NCAT Report 14-03

EVALUATION OF A RUBBER-MODIFIED MIXTURE IN ALABAMA

Interim Report

By
J. Richard Willis
Carolina Rodezno
Adam Taylor
Nam Tran

June 2014

National Center for Asphalt Technology
NCAT
at AUBURN UNIVERSITY

277 Technology Parkway ■ Auburn, AL 36830

EVALUATION OF A RUBBER-MODIFIED MIXTURE IN ALABAMA

Interim Report

By

J. Richard Willis
Carolina Rodezno
Adam Taylor
Nam Tran

National Center for Asphalt Technology
Auburn University, Auburn, Alabama

Sponsored by
Alabama Department of Transportation

NCAT Report 14-03

June 2014

ACKNOWLEDGEMENTS

This project was sponsored by Alabama Department of Transportation. The project team appreciates and thanks the Alabama Department of Transportation for their sponsorship of this project.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of Alabama Department of Transportation or the National Center for Asphalt Technology, or Auburn University. This report does not constitute a standard, specification, or regulation. Comments contained in this paper related to specific testing equipment and materials should not be considered an endorsement of any commercial product or service; no such endorsement is intended or implied.

TABLE OF CONTENTS

1 INTRODUCTION

The utilization of scrap tire rubber in asphalt started in the mid-1960s when ground tire rubber (GTR) was placed in asphalt surface treatments such as chip seal applications. In the 1970s, rubber modified asphalt mixtures were used as a stress absorbing membrane interlayer. Since then, its use extended to hot mix asphalt (HMA) and has continued to evolve due to the rubber's enhancement of mixture performance including improved rutting resistance, thermal reflectivity, and resistance to fatigue cracking. Other reported benefits of using rubber modified asphalt mixtures include reduction in maintenance, smooth riding, skid resistance, and noise reduction (*1, 2, 3*).

The disposal of scrap tires is a major waste management concern. Using GTR in asphalt mixtures can reduce the waste material in landfills. Additionally, studies have shown the addition of GTR to asphalt mixtures does not significantly increase undesirable compound emissions such as CO_2 (*4*).

To date, Arizona, California, Florida, and Texas have successfully developed and specified the most rubberized asphalt products. Between 1995 and 2001, these states reused over 35.6 million tires in asphalt paving applications (*5*).

When rubber modified asphalt mixtures are evaluated, it is important to distinguish between the different processes and applications that are currently used. As it is well known, the processes of applying GTR in asphalt mixtures can be divided into two broad categories: a dry process or a wet process. In the dry process, crumb rubber is blended with the aggregate before the asphalt binder is added to the mix. The GTR particles in this process are generally coarser than those in the wet process and are considered part of the aggregate structure (*2*).

In the wet process, the GTR is blended with the asphalt binder and is then mixed with the aggregate. When asphalt cement and GTR are blended together the crumb rubber swells and softens. Some of the factors that influence this reaction include blending temperature, the reaction time, the type and amount of mechanical mixing, the size and texture of the crumb rubber, and the aromatic component of the asphalt cement (*6*). In general, GTR is added to an asphalt binder to improve the binder properties by increasing the binder's temperature range. In the United States, the addition of GTR is typically conducted using the asphalt rubber-wet process.

While environmental stewardship is important, some state agencies and contractors are investigating rubber-modified asphalt mixtures as a substitute for using polymers such as styrene-butadiene-styrene (SBS) in asphalt mixtures. If rubber-modified mixtures can perform equivalently to polymer-modified mixtures, state agencies and contractors will have additional tools for achieving the desired asphalt mixture properties needed to withstand pavement distresses.

2 OBJECTIVE AND SCOPE

The objectives of this research were twofold. First, a laboratory testing plan was developed to predict the field performance of the mixtures. Secondly, the research team monitored the field performance of a rubber-modified asphalt mixture in Alabama for a period of five years to determine if the mixture was durable in field conditions. Second, a laboratory testing plan was developed to validate the mixture's field performance.

To complete these objectives, the production and construction of a rubber-modified asphalt mixture and a control polymer-modified asphalt mixture were monitored in August 2010. In addition to monitoring the construction of the project, each mixture and binder was sampled at the plant and taken to the National Center for Asphalt Technology (NCAT) laboratories for mixture and binder characterization. NCAT would return to the site yearly to assess the field performance of the mixtures in terms of cracking, rutting, texture, and ride quality.

3 MIXTURES

Two mixtures were produced at the APAC Mid-South plant in Dothan, Alabama, on August 10, 2010. Both mixtures were 19.0 mm maximum aggregate size mixtures designed for equivalent single axle load (ESAL) category level "E." The aggregate structure was designed using #78 granite from Lochapoka, Alabama; #89 limestone from Saginaw, Alabama; limestone screenings from Saginaw, Alabama; shot gravel from Phenix City, Alabama; sand from Hilton, Georgia; and 20 percent reclaimed asphalt pavement (RAP). The primary difference between the two mixtures was the asphalt binder selected. The first mixture used a PG 67-22 asphalt binder that had been modified with 11 percent #30-40 mesh GTR by weight of the binder using the wet process. The second mixture used SBS to modify the original asphalt. The designs for both mixtures including gradations and mixture volumetrics are given in Table 3.1.

Due to the differences in the GTR and SBS modified binders, the asphalt contents of the mixtures and gradations varied slightly between the two mixtures. The mixture modified with rubber had an asphalt content of 5.5 percent while the polymer-modified mixtures had 5.1 percent asphalt. This mix was intentionally designed with a higher asphalt content. Additionally, based on typical material variability at the plant, the rubber-modified mixture had 0.5 percent more dust than the polymer modified mixture. These differences result in the volumetric differences seen in Table 3.1.

The contractor originally planned to produce 500 tons of the rubber modified mixture; however, only 250 tons were actually produced due to a problem which occurred during production. The rubber modified binder was brought to the plant in its tanker (Figure 3.1) which pumped directly into the asphalt plant from a horizontal tanker (Figure 3.2). As the volume of binder decreased in the truck, the pump began to pull air into the connection instead of asphalt. This caused the asphalt content of the rubber-modified mixture to decrease. The contractor elected to stop producing the rubber modified mixture and finish the project using the polymer-modified mixture rather than risk producing a mix with low asphalt content. This

seemed to be an isolated issue unrelated to the rubber-modified mixture. A literature search has not found any other instances where such a problem occurred during the production of asphalt mixtures using rubber-modified binders.

The mixtures were transported 10.1 miles from the plant to US 231-S where they were placed in the outside lane. The target thickness for each mixture was 1.5 inches thick with 93 percent density. Four cores were taken from each mixture to determine their thicknesses and in-place densities. Table 3.2 shows the average density and thickness of each mixture. A two-sample *t*-test ($\alpha = 0.05$) shows there are no statistical differences between the densities ($p = 0.10$) or thicknesses ($p = 0.81$) of the two mixtures.

TABLE 3.1 Mix Design Information

Sieve Size, mm	**Rubber-Modified Mixture**	**Polymer-Modified Mixture**
	Percent Passing	
19.0	100	100
12.5	97	97
9.5	89	90
4.75	59	59
2.36	41	42
1.18	32	34
0.6	25	26
0.3	12	12
.15	7	7
0.075	5.1	4.6
Volumetric and Mixture Properties		
Gyrations	60	60
AC, %	5.5	5.1
AC from RAP, %	1.1	0.93
AC from Virgin Binder, %	4.4	4.17
Anti-strip, %	0.0	0.0
Effective AC, %	5.44	4.95
Dust/Asphalt Ratio	0.93	0.93
% VMA	16.5	15.5

FIGURE 3.1 Tanker with rubber-modified binder

FIGURE 3.2 Rubber-modified binder pumped to plant

TABLE 3.2 Mixture Density and Thickness

Mixture	In-Place Density, %	Thickness, in
Polymer-Modified	93.8	1.63
Rubber-Modified	92.9	1.60

4 LABORATORY TESTING

Approximately 30 five-gallon buckets of each mix were sampled during production for additional testing at the NCAT laboratory. One five-gallon bucket of each asphalt binder was also sampled from the tanks for binder characterization. The laboratory tests were designed to assess how the mixture might perform in the field.

4.1 Binder Properties

4.1.1 Methodology

Both the polymer-modified and rubber-modified asphalt binders were tested and graded according to AASHTO M 320-10. Additionally, performance grading using the multiple stress creep recovery (MSCR) in compliance with AASHTO MP 19-10 was followed to further characterize the binders. To determine this performance grade, the MSCR test was conducted at 64°C to determine the non-recoverable creep compliance of the binders. The same rolling thin film oven (RTFO) aged specimen utilized in the dynamic shear rheometer (DSR) test according to AASHTO T 315 was also used in the MSCR test.

4.1.2 Binder Testing Results

The asphalt binders were tested and graded according to AASHTO M 320-10. Detailed results are provided in Appendix A. Table 4.1 summarizes the true grade and performance grade of each binder. It should be noted that the rubber-modified binder was intended to be a PG 76-22 asphalt binder; however, the *m*-value of the binder did not meet the criterion for a low temperature grade of -22°C. Therefore, the binder was graded one performance grade higher than expected for the critical low temperature. Both binders met the appropriate high temperature grade for the region.

