
Table 25: Dynamic Modulus Data for HMA Mix Containing Normal Ground Shingles

| Frequency (Hz) | Temperature (°C) | N6.5D3 $|E'\vert$ (MPa) | N6.5D4a $|E'\vert$ (MPa) | N6.5D4c $|E'\vert$ (MPa) |
|---------------|-----------------|-------------|-----------------|-----------------|
| 0.1           | -20             | 25773.288   | 31137.53        | 31443.213       |
| 0.2           | -20             | 26293.389   | 31739.851       | 32028.58        |
| 0.5           | -20             | 27608.086   | 33256.819       | 33302.368       |
| 1             | -20             | 30881.026   | 33195.05        | 33944.708       |
| 2             | -20             | 30353.755   | 33659.308       | 35032.767       |
| 5             | -20             | 31738.543   | 34817.022       | 36353.953       |
| 10            | -20             | 33327.426   | 35462.313       | 37237.087       |
| 20            | -20             | 33314.234   | 37349.363       | 38806.511       |
| 0.1           | -10             | 19399.32    | 20004.024       | 22112.23        |
| 0.2           | -10             | 20206.901   | 21443.431       | 22570.696       |
| 0.5           | -10             | 21642.462   | 22763.251       | 24290.327       |
| 1             | -10             | 22867.91    | 24219.168       | 25361.564       |
| 2             | -10             | 23869.181   | 25179.492       | 26687.799       |
| 5             | -10             | 25325.176   | 26965.557       | 27976.284       |
| 10            | -10             | 26520.473   | 28263.642       | 28491.661       |
| 20            | -10             | 27910.371   | 30693.958       | 29981.519       |
| 0.1           | 0               | 11902.304   | 12881.66        | 14511.091       |
| 0.2           | 0               | 13683.203   | 13972.979       | 15989.963       |
| 0.5           | 0               | 15020.445   | 15280.685       | 17200.514       |
| 1             | 0               | 16427.86    | 16846.215       | 18074.108       |
| 2             | 0               | 17737.52    | 18680.665       | 19317.63        |
| 5             | 0               | 19667.36    | 21294.938       | 21104.857       |
| 10            | 0               | 20967.598   | 22990.643       | 22754.474       |
| 20            | 0               | 22441.165   | 24433.484       | 23799.95        |
| 0.1           | 10              | 4698.123    | 4529.3755       | 5906.9355       |
| 0.2           | 10              | 5651.5738   | 5593.2615       | 7123.3495       |
| 0.5           | 10              | 7072.7768   | 7103.9685       | 8317.897        |
| 1             | 10              | 8302.1998   | 8483.5635       | 8871.3605       |
| 2             | 10              | 9427.6083   | 9785.8585       | 10102.975       |
| 5             | 10              | 11083.967   | 12229.989       | 12060.062       |
| 10            | 10              | 12430.265   | 14344.656       | 13504.43        |
| 20            | 10              | 13307.982   | 16753.233       | 15276.588       |
| 0.1           | 20              | 1520.8095   | 1551.5085       | 1947.8005       |
| 0.2           | 20              | 1888.292    | 2058.9655       | 2391.0225       |
| 0.5           | 20              | 2805.374    | 2848.49         | 4260.3785       |
| 1             | 20              | 3731.736    | 3647.514        | 5291.1475       |
| 2             | 20              | 4028.7025   | 4556.34         | 5845.0185       |
| 5             | 20              | 5185.0313   | 6467.9665       | 6645.1315       |
| 10            | 20              | 6287.5928   | 8023.7705       | 7488.5805       |
| 20            | 20              | 7371.4175   | 9703.8955       | 8892.391        |
Table 26: Dynamic Modulus Data for HMA Mix Containing +50 Mesh Shingles

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Temperature (°C)</th>
<th>G6.0D1</th>
<th>E* (MPa)</th>
<th>G6.0D2a</th>
<th>E* (MPa)</th>
<th>G6.0D4a</th>
<th>E* (MPa)</th>
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<tbody>
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<td>-20</td>
<td>20431.525</td>
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<td>12860.776</td>
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<td>17212.862</td>
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### Appendix 5: HMA with RAS - Dynamic Modulus and Phase Angle t-test Data

#### Table 28: Student t-test Values for Significant Difference in $|E^*|$ Reduced Frequency

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#### Table 29: Student t-test Values for Significant Difference in $\delta$ Reduced Frequency

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Table 30: Binder Modulus for Recovered Binder from HMA Mixes, Virgin Binder