TABLE 4.1 Performance Grading of Binders

Mixture	True Grade	Performance Grade
Rubber-Modified	80.4 – 21.9	76 – 16
Polymer-Modified	79.2 – 24.4	76 – 22

Table 4.2 summarizes the MSCR test results. Table 4.3 shows the acceptable non-recoverable creep compliance at 3.2 kPa and percent differences for varying levels of traffic as specified in AASHTO MP 19-10. Based on the MSCR test results, both binders were graded “E” for extremely heavy traffic. According to AASHTO MP 19-10, extremely high traffic grade “E” is for traffic greater than 30 million equivalent single axle loads (ESALs) or standing traffic such as toll plazas and port facilities.

TABLE 4.2 Non-recoverable Creep Compliance at Multiple Stress Levels

Binder	Test Temperature, °C	$J_{nr0.1}$, kPa^{-1}	$J_{nr3.2}$, kPa^{-1}	J_{nrdiff}, %	Performance Grade
Polymer-Modified	64	0.19	0.20	8.21	64 – 22 E
Rubber-Modified	64	0.32	0.43	33.87	64 – 16 E

NOTE: Jnr0.1 = average non-recoverable creep compliance at 0.1 kPa; Jnr3.2 = average non-recoverable creep compliance at 3.2 kPa; Jnrdiff = percent difference in non-recoverable creep compliance between 0.1 kPa and 3.2 kPa

TABLE 4.3 Requirements for Non-Recoverable Creep Compliance (AASHTO MP 19-10)

Traffic Level	Max $J_{nr3.2}$, kPa^{-1}	Max J_{nrdiff}, %
Standard Traffic "S" Grade	4.0	75
Heavy Traffic "H" Grade	2.0	75
Very Heavy Traffic "V" Grade	1.0	75
Extremely Heavy Traffic "E" Grade	0.5	75

NOTE: The specified test temperature is based on the average 7-day maximum pavement design temperature

4.2 Moisture Susceptibility

4.2.1 Methodology

Moisture susceptibility testing was performed in accordance with ALDOT 361. For each of the mixtures, two sets of three specimens were used to determine the tensile strength ratio (TSR). All of the specimens were compacted to a height of 95 mm and an air void tolerance of 7 ± 0.5 percent. One set of specimens was tested with no moisture conditioning while the other three were conditioned through a vacuum saturation process. During this process, 55 to 80 percent of the interval voids were filled with water. Unlike AASHTO T 283, ALDOT 361 does not require the saturated samples to undergo a freeze-thaw cycle. Instead, the specimens were placed in a 60 ±1°C water bath for 24 ± 1 hours. All samples, conditioned and unconditioned, were brought to room temperature in a 25 ± 0.5°C water bath to equilibrate the sample temperature immediately preceding testing. The indirect tensile strength was then calculated using equation 4.1 based on the failure loading and measured specimen dimensions. The tensile strength ratio was then calculated for each set by dividing the average tensile strength of the conditioned specimens by the average tensile strength of the unconditioned specimens. TSR values greater than 0.80 are typically considered adequate to resist moisture damage. The Pine Instruments Marshall Stability Press used for determining indirect tensile strength is shown in Figure 4.1

$$S_t = \frac{2 * P}{3.14 * D * t} \quad (4.1)$$

where

S_t = tensile strength (psi)
P = average load (lb)
D = specimen diameter (in.)
t = specimen thickness (in.)

FIGURE 4.1 Pine Instruments Marshall Stability Press

4.2.2 Moisture Susceptibility Results

Moisture susceptibility testing was performed on the polymer-modified and rubber-modified mixtures in accordance with ALDOT 361. A summary of the TSR testing results is presented in Appendix B. Both the saturation and air void requirements specified in ALDOT 361 were met for each specimen tested.

Table 4.4 gives a summary of the results from the TSR testing on the two mixtures. While both mixtures passed the 0.80 required TSR, the rubber-modified mixture had a TSR slightly less than the polymer-modified mixture. Table 4.4 also provides the average splitting tensile strengths of both mixtures. A *t*-test ($\alpha = 0.05$) was used to compare the splitting tensile strengths of both mixtures in the conditioned and unconditioned states. The statistical analysis showed both mixtures had equivalent splitting tensile strengths in both the conditioned ($p = 0.92$) and unconditioned ($p = 0.61$) states. Since both the conditioned and unconditioned tensile strengths of the mixtures are statistically equivalent and both mixtures pass the TSR criterion, one would expect the mixtures to have similar resistance to moisture damage.

TABLE 4.4 Summary of TSR Testing

Mix ID	Treatment	Air Voids (%)	Saturation (%)	Tensile Strength (psi)	TSR
Polymer-Modified	Conditioned	7.1	63.7	159.6	0.93
	Unconditioned	7.0	NA	171.4	
Rubber-Modified	Conditioned	6.9	59.7	158.4	0.90
	Unconditioned	6.8	NA	176.3	

4.3 Dynamic Modulus

4.3.1 Methodology

Dynamic Modulus testing was performed for both the rubber and polymer modified mixes. The samples for this testing were prepared in accordance with AASHTO PP60-09 from re-heated plant-produced mix. The samples were compacted to a height of 175 mm and a diameter of 150 mm and prepared to meet the tolerances outlined in Table 4.5. The tolerances in Table 4.5 represent tolerances on the final sample that had been cut and cored from the interior of the larger Superpave gyratory compactor (SGC) sample. Three samples were prepared for testing from each mix. It should be noted that the specification recommends ± 0.5 percent air voids as a reasonable tolerance for the cut samples. However, it does not specify a target air void content. A target air void content of 7 ± 0.5 percent was selected for this project. This is a common target for the air void content of an in-place pavement post-compaction and is a typical target for HMA performance testing samples in the laboratory.

TABLE 4.5 Production Tolerances for Dynamic Modulus and Flow Number Specimens (AASHTO PP60-09)

Parameter	Tolerance
Average Diameter	100 to 104 mm
Standard Deviation of Diameter	≤ 0.5 mm
Height	147.5 mm to 152.5 mm
End Flatness	≤ 0.5 mm
End Perpendicularity	≤ 1.0 mm

Dynamic Modulus testing was performed in an IPC Global Asphalt Mixture Performance Tester (AMPT), shown in Figure 4.2. Dynamic Modulus testing is performed in order to quantify the stiffness of the asphalt mixture over a wide range of testing temperatures and loading rates (or frequencies). The temperatures and frequencies used for testing these mixes are those recommended by AASHTO PP 61-10. For this methodology, the high test temperature is dependent on the high PG grade of the base binder utilized in the mix being tested. Table 4.6 shows the general outline of temperatures and frequencies used, while Table 4.7 shows the selection criteria for the high testing temperature. For this project, a high test temperature of 45°C was selected since the base binder was a PG 76-22. It should be noted, however, that this high test temperature could be reduced if poor quality test data is observed. Quality of test data will be better defined later in this report.

FIGURE 4.2 IPC Global Asphalt Mixture Performance Tester

TABLE 4.6 Temperatures and Frequencies used for Dynamic Modulus Testing

Test Temperature (°C)	Loading Frequencies (Hz)
4.0	10, 1, 0.1
20.0	10, 1, 0.1
High Testing Temperature	10, 1, 0.1, 0.01

TABLE 4.7 High Test Temperature for Dynamic Modulus Testing

High PG Grade of Base Binder	High Test Temperature (°C)
PG 58-XX and lower	35
PG 64-XX and PG 70-XX	40
PG 76-XX and higher	45

Dynamic Modulus testing was performed in accordance with AASHTO TP 79-10. This testing was performed both confined and unconfined. Unconfined data is most commonly used for dynamic modulus testing since the MEPDG was calibrated using unconfined dynamic modulus data. Unconfined testing is also significantly easier to perform than confined testing. However, it can be argued that confined testing gives a better representation of pavement in-situ since the confinement represents the overburden surrounding the asphalt material. Confinement for this project was set at the level of 20 psi.

Test data were screened for data quality in accordance with the limits set in AASHTO TP 79-10. A summary of these data quality statistics is given in Table 4.8. Variability of Dynamic Modulus values at specific temperatures and frequencies ideally have a coefficient of variation (COV) at or below 13 percent. However, certain modified mixtures have a tendency to show greater modulus variability at the high testing temperature. All data were checked for reasonableness

as well (reduction in moduli with increasing temperature, slower loading). Data with borderline data quality statistics were evaluated on a case by case basis.

TABLE 4.8 Dynamic Modulus Data Quality Threshold Values

Data Quality Statistic	Limit
Deformation Drift	No Limit in Direction of Applied Load
Peak-to-Peak Strain	75 to 125 microstrain (unconfined tests)
	85 to 115 microstrain (confined tests)
Load Standard Error	< 10%
Deformation Standard Error	< 10%
Deformation Uniformity	< 30%
Load Drift	< 2%
Phase Angle Uniformity	< 3°

The collected data were used to generate a master curve for each individual mix. The master curve uses the principle of time-temperature superposition to horizontally shift data at multiple temperatures and frequencies to a reference temperature so that the stiffness data can be viewed without temperature as a variable. This method of analysis allows for visual relative comparisons to be made between multiple mixes. An example of using the time-temperature superposition principle to generate a master curve is shown in Figure 4.3.

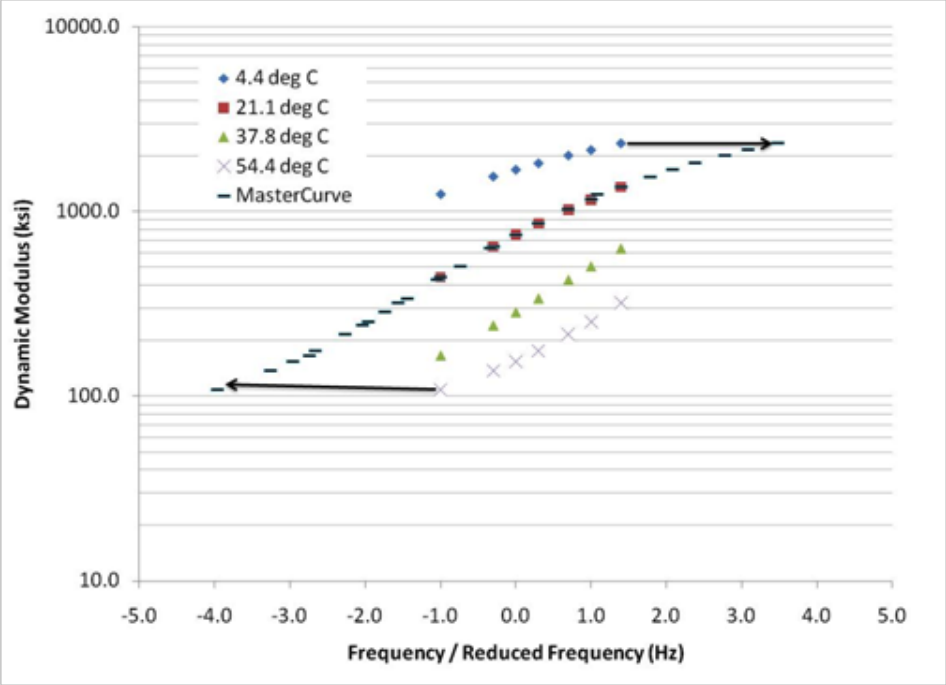

FIGURE 4.3 Example master curve generation

Generation of the master curve also allows for generation of the dynamic modulus data over the entire range of temperatures and frequencies required for mechanistic-empirical pavement design using the MEPDG. By having an equation for the curve describing the stiffness behavior

of the asphalt mix, both interpolated and extrapolated data points at various points along the curve can then be calculated. The temperatures and frequencies needed as an input for the MEPDG are listed in Section 10.6.1 of AASHTO PP 61-10.

Data analysis was conducted per the methodology in AASHTO PP 61-10. The general form of the master curve equation is shown as Equation 4.2. As mentioned, the dynamic modulus data are shifted to a reference temperature. This is done by converting testing frequency to a reduced frequency using the Arrhenius equation (Equation 4.3). Substituting Equation 4.3 into Equation 4.2 yields the final form of the master curve equation, shown as Equation 4.4. The shift factors required at each temperature are given in Equation 4.5 (the right-hand portion of Equation 4.3). A reference temperature of 20°C was used for this analysis. The limiting maximum modulus in Equation 4.4 is calculated using the Hirsch Model, shown as Equation 4.6. The Pc term, Equation 4.7, is simply a variable required for Equation 4.7. A limiting binder modulus of 1 GPa is assumed for this equation. Non-linear regression is then conducted using the Solver function in EXCEL® to develop the coefficients for the master curve equation. Typically, these curves have an S_e/S_y term of less than 0.05 and an R^2 value of greater than 0.99. Definitions for the variables in Equations 4.2-4.7 are given in Table 4.9.

$$Log|E^*| = \partial + \frac{(Max-\partial)}{1+e^{\beta+\gamma log f_r}} \quad (4.2)$$

$$log f_r = log\ f + \frac{\Delta E_a}{19.14714}\left[\frac{1}{T} - \frac{1}{T_r}\right] \quad (4.3)$$

$$log|E^*| = \partial + \frac{(Max-\partial)}{1+e^{\beta+\gamma\left\{logf+\frac{\Delta E_a}{19.14714}\left[\frac{1}{T}-\frac{1}{T_r}\right]\right\}}} \quad (4.4)$$

$$\log\left[a(T)\right] = \frac{\Delta E_a}{19.14714}\left[\frac{1}{T} - \frac{1}{T_r}\right] \quad (4.5)$$

$$|E^*|_{max} = P_c\left[4{,}200{,}000\left(1-\frac{VMA}{100}\right) + 435{,}000\left(\frac{VFA*VMA}{10{,}000}\right) + \frac{1-P_c}{\frac{\left(1-\frac{VMA}{100}\right)}{4{,}200{,}000}+\frac{VMA}{435{,}000(VFA)}}\right] \quad (4.6)$$

$$P_c = \frac{\left(20+\frac{435{,}000(VFA)}{VMA}\right)^{0.58}}{650+\left(\frac{435{,}000(VFA)}{VMA}\right)^{0.58}} \quad (4.7)$$

TABLE 4.9 Master Curve Equation Variable Descriptions

Variable	Definition
|E*|	Dynamic Modulus, psi
δ,β, and γ	Fitting Parameters
Max	Limiting Maximum Modulus, psi
f_r	Reduced Frequency at the Reference Temperature, Hz
f	Loading Frequency at the Test Temperature, Hz
ΔE_a	Activation Energy (treated as a fitting parameter)

T	Test Temperature, ^{o}K
T_r	Reference Temperature, ^{o}K
a(T)	Shift Factor at Temperature, T
$\|E^*\|_{max}$	Limiting Maximum HMA Dynamic Modulus, psi
VMA	Voids in Mineral Aggregate, %
VFA	Voids Filled with Asphalt, %

4.3.2 Dynamic Modulus Test Results

Detailed results of individual dynamic modulus tests are given in Appendix C. Figure 4.4 shows the dynamic modulus master curves for both mixes on the logarithmic scale while Figure 4.5 shows the dynamic modulus master curves for both mixes on the arithmetic scale. The logarithmic scale is better for viewing the master curves and making relative comparisons at the high temperature, low loading frequency portion of the curve. The arithmetic scale is better for viewing the master curves and making relative comparisons at the low temperature, high loading frequency portion of the curve.

Figure 4.4 shows the dynamic modulus master curves on a logarithmic scale and it demonstrates how the presence of confinement affects the dynamic modulus results at the high temperature, slower loading frequency portion of the master curve (left hand side). The relative rankings of the tested mixes, from stiffest to softest, are as follows: rubber-modified (confined), polymer-modified (confined), rubber-modified (unconfined), and polymer-modified (unconfined). Given the data in Figure 4.4, it appears that both the presence of the rubber-modification and the presence of confining pressure had a significant impact on the dynamic modulus test results.

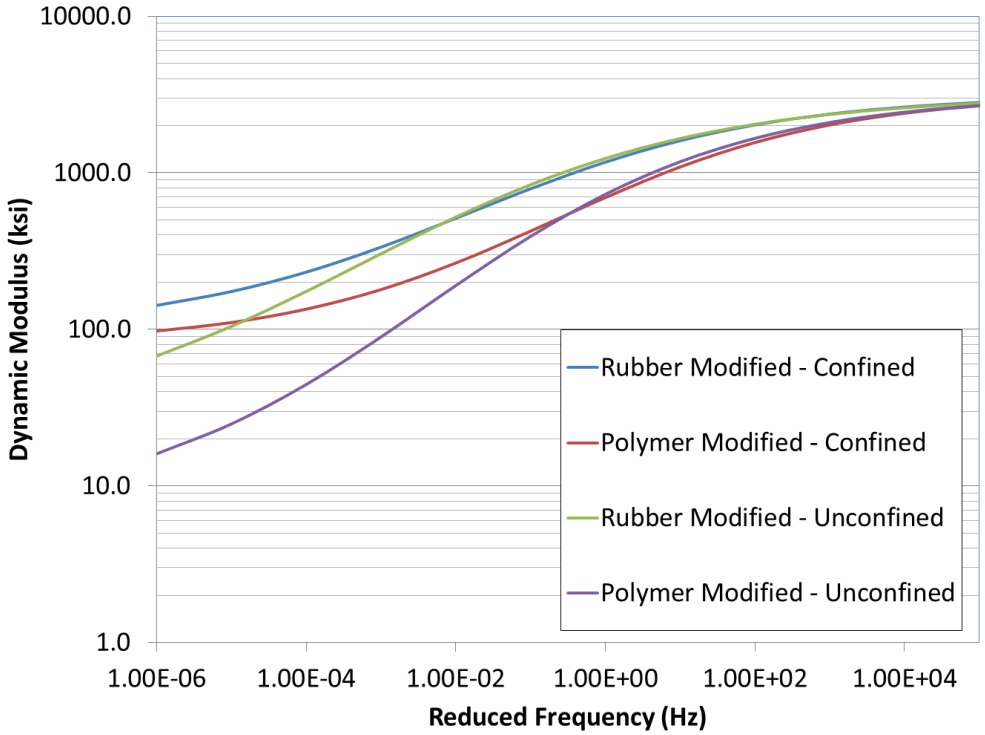

FIGURE 4.4 Master curves on logarithmic scale

Figure 4.5 presents the dynamic modulus master curves on an arithmetic scale, and it shows a very large difference in dynamic modulus between the two mixes at the cold temperature, fast loading frequency end of the master curve. The presence of confinement appears to have very little effect on the results at this end of the master curve. At the intermediate temperature data range (middle portion of the curve), there is an approximately 500 ksi difference in stiffness between the two mixes. At the extreme cold temperature end (far right side) of the master curve, this difference narrows to approximately 100 ksi.