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Appendix 7: HMA with RAS - TSRST Data

Figure 69: TSRST Chart from Specimen R5.7D3b

Figure 70: TSRST Chart from Specimen R5.7D4a
Figure 71: TSRST Chart from Specimen R5.7D4b

Figure 72: TSRST Chart from Specimen N6.5D3
Figure 73: TSRST Chart from Specimen N6.5D4a

Figure 74: TSRST Chart from Specimen L6.1D2
Figure 75: TSRST Chart from Specimen L6.1D3a

Figure 76: TSRST Chart from Specimen L6.1D3b
Figure 77: TSRST Chart from Specimen G6.0D2a

Figure 78: TSRST Chart from Specimen G6.0D4a
Appendix 8: HMA with High-RAP - Virgin Binder $|G^*|$ and $\delta_{\text{binder}}$ Master Curves

Figure 79: Virgin Binder $|G^*|$ Master Curve Comparison
Figure 80: Virgin FL Binder $|G^*|$ Master Curve

Figure 81: Virgin MN Binder $|G^*|$ Master Curve
Figure 82: Virgin NH Binder $|G^*|$ Master Curve Comparison

Figure 83: Virgin UT Binder $|G^*|$ Master Curve Comparison
Figure 84: Virgin Binder $\delta_{\text{Binder}}$, Master Curve Comparison

Figure 85: Virgin FL Binder $\delta_{\text{Binder}}$, Master Curve
Figure 86: Virgin MN Binder $\delta_{\text{Binder}}$ Master Curve

Figure 87: Virgin NH Binder $\delta_{\text{Binder}}$ Master Curve Comparison
Figure 88: Virgin UT Binder $\delta_{\text{Binder}}$ Master Curve Comparison
Appendix 9: HMA with High-RAP: Back-Calculated $|G^*|$ vs. Measured Virgin Binder $|G^*|$

Figure 89: $|G^*|$ Comparison for FL mix - 9.5 mm - 0% RAP - PG 64-22
Figure 90: $|G^*|$ Comparison for FL mix - 9.5 mm - 40% RAP - PG 64-22

Figure 91: $|G^*|$ Comparison for FL mix - 19.0 mm - 0% RAP - PG 64-22
Figure 92: $|G^*|$ Comparison for FL mix - 19.0 mm - 40% RAP - PG 64-22

Figure 93: $|G^*|$ Comparison for MN mix - 9.5 mm - 0% RAP - PG 58-28B
Figure 94: $|G^*|$ Comparison for MN mix - 9.5 mm - 40% RAP - PG 58-28B

Figure 95: $|G^*|$ Comparison for MN mix - 19.0 mm - 0% RAP - PG 58-28B
Figure 96: $|G^*|$ Comparison for MN mix - 19.0 mm - 40% RAP - PG 58-28B

Figure 97: $|G^*|$ Comparison for NH mix - 12.5 mm - 0% RAP - PG 58-28A
Figure 98: $|G^*|$ Comparison for NH Mix - 12.5 mm - 0% RAP - PG 58-28B

Figure 99: $|G^*|$ Comparison for NH Mix - 12.5 mm - 0% RAP - PG 70-28A
Figure 100: $|G^*|$ Comparison for NH Mix - 12.5 mm - 0% RAP - PG 70-28B

Figure 101: $|G^*|$ Comparison for NH Mix - 12.5 mm - 25% RAP - PG 58-28A
Figure 102: $|G^*|$ Comparison for NH Mix - 12.5 mm - 25% RAP - PG 70-28A

Figure 103: $|G^*|$ Comparison for NH Mix - 12.5 mm - 55% RAP - PG 58-28A
Figure 104: $|G^*|$ Comparison for NH Mix - 12.5 mm - 55% RAP - PG 58-28B

Figure 105: $|G^*|$ Comparison for NH Mix - 12.5 mm - 55% RAP - PG 70-28A
Figure 106: $|G^*|$ Comparison for NH Mix - 12.5 mm - 55% RAP - PG 70-28B

Figure 107: $|G^*|$ Comparison for UT Mix - 12.5 mm - 0% RAP - PG 58-34A
Figure 108: $|G^*|$ Comparison for UT Mix - 12.5 mm - 0% RAP - PG 58-34B

Figure 109: $|G^*|$ Comparison for UT Mix - 12.5 mm - 0% RAP - PG 64-34B
Figure 110: $|G^*|$ Comparison for UT Mix - 12.5 mm - 25% RAP - PG 58-34A