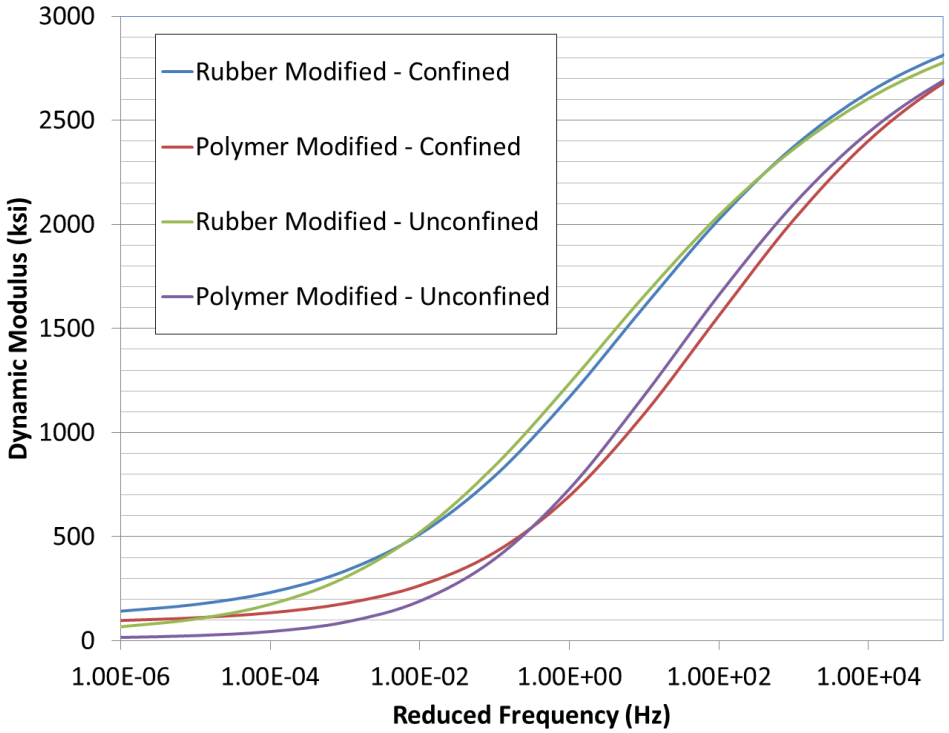

FIGURE 4.5 Master curves on arithmetic scale

Dynamic modulus data and master curves on their own are not an indicator of mixture performance. These data can be coupled with performance prediction software, such as the Mechanistic-Empirical Pavement Design Guide (MEPDG), to determine the overall effect dynamic modulus has in mixture performance. Table 4.10 contains the master curve coefficients as defined in Equation 4.5 and Appendix C contains the dynamic modulus data that would be needed to perform an MEPDG simulation.

TABLE 4.10 Master Curve Coefficients

Mix ID	Confined or Unconfined Testing (C or UC)	Max E* (Ksi)	Delta	Beta	Gamma	E_A	R^2	S_e/S_y
Rubber Modified	C	3123.6	98.4	-0.925	-0.508	194888.3	0.989	0.074
Polymer Modified	C	3152.0	80.7	-0.354	-0.543	192220.7	0.998	0.031
Rubber Modified	UC	3123.6	22.0	-1.469	-0.450	213409.2	0.997	0.037
Polymer Modified	UC	3152.0	6.7	-1.164	-0.494	190558.9	0.996	0.044

4.4 Asphalt Pavement Analyzer

4.4.1 Methodology

The permanent deformation susceptibility of the two mixtures was evaluated using the Asphalt Pavement Analyzer (APA) shown in Figure 4.6. Testing was performed in accordance with AASHTO TP 63. The samples were compacted to a height of 75 mm with a target air void level of 7 ± 0.5 percent. Six replicates were tested for each mixture. The samples were tested at 67°C which is the standard testing temperature used by the Alabama Department of Transportation. Each sample was loaded by a 100 lb steel wheel resting atop a pneumatic hose with 100 psi of pressure. Manual depth readings were taken at two locations on each sample before and after the 8,000 loads had been applied to the sample to determine rut depths.

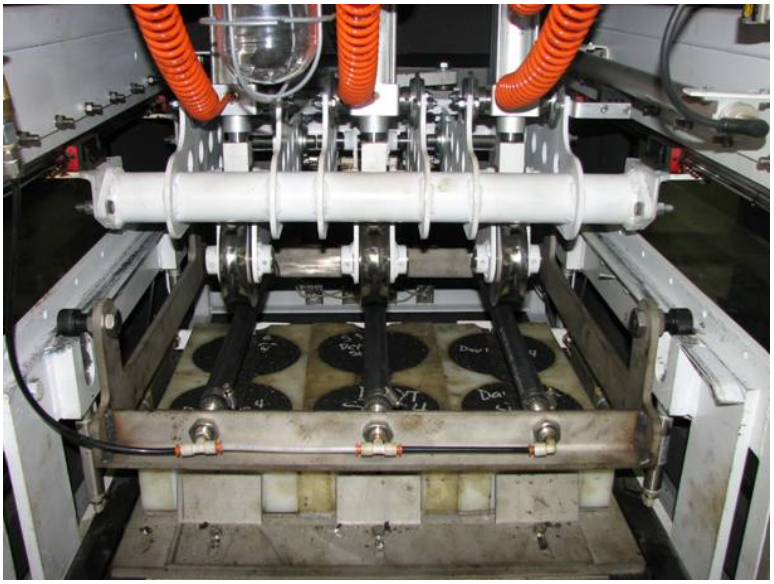

FIGURE 4.6 Asphalt Pavement Analyzer

4.4.2 Test Results

A complete list of the test results for the two mixtures is given in Appendix D. Table 4.11 provides manual rut depth measurements for the two mixtures tested in the APA. A two sample *t*-test (α = 0.05) showed there was no statistical difference in the rut depths of these mixtures. (*p* = 0.82).

TABLE 4.11 APA Test Results

Mixture	Average Rut Depth, mm	StDev, mm	COV,%
Rubber Modified	2.39	1.4	57.5
Polymer Modified	2.52	0.33	13.3

The APA is typically used as a "go/no-go" type test to ensure mixtures susceptible to rutting are not placed on heavily trafficked highways. Past research at the Test Track has shown that if a mixture has an average APA rut depth less than 5.5 mm, it should be able to withstand at least 10 million equivalent single axle loads (ESALs) of traffic without accumulating more than 12.5 mm of field rutting (*7*). Considering this threshold, a one-sample *t*-test (α = 0.05) shows both the rubber modified (*p* = 0.03) and polymer modified (*p* = 0.00) mixtures had rut depths significantly less than this threshold. ALDOT additionally requires mixtures have less than 4 mm of rutting in the APA before they can be used as the wearing course of a pavement structure. A one-sample *t*-test (α = 0.05) once again showed that both the rubber modified (*p* = 0.035) and polymer modified (*p* = 0.00) mixtures had rut depths significantly less than 4 mm. Since both mixtures pass these requirements, neither should be susceptible to rutting in the field.

4.5 Flow Number

4.5.1 Methodology

The flow number (F_n) of each mixture was determined using the AMPT. New samples were fabricated for flow number which met the specifications described in section 4.4.1. F_n tests were conducted at a temperature of 60.5°C, which is consistent with the LTPPBind v. 3.1 50 percent reliability temperature 20 mm below the surface of the pavement for Dothan, Alabama. The specimens were tested unconfined using a deviator stress of 87 psi. Each sample was tested until the samples reached 10 percent axial strain. The point of tertiary flow was determined using the Francken model (Equation 4.8) (*8*). A non-linear regression analysis was used to fit the model to the test data.

$$\varepsilon_p(N) = aN^b + c(e^{dN} - 1) \quad (4.8)$$

where

$\varepsilon_p(N)$ = permanent strain at 'N' cycles
N = number of cycles
a,b,c,d = regression coefficients

4.5.2 Test Results

A complete list of flow number test results for each mixture is provided in Appendix E. The average flow number of three test results for each mixture using the Francken Model is shown in Figure 4.7. As seen, one test result from the polymer modified mixture had a flow number nearly three times larger than the two other test results. Using this test result, the coefficient of variation for the polymer modified mixture flow number was 70.6 percent. When this point was removed from the dataset, the average flow number for the polymer modified mixture was reduced to 327 compared to 660 for the rubber modified mixture. While a statistical *t*-test (α = 0.05) shows statistical equivalence between the performance of the mixtures (*p*-value = 0.053),

the numerical difference between the two suggests the rubber mixture will perform better than the polymer modified mixture in terms of resistance to permanent deformation.

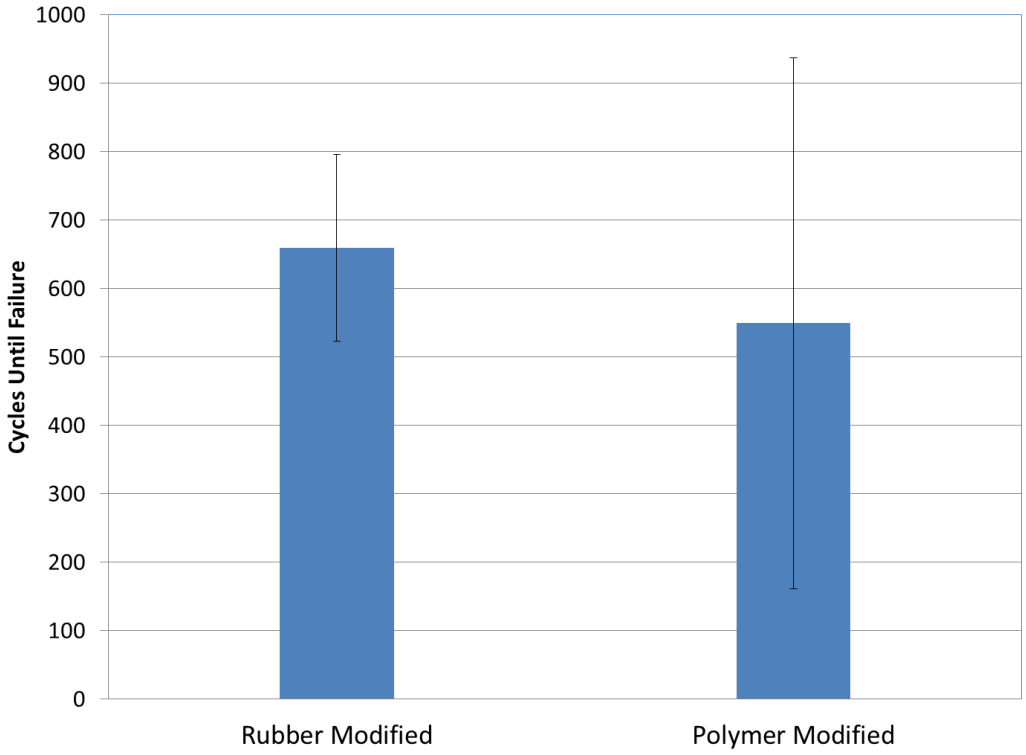

FIGURE 4.7 Flow Number test results

4.6 Hamburg Wheel-Tracking Device

4.6.1 Methodology

Hamburg wheel-tracking testing (HWTT), Figure 4.8, was performed to assess both the rutting and stripping susceptibility of the polymer and rubber modified asphalt mixtures. For each mixture, four samples were tested. After compacting the 150 mm diameter and 115 mm tall specimens, they were trimmed so that the specimens had heights between 38 and 50 mm. The targeted air voids of the cut specimens was 7 ± 2 percent as specified by AASHTO T 324.

The samples were tested under a 158 ± 1 lb wheel load for 10,000 cycles (20,000 passes). The samples were submerged in a 50.0°C water bath while being tested. Rut depths were measured by an LVDT which recorded the relative vertical position of wheel after each loading cycle. After testing, these data were used to determine the stripping inflection point of each mixture. Figure 4.9 illustrates the typical output of HWTT. The data show the progression of the rut depth with the number of cycles. From this curve, two tangents are evident: the steady-state rutting portion of the curve and the portion of the curve after stripping. The intersection of these two curve-tangents is quantified as the stripping inflection point (SIP). Comparing the stripping

inflection points and rutting rates of the mixtures gives a measure of the relative moisture and deformation susceptibility of each mixture.

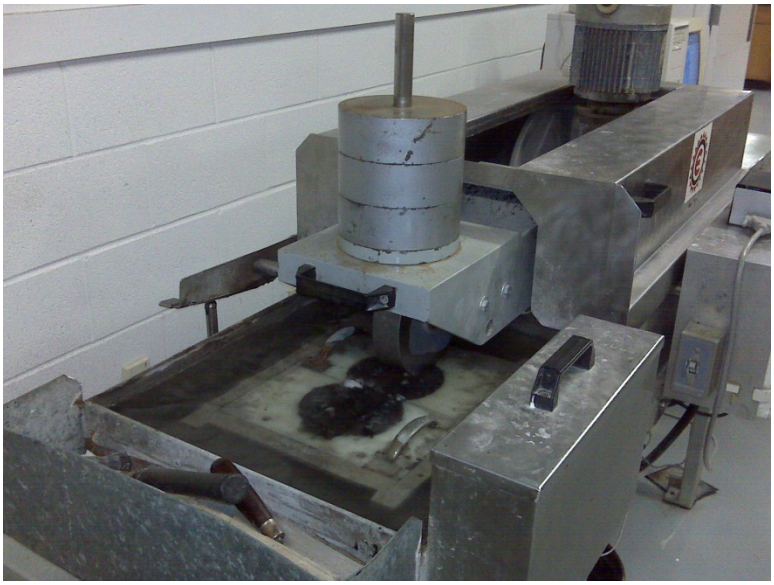

FIGURE 4.8 Hamburg Wheel-Tracking Device

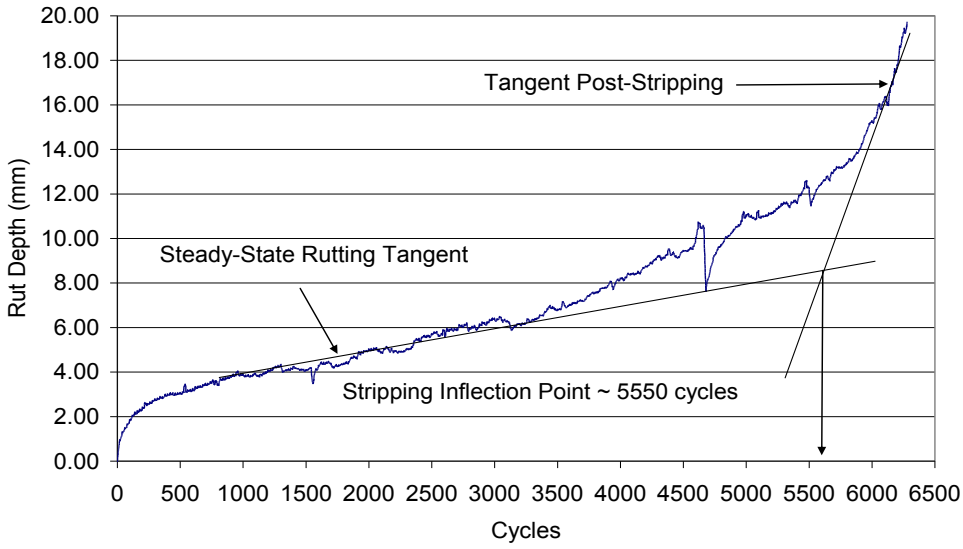

FIGURE 4.9 Example of Hamburg raw data output

4.6.2 Test Results

The complete set of HWTT results is given in Appendix F. Table 4.12 provides the average results for the HWTT results of the two mixtures. While statistical analyses cannot be conducted on the test results of these mixtures, the rutting rates, total rut depths, and stripping inflection points of the two mixtures are comparable. Currently, some agencies require mixtures have less than 4 mm of total rutting and a stripping inflection point greater than 5,000

cycles to prevent rutting and moisture damage, respectively (*9*). Both the rubber modified and polymer mixtures pass these criteria.

TABLE 4.12 Hamburg Test Results

Mixture	Average Rutting Rate, mm/hr	Average Total Rutting, mm	Stripping Inflection Point, cycles
Rubber Modified	0.3	1.3	None
Polymer Modified	0.4	1.4	None

4.7 Energy Ratio

4.7.1 Methodology

The energy ratio has been developed to assess a mixture's resistance to top-down or surface cracking (*10*). To determine this property of these mixtures, three specimens, 150 mm in diameter by approximately 38 mm thick, cut from gyratory compacted samples, were prepared, and one set of indirect tension tests: resilient modulus, creep compliance, and tensile strength was performed at 10°C for each mix.

The energy ratio, ER, is given by:

$$ER = \frac{DCSE_f \cdot \left[7.294 \cdot 10^{-5} \cdot \sigma^{-3.1}(6.36 - St) + 2.46 \cdot 10^{-8}\right]}{m^{2.98} \cdot D_1} \quad (4.9)$$

To evaluate the top-down cracking performance of a given pavement, tensile stress, σ, obtained at the bottom of the asphalt layer using elastic layer analysis, and mixture properties (resilient modulus, M_r, power function parameters, D_1 and m, tensile strength, S_t, and dissipated creep strain energy at failure, $DCSE_f$) are required as inputs of the top-down cracking model. Stress was assumed to be 150 psi. In this model, each property can be obtained from the three mixture tests.