Figure 111: $|G^*|$ Comparison for UT Mix - 12.5 mm - 55% RAP - PG 58-34A WMA
Figure 112: $|G^*|$ Comparison for UT Mix - 12.5 mm - 55% RAP - PG 58-34A

Figure 113: $|G^*|$ Comparison for UT Mix - 12.5 mm - 55% RAP - PG 58-34B
Figure 114: $|G^*|$ Comparison for UT Mix - 12.5 mm - 55% RAP - PG 64-34B
Appendix 10: HMA with High-RAP - Back-Calculated $\delta_{\text{Binder}}$ vs. Measured Virgin Binder $\delta_{\text{Binder}}$

Figure 115: $\delta_{b}$ Comparison for FL Mix - 9.5 mm - 0% RAP - PG 64-22

Figure 116: $\delta_{b}$ Comparison for FL Mix - 9.5 mm - 40% RAP - PG 64-22
Figure 117: δ₀ Comparison for FL Mix - 19.0 mm - 0% RAP - PG 64-22

Figure 118: δ₀ Comparison for FL Mix - 19.0 mm - 0% RAP - PG 64-22
Figure 119: $\delta_6$ Comparison for MN Mix - 9.5 mm - 0% RAP - PG 58-28B

Figure 120: $\delta_6$ Comparison for MN Mix - 9.5 mm - 40% RAP - PG 58-28B
Figure 121: $\delta_0$ Comparison for MN Mix - 19.0 mm - 0% RAP - PG 58-28B

Figure 122: $\delta_0$ Comparison for MN Mix - 19.0 mm - 40% RAP - PG 58-28B
Figure 123: $\delta_b$ Comparison for NH Mix - 12.5 mm - 0% RAP - PG 58-28A

Figure 124: $\delta_b$ Comparison for NH Mix - 12.5 mm - 0% RAP - PG 58-28B
Figure 125: $\delta_b$ Comparison for NH Mix - 12.5 mm - 0% RAP - PG 70-28A

Figure 126: $\delta_b$ Comparison for NH Mix - 12.5 mm - 0% RAP - PG 70-28B
Figure 127: $\delta_6$ Comparison for NH Mix - 12.5 mm - 25% RAP - PG 58-28A

Figure 128: $\delta_6$ Comparison for NH Mix - 12.5 mm - 25% RAP - PG 70-28A
Figure 129: $\delta_0$ Comparison for NH Mix - 12.5 mm - 55% RAP - PG 58-28A

Figure 130: $\delta_0$ Comparison for NH Mix - 12.5 mm - 55% RAP - PG 58-28B
Figure 131: $\delta_b$ Comparison for NH Mix - 12.5 mm - 55% RAP - PG 70-28A

Figure 132: $\delta_b$ Comparison for NH Mix - 12.5 mm - 55% RAP - PG 70-28B
Figure 133: δ₀ Comparison for UT Mix - 12.5 mm - 0% RAP - PG 58-34A

Figure 134: δ₀ Comparison for UT Mix - 12.5 mm - 0% RAP - PG 58-34B
Figure 135: $\delta_b$ Comparison for UT Mix - 12.5 mm - 0% RAP - PG 64-34B

Figure 136: $\delta_b$ Comparison for UT Mix - 12.5 mm - 25% RAP - PG 58-34A
Figure 137: $\delta_b$ Comparison for UT Mix - 12.5 mm - 55% RAP - PG 58-34A WMA

Figure 138: $\delta_b$ Comparison for UT Mix - 12.5 mm - 55% RAP - PG 58-34A
Figure 139: $\delta_b$ Comparison for UT Mix - 12.5 mm - 55% RAP - PG 58-34B

Figure 140: $\delta_b$ Comparison for UT Mix - 12.5 mm - 55% RAP - 64-34B
### Appendix 11: HMA with High-RAP - Effective PG Upper Limits