The resilient modulus is obtained in a load control mode by applying a repeated haversine waveform load with a loading period of 0.1 s followed by a rest period of 0.9 s and is determined from the stress-strain curve. The power function parameters are obtained by fitting the creep compliance curve performed using a constant load control mode, and the tensile strength and dissipated creep strain energy at failure are determined from the stress-strain curve of a given mixture from the strength test. The detailed testing procedures and data interpretation methods for the resilient modulus, creep compliance, and tensile strength tests are described in Roque and Buttlar (*10*), Buttlar and Roque (*11*), and Roque et al. (*12*).

4.7.2 Test Results

Table 4.13 summarizes the ER data for two mixtures tested in this phase of the research. The ER values determined would be the indicators of cracking performance of the sections with different binders. Again, the energy ratio is calculated by analyzing multiple test samples to arrive at a singular value. Therefore, statistical analyses could not be completed on these data.

TABLE 4.13 Energy Ratio Test Results

Mixture	**Rubber-Modified**	**Polymer-Modified**
m-value	0.297	0.339
D_1	5.33E-07	6.13E-07
S_t (MPa)	2.63	2.23
M_r (GPa)	11.60	11.16
FE (kJ/m^3)	2.4	3.0
$DSCE_{HMA}$ (kJ/m^3)	2.1	2.8
Stress (psi)	150	150
A	4.54E-08	4.76E-08
$DSCE_{MIN}$ (kJ/m^3)	0.314	0.513
ER	6.68	5.42

After analyzing the data, one sees that there are substantial differences in the energy ratios of polymer-modified and rubber-modified mixtures. The rubber-modified mixture has a higher ER. This suggests it would perform better in terms of surface cracking. However, as previously mentioned, statistical analyses could not be completed on the data due to the final results being aggregated to form one value.

Current recommendations suggest that a minimum ER of 1.95 is needed if trafficking is less than 1,000,000 ESALs per year (*13*). Both mixtures have ER values which exceed this criterion. Therefore, it is not expected that these mixtures will exhibit signs of surface cracking.

5 FIELD PERFORMANCE

While laboratory testing can be used to evaluate and predict mixture performance in the field, the ultimate proof of a technology's appropriateness is field performance. The field performance of each test section was evaluated to assess rutting, cracking, texture, and smoothness. The rut depths, texture, and smoothness of each test section were evaluated using an inertial profiler while cracking was assessed by monitoring three one hundred foot test strips on each test section. Detailed condition surveys were not conducted before paving occurred due to project timing; therefore, it was assumed in this relatively short stretch of highway that the pavement conditions were similar.

5.1 Initial Profiler Measurements

An inertial profiler was used to characterize the rutting, smoothness, and texture of the two mixtures placed on US 231-S. The profiler completed three laps over each test section at 45 miles per hour to differentiate performance between the two test sections.

Initial inertial profiler measurements were completed on both test sections on September 8, 2010. Additionally, the test sections were characterized one year later on September 20, 2011. The inertial profiler combines the profiles from both rear lasers into a single data stream. A virtual string line is generated from the lasers across the 12 foot lane containing 50 datapoints. The two largest deviations from the string line are the rut depths. The average rut depth, texture, and smoothness in terms of International Roughness Index (IRI) in both wheelpaths are given in Table 5.1 for both the initial and one year data.

Additionally, two-sample *t*-tests ($\alpha = 0.05$) were conducted to determine if there was a statistical difference in the performance of the two test sections. At time zero, there were no statistical differences in the performance of the mixtures in terms of smoothness, texture and rutting. However, after one year of trafficking, the rubber-modified test section had statistically more rutting and less texture than the polymer-modified test section. The difference in rutting in the two test sections is 0.6 mm, and both sections still have minimal rutting over the first year of trafficking. Therefore, while there is more rutting in the rubber-modified test section, there is no real practical difference in terms of mixture performance.

TABLE 5.1 Field Measurements

	Time Zero			Year 1		
	Rubber-Modified	Polymer-Modified	*p*-value (α = 0.05)	Rubber-Modified	Polymer-Modified	*p*-value (α = 0.05)
Rutting, mm	1.3	1.5	0.072	5.6	5.0	0.001
RIRI, in/mile	35.3	36.6	0.299	37.5	36.9	0.630
LIRI, in/mile	33.9	34.1	0.859	33.6	34.6	0.353
Texture, mm	0.41	0.42	0.553	0.37	0.40	0.000

5.2 Cracking

Three subsections, each measuring 100 feet long, were randomly chosen to assess the cracking in both the rubber-modified and polymer-modified test sections. Cracking is monitored by visually assessing the pavement surfaces for cracks. After one year of trafficking, both sections are free of cracks.

5.3 Summary

Both test sections are performing well in the field. While the rubber-modified section has statistically more rutting than the polymer-modified test section, the total rut depths in the test section are minimal and not practically different. The smoothness of both mixtures is statistically similar in both the left and right wheel paths. The rubber-modified mixture has a slightly lower texture than the polymer-modified mixture; however, there are no practical textural differences. Additionally, neither mix has shown evidence of cracking.

6 CONCLUSIONS AND RECOMMENDATIONS

Based on this research, the following conclusions can be drawn about plant-produced rubber modified asphalt mixtures.

- The rubber-modified and polymer-modified binders had similar high temperature performance grades; however, the *m*-value of the rubber-modified binder did not pass the standard at -22°C.
- MSCR test results showed both binders were expected to carry traffic level “E” at 64°C.
- The polymer-modified mixture had a slightly higher TSR value than the rubber-modified mixture; however, both mixtures exceed the minimum threshold of 0.80. Additionally, both mixtures had statistically identical conditioned and unconditioned strengths due to variability and a small sample size suggesting no true difference in performance between the mixtures.
- The rubber-modified mixture was typically stiffer than the polymer-modified mixture in terms of dynamic modulus testing. The stiffness differences were most noticeable at the hotter and intermediate temperatures.
- Both mixtures had statistically less than 4 mm of rutting in the APA. There were no statistical differences in mixture laboratory performance between the two mixtures.

- HWTT test results show both mixtures should be resistant to rutting and moisture damage as the total rut depths of both mixtures were less than 4 mm and the SIPs were greater than 5,000 cycles.
- The rubber-modified mixture had a higher ER than the polymer-modified mixture. This suggests the rubber-modified mixture will be more resistant to surface cracking than the polymer-modified mixture. It should be noted that both mixtures have ERs greater than 1.95, which is required for trafficking less than 1 million ESALs per year.
- After construction, both mixtures were performing equivalently in terms of rutting, smoothness, and texture.
- After one year of trafficking, the rubber-modified test section has more rutting and less texture than the polymer-modified test section. However, both mixtures are performing adequately in terms of rutting as both mixtures and there is no practical difference in field performance.

Based on this research the following recommendations should be considered.

- Since laboratory tests and one year of field performance suggest similar performance between rubber-modified and polymer-modified dense-graded mixtures, ALDOT should consider allowing GTR as an alternative to polymer in surface mixtures at the contractor's request. These mixtures should be required to meet the minimum APA requirements already in place for state surface mixtures. Additionally, the high and low temperature binder grades of the mixtures should meet the binder specifications and be tested for compliance.
- The pavements will continue to be monitored for the remainder of the five years for further evaluation of surface texture, IRI, rutting, and cracking.