#### Table 32: Effective PG Upper Limits

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<td>95.0</td>
<td>64.8</td>
</tr>
<tr>
<td>MN - 19.0 mm - 0% RAP - 58-28B</td>
<td>71.8</td>
<td>77.2</td>
<td>63.1</td>
</tr>
<tr>
<td>MN - 19.0 mm - 40% RAP - 58-28B</td>
<td>89.5</td>
<td>97.9</td>
<td>61.8</td>
</tr>
<tr>
<td>NH - 12.5 mm - 0% RAP - 58-28A</td>
<td>86.6</td>
<td>101.0</td>
<td>62.3</td>
</tr>
<tr>
<td>NH - 12.5 mm - 25% RAP - 58-28A</td>
<td>89.9</td>
<td>117.5</td>
<td>60.1</td>
</tr>
<tr>
<td>NH - 12.5 mm - 55% RAP - 58-28A</td>
<td>90.8</td>
<td>125.0</td>
<td>61.0</td>
</tr>
<tr>
<td>NH - 12.5 mm - 0% RAP - 58-28B</td>
<td>86.1</td>
<td>87.8</td>
<td>62.1</td>
</tr>
<tr>
<td>NH - 12.5 mm - 55% RAP - 58-28B</td>
<td>116.1</td>
<td>100.3</td>
<td>62.1</td>
</tr>
<tr>
<td>NH - 12.5 mm - 0% RAP - 70-28A</td>
<td>93.0</td>
<td>122.5</td>
<td>74.2</td>
</tr>
<tr>
<td>NH - 12.5 mm - 25% RAP - 70-28A</td>
<td>91.1</td>
<td>136.3</td>
<td>71.1</td>
</tr>
<tr>
<td>NH - 12.5 mm - 55% RAP - 70-28A</td>
<td>92.9</td>
<td>126.0</td>
<td>70.2</td>
</tr>
<tr>
<td>NH - 12.5 mm - 0% RAP - 70-28B</td>
<td>86.0</td>
<td>127.5</td>
<td>73.9</td>
</tr>
<tr>
<td>NH - 12.5 mm - 55% RAP - 70-28B</td>
<td>91.1</td>
<td>133.1</td>
<td>73.1</td>
</tr>
<tr>
<td>UT - 12.5 mm - 0% RAP - 58-34A</td>
<td>83.2</td>
<td>75.2</td>
<td>63.1</td>
</tr>
<tr>
<td>UT - 12.5 mm - 25% RAP - 58-34A</td>
<td>98.1</td>
<td>83.6</td>
<td>61.9</td>
</tr>
<tr>
<td>UT - 12.5 mm - 55% RAP - 58-34A</td>
<td>100.0</td>
<td>122.0</td>
<td>62.9</td>
</tr>
<tr>
<td>UT - 12.5 mm - 55% RAP - 58-34A WMA</td>
<td>96.1</td>
<td>126.0</td>
<td>61.8</td>
</tr>
<tr>
<td>UT - 12.5 mm - 0% RAP - 58-34B</td>
<td>78.2</td>
<td>77.0</td>
<td>62.0</td>
</tr>
<tr>
<td>UT - 12.5 mm - 55% RAP - 58-34B</td>
<td>83.1</td>
<td>99.2</td>
<td>59.0</td>
</tr>
<tr>
<td>UT - 12.5 mm - 0% RAP - 64-34B</td>
<td>79.8</td>
<td>78.3</td>
<td>73.8</td>
</tr>
<tr>
<td>UT - 12.5 mm - 55% RAP - 64-34B</td>
<td>83.1</td>
<td>118.0</td>
<td>73.8</td>
</tr>
</tbody>
</table>
Figure 141: Effective PG Upper Limit Based on Christensen-Anderson $|G^*|$ and $\delta_b$ Fits, Sorted by Virgin Binder PG Upper Limit
Figure 142: Effective PG Upper Limit Based on Rowe's Generalized Logistic Function $|G^*|$ and $\delta_b$ Fits
Figure 143: Effective PG Upper Limit for Virgin Binders Based on Generalized Logistic Function $|G^*|$ and $\delta_b$ Fits
Figure 144: Effective PG Upper Limit Based on Christensen-Anderson $|G^*|$ and $\delta_\mu$ Fits, sorted by RAP content
Figure 145: Effective PG Upper Limit Based on Rowe’s Generalized Logistic Function \(|G^*|\) and \(\delta_6\) Fits, sorted by RAP content
Figure 146: Effective PG Upper Limit of FL mixes Based on Christensen-Anderson Fits

Figure 147: Effective PG Upper Limit of MN mixes Based on Christensen-Anderson Fits
Figure 148: Effective PG Upper Limit of NH mixes Based on Christensen-Anderson Fits

Figure 149: Effective PG Upper Limit of UT mixes Based on Christensen-Anderson Fits
Figure 150: Effective PG Upper Limit of FL mixes Based on Rowe's Fits

Figure 151: Effective PG Upper Limit of MN mixes Based on Rowe's Fits
Figure 152: Effective PG Upper Limit of NH mixes Based on Rowe's Fits

Figure 153: Effective PG Upper Limit of UT mixes Based on Rowe's Fits