7 REFERENCES

1. Kaloush, K.E., M.W. Witczak, G.B. Way, A. Zborowski, M. Abojaradeh, and A. Sotil. *Performance Evaluation of Arizona Asphalt Rubber Mixtures Using Advanced Dynamic Material Characterization Tests*. Final Report, Arizona State University, Tempe, Arizona, July 2002.
2. Huang, B., L.N. Mohammad, P.S. Graves, and C. Abadie. Louisiana Experience with Crumb Rubber-Modified Hot-Mix Asphalt Pavement. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1789, National Academies of Sciences, Washington, D.C., 2002, pp. 1-13.
3. Way, G.B. Flagstaff I-40 Asphalt Rubber Overlay Project – Ten Years of Success. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1723, National Academies of Sciences, Washington, D.C., 2000, pp. 45-52.
4. Gunkel, K. *Evaluation of Exhaust Gas Emissions and Worker Exposure from Asphalt Rubber Binders in Hot Mix Asphalt*. Wildwood Environmental Engineering Consultants, Inc., Michigan Department of Transportation, March 1994.
5. Rubber Pavement Association. *Air Quality Issues and Best Management Practices with the Production of Asphalt Rubber Asphalt Concrete*. 2002.
6. Turner Fairbanks Highway Research Center. *User Guidelines for Waste and Byproduct Materials in Pavement Construction*. Federal Highway Administration, Washington, D.C., 2005.
7. Tran, N.H., R.C. West, R.B. Powell, and A.N. Kvasnak. Evaluation of AASHTO Rut Test Procedure using the Asphalt Pavement Analyzer. *Journal of the Association of Asphalt Paving Technologists*, Vol. 78, 2009, pp. 1-24.
8. Biligiri, K.P., K.E. Kaloush, M.W. Mamlouk, and M.W. Witczak, Rational Modeling of Tertiary Flow of Asphalt Mixtures. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2001, National Academies of Sciences, Washington, D.C., 2007, pp. 63-72.
9. Aschenbrener, T., R. Terrel, and R. Zamora. *Comparison of the Hamburg Wheel-Tracking Device and the Environmental Conditional System to Pavements of Known Stripping Performance.* CDOT-DTD-R-94-1. Colorado Department of Transportation, Denver, CO, January 1994.
10. Roque, R. and W.G. Buttlar. The Development of a Measurement and Analysis System to Accurately Determine Asphalt Concrete Properties Using the Indirect Tensile Mode. *Journal of the Association of Asphalt Paving Technologists*, Vol. 61, 1992, pp. 304-332.
11. Buttlar, W.G. and R. Roque. Development and Evaluation of the Strategic Highway Research Program Measurement and Analysis System for Indirect Tensile Testing at Low Temperatures. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1454, National Academies of Sciences, Washington, D.C., 1994, pp. 163-171.
12. Roque, R., W.G. Buttlar, B.E. Ruth, M. Tia, S.W. Dickison, and B. Reid. *Evaluation of SHRP Indirect Tension Tester to Mitigate Cracking in Asphalt Concrete Pavements and Overlays*. Final Report, FDOT B-9885. University of Florida, Gainesville, FL, 1997.

13. Roque, R., B. Birgisson, C. Drakos, and B. Dietrich. A Mechanics-Based Prediction Model for Thermal Cracking of Asphaltic Concrete Pavements. *Journal of the Association of Asphalt Paving Technologists*, Vol. 73, 2004, pp. 229-260.

APPENDIX A
BINDER TESTING RESULTS

TABLE A.1 Performance Grading of Polymer Binder

Original Binder				
Test, Method			**Test Results**	**Specification**
Rotational Viscosity @ 135°C, AASHTO T 316, PaS			1.862	≤ 3 PaS
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* / sinδ, kPa	
76	1.21	69.0	1.30	≥ 1.00 kPa
82	0.76	69.9	0.81	
Rolling Thin Film (RTFO) Aged Binder, AASHTO T 240				
Mass Change, %			-0.075	≤ 1.00%
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* / sinδ, kPa	
76	2.58	64.4	2.859	≥ 2.20 kPa
82	1.594	65.6	1.751	
Pressure Aging Vessel (PAV) Aged Binder, AASHTO R28				
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* sinδ, kPa	
22	5701	42.9	3882	≤ 5,000 kPa
19	8520	40.3	5513	
Bending Beam Rheometer (BBR) AASHTO T313				
Test Temperature, °C				
-12	Stiffness, Mpa		145	≤ 300 Mpa
	m-value		0.319	≥ 0.300
-18	Stiffness, Mpa		295	
	m-value		0.272	
True Grade	79.2 -24.4			
PG Grade	76 - 22			

TABLE A.2 Performance Grading of Rubber Binder

Original Binder				
Test, Method			**Test Results**	**Specification**
Rotational Viscosity @ 135°C, AASHTO T 316, PaS			1.812	≤ 3 PaS
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* / sinδ, kPa	
76	1.51	77.4	1.55	≥ 1.00 kPa
82	0.87	79.3	0.88	
Rolling Thin Film (RTFO) Aged Binder, AASHTO T 240				
Mass Change, %			-0.105	≤ 1.00%
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* / sinδ, kPa	
76	3.23	73.2	3.37	≥ 2.20 kPa
82	1.82	85.4	1.88	
Pressure Aging Vessel (PAV) Aged Binder, AASHTO R28				
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* sinδ, kPa	
22	6590	40.3	4263	≤ 5,000 kPa
19	9510	38	5850	
Bending Beam Rheometer (BBR) AASHTO T313				
Test Temperature, °C				
-6	Stiffness, Mpa		73	≤ 300 Mpa
	m-value		0.354	≥ 0.300
-12	Stiffness, Mpa		155	
	m-value		0.299	
True Grade	80.4 -21.9			
PG Grade	76 - 16			

APPENDIX B
TENSILE STRENGTH RATIO TEST RESULTS

TABLE B.1 TSR Results

Mixture	Conditioning	Sample	Air Voids, %	Saturation, %	Indirect Tensile Strength, psi
Polymer Modified	Saturated	51	7.2	62.7	162.4
	Saturated	96	6.8	67.4	156.5
	Saturated	59	7.3	60.9	159.8
	Unsaturated	97	7.0	NA	169.5
	Unsaturated	95	6.9	NA	172.4
	Unsaturated	57	7.3	NA	172.3
Rubber Modified	Saturated	101	7.0	58.0	177.8
	Saturated	99	7.1	58.6	145.4
	Saturated	55	6.5	62.6	152.0
	Unsaturated	53	6.6	NA	176.3
	Unsaturated	98	6.6	NA	163.4
	Unsaturated	100	7.2	NA	186.9

APPENDIX C
DYNAMIC MODULUS TEST RESULTS

TABLE C.1 Dynamic Modulus Results

Mix ID	Confining Pressure, psi	Sample ID	Voids, %	Temp, C	Freq, Hz	E*, MPa	δ, degrees
Rubber Modified	20	38	7.3	4	10	16949	6.53
Rubber Modified	20	38	7.3	4	1	14350	7.52
Rubber Modified	20	38	7.3	4	0.1	11873	9
Rubber Modified	20	38	7.3	20	10	10178	10.67
Rubber Modified	20	38	7.3	20	1	7705	12.86
Rubber Modified	20	38	7.3	20	0.1	5596	15.63
Rubber Modified	20	38	7.3	40	10	4972	17.61
Rubber Modified	20	38	7.3	40	1	3230	20.76
Rubber Modified	20	38	7.3	40	0.1	2056	23.68
Rubber Modified	20	38	7.3	40	0.01	1413	24.64
Rubber Modified	20	38	7.3	45	10	4507	18.41
Rubber Modified	20	38	7.3	45	1	2958	20.87
Rubber Modified	20	38	7.3	45	0.1	1926	22.69
Rubber Modified	20	38	7.3	45	0.01	1316	22.83
Rubber Modified	20	39	7.2	4	10	18311	6.27
Rubber Modified	20	39	7.2	4	1	15626	7.17
Rubber Modified	20	39	7.2	4	0.1	12987	8.61
Rubber Modified	20	39	7.2	20	10	10948	10.76

Mix ID	Confining Pressure, psi	Sample ID	Voids, %	Temp, C	Freq, Hz	E*, MPa	δ, degrees
Rubber Modified	20	39	7.2	20	1	8331	12.96
Rubber Modified	20	39	7.2	20	0.1	6096	15.69
Rubber Modified	20	39	7.2	40	10	5297	17.42
Rubber Modified	20	39	7.2	40	1	3498	20.35
Rubber Modified	20	39	7.2	40	0.1	2261	23.04
Rubber Modified	20	39	7.2	40	0.01	1573	24.04
Rubber Modified	20	39	7.2	45	10	4510	19
Rubber Modified	20	39	7.2	45	1	2947	21.38
Rubber Modified	20	39	7.2	45	0.1	1945	22.93
Rubber Modified	20	39	7.2	45	0.01	1410	22.26
Rubber Modified	20	47	7.3	4	10	17021	7.97
Rubber Modified	20	47	7.3	4	1	13790	9.63
Rubber Modified	20	47	7.3	4	0.1	10683	12.15
Rubber Modified	20	47	7.3	20	10	9216	14.48
Rubber Modified	20	47	7.3	20	1	6431	17.5
Rubber Modified	20	47	7.3	20	0.1	4314	20.34
Rubber Modified	20	47	7.3	40	10	4136	21.62
Rubber Modified	20	47	7.3	40	1	2567	23.18
Rubber Modified	20	47	7.3	40	0.1	1649	22.98
Rubber Modified	20	47	7.3	40	0.01	1177	21.49

Mix ID	Confining Pressure, psi	Sample ID	Voids, %	Temp, C	Freq, Hz	E*, MPa	δ, degrees
Rubber Modified	20	47	7.3	45	10	3364	22.22
Rubber Modified	20	47	7.3	45	1	2109	22.7
Rubber Modified	20	47	7.3	45	0.1	1412	21.57
Rubber Modified	20	47	7.3	45	0.01	1063	19.41
Rubber Modified	0	38	7.3	4	10	17658	6.1
Rubber Modified	0	38	7.3	4	1	15090	7.11
Rubber Modified	0	38	7.3	4	0.1	12536	8.6
Rubber Modified	0	38	7.3	20	10	11291	10.19
Rubber Modified	0	38	7.3	20	1	8649	12.41
Rubber Modified	0	38	7.3	20	0.1	6306	15.13
Rubber Modified	0	38	7.3	45	10	3851	20.53
Rubber Modified	0	38	7.3	45	1	2319	23.68
Rubber Modified	0	38	7.3	45	0.1	1337	26.32
Rubber Modified	0	38	7.3	45	0.01	769.2	27.45
Rubber Modified	0	39	7.2	4	10	17930	6.32
Rubber Modified	0	39	7.2	4	1	15293	7.35
Rubber Modified	0	39	7.2	4	0.1	12680	8.92
Rubber Modified	0	39	7.2	20	10	11562	10.34
Rubber Modified	0	39	7.2	20	1	8902	12.49
Rubber Modified	0	39	7.2	20	0.1	6545	15.18

Mix ID	Confining Pressure, psi	Sample ID	Voids, %	Temp, C	Freq, Hz	E*, MPa	δ, degrees
Rubber Modified	0	39	7.2	45	10	4126	20.28
Rubber Modified	0	39	7.2	45	1	2542	23.34
Rubber Modified	0	39	7.2	45	0.1	1500	25.84
Rubber Modified	0	39	7.2	45	0.01	873.8	26.78
Rubber Modified	0	47	7.3	4	10	17805	7.78
Rubber Modified	0	47	7.3	4	1	14464	9.61
Rubber Modified	0	47	7.3	4	0.1	11221	12.1
Rubber Modified	0	47	7.3	20	10	9892	13.89
Rubber Modified	0	47	7.3	20	1	6904	17.22
Rubber Modified	0	47	7.3	20	0.1	4517	20.73
Rubber Modified	0	47	7.3	45	10	2817	24.46
Rubber Modified	0	47	7.3	45	1	1556	25.76
Rubber Modified	0	47	7.3	45	0.1	841.4	25.23
Rubber Modified	0	47	7.3	45	0.01	485.5	22.7
Polymer Modified	20	44	7.2	4	10	13720	9.91
Polymer Modified	20	44	7.2	4	1	10671	12.16
Polymer Modified	20	44	7.2	4	0.1	7867	15.21
Polymer Modified	20	44	7.2	20	10	7770	16.18
Polymer Modified	20	44	7.2	20	1	5108	19.89
Polymer Modified	20	44	7.2	20	0.1	3170	23.38

Mix ID	Confining Pressure, psi	Sample ID	Voids, %	Temp, C	Freq, Hz	E*, MPa	δ, degrees
Polymer Modified	20	44	7.2	40	10	3227	24.09
Polymer Modified	20	44	7.2	40	1	1903	25.13
Polymer Modified	20	44	7.2	40	0.1	1214	24.05
Polymer Modified	20	44	7.2	40	0.01	883.5	21.8
Polymer Modified	20	44	7.2	45	10	2482	24.49
Polymer Modified	20	44	7.2	45	1	1527	23.17
Polymer Modified	20	44	7.2	45	0.1	1062	20.28
Polymer Modified	20	44	7.2	45	0.01	832.3	17.51
Polymer Modified	20	45	7.4	4	10	14272	8.53
Polymer Modified	20	45	7.4	4	1	11352	10.31
Polymer Modified	20	45	7.4	4	0.1	8337	13.71
Polymer Modified	20	45	7.4	20	10	7340	16.75
Polymer Modified	20	45	7.4	20	1	4801	20.66
Polymer Modified	20	45	7.4	20	0.1	2982	24.17
Polymer Modified	20	45	7.4	40	10	2806	25.5
Polymer Modified	20	45	7.4	40	1	1674	25.67
Polymer Modified	20	45	7.4	40	0.1	1085	24.34
Polymer Modified	20	45	7.4	40	0.01	826.3	22.3
Polymer Modified	20	45	7.4	45	10	2180	24.62
Polymer Modified	20	45	7.4	45	1	1371	22.46

Mix ID	Confining Pressure, psi	Sample ID	Voids, %	Temp, C	Freq, Hz	E*, MPa	δ, degrees
Polymer Modified	20	45	7.4	45	0.1	985.2	19.27
Polymer Modified	20	45	7.4	45	0.01	801.4	16.5
Polymer Modified	20	48	7	4	10	13485	10.31
Polymer Modified	20	48	7	4	1	10192	13.18
Polymer Modified	20	48	7	4	0.1	7160	17.16
Polymer Modified	20	48	7	20	10	6766	19.08
Polymer Modified	20	48	7	20	1	4159	23.53
Polymer Modified	20	48	7	20	0.1	2432	26.83
Polymer Modified	20	48	7	40	10	2454	26.41
Polymer Modified	20	48	7	40	1	1445	24.64
Polymer Modified	20	48	7	40	0.1	992.6	21.12
Polymer Modified	20	48	7	40	0.01	795	18.11
Polymer Modified	20	48	7	45	10	1918	25.32
Polymer Modified	20	48	7	45	1	1220	21.29
Polymer Modified	20	48	7	45	0.1	921.4	16.53
Polymer Modified	20	48	7	45	0.01	795	12.64
Polymer Modified	0	44	7.2	4	10	15083	9.42
Polymer Modified	0	44	7.2	4	1	11815	11.65
Polymer Modified	0	44	7.2	4	0.1	8710	14.59
Polymer Modified	0	44	7.2	20	10	7509	16.78

Mix ID	Confining Pressure, psi	Sample ID	Voids, %	Temp, C	Freq, Hz	E*, MPa	δ, degrees
Polymer Modified	0	44	7.2	20	1	4827	20.93
Polymer Modified	0	44	7.2	20	0.1	2863	24.92
Polymer Modified	0	44	7.2	45	10	2170	28.3
Polymer Modified	0	44	7.2	45	1	1043	29.81
Polymer Modified	0	44	7.2	45	0.1	487.3	28.64
Polymer Modified	0	44	7.2	45	0.01	245.5	23.69
Polymer Modified	0	45	7.4	4	10	15209	8.74
Polymer Modified	0	45	7.4	4	1	12014	10.96
Polymer Modified	0	45	7.4	4	0.1	8914	13.96
Polymer Modified	0	45	7.4	20	10	7469	17
Polymer Modified	0	45	7.4	20	1	4773	21.32
Polymer Modified	0	45	7.4	20	0.1	2791	25.4
Polymer Modified	0	45	7.4	45	10	1768	29.53
Polymer Modified	0	45	7.4	45	1	813.8	30.31
Polymer Modified	0	45	7.4	45	0.1	386.1	28.34
Polymer Modified	0	45	7.4	45	0.01	207.4	23
Polymer Modified	0	48	7	4	10	14955	9.83
Polymer Modified	0	48	7	4	1	11428	12.67
Polymer Modified	0	48	7	4	0.1	8103	16.52
Polymer Modified	0	48	7	20	10	7275	19.26

Mix ID	Confining Pressure, psi	Sample ID	Voids, %	Temp, C	Freq, Hz	E*, MPa	δ, degrees
Polymer Modified	0	48	7	20	1	4392	24.23
Polymer Modified	0	48	7	20	0.1	2381	28.41
Polymer Modified	0	48	7	45	10	1269	32.36
Polymer Modified	0	48	7	45	1	503	32.31
Polymer Modified	0	48	7	45	0.1	248.4	27.18
Polymer Modified	0	48	7	45	0.01	159.4	20.24

APPENDIX D
ASPHALT PAVEMENT ANALYZER TEST RESULTS

TABLE D.1 Asphalt Pavement Analyzer Test Results

Section	Test Temperature (°C)	Pressure (psi)	Loading Force (lbs)	Sample ID	Sample Air Voids (%)	Manual Rut Depth (mm) (25-Final)
Rubber Modified	67	100	100	11	6.9%	4.64
Rubber Modified	67	100	100	21	6.6%	0.89
Rubber Modified	67	100	100	12	6.6%	2.95
Rubber Modified	67	100	100	20	6.7%	1.66
Rubber Modified	67	100	100	15	6.6%	2.87
Rubber Modified	67	100	100	19	6.8%	1.35
Polymer Modified	67	100	100	22	6.8%	2.01
Polymer Modified	67	100	100	25	7.0%	2.49
Polymer Modified	67	100	100	17	6.8%	2.47
Polymer Modified	67	100	100	23	6.8%	2.48
Polymer Modified	67	100	100	24	6.7%	3.06
Polymer Modified	67	100	100	18	7.1%	2.63

APPENDIX E
FLOW NUMBER TEST RESULTS

TABLE E.1 Flow Number Test Results

Mixture	Sample	Testing Temperature, °C	Confining Stress, psi	Deviator Stress, psi	Flow Number, cycles
Rubber Modified	86	60.5	0	87	759
Rubber Modified	87	60.5	0	87	504
Rubber Modified	88	60.5	0	87	716
Polymer Modified	85	60.5	0	87	994
Polymer Modified	90	60.5	0	87	279
Polymer Modified	91	60.5	0	87	375

APPENDIX F
HAMBURG WHEEL TRACKING DEVICE TEST RESULTS

TABLE F.1 HWTD Test Results

Mixture	Sample	Air Voids, %	Rutting Rate, mm/hr	Total Rutting at 10,000 cycles, mm	Stripping Inflection Point, cycles
Rubber Modified	75A	7.1	0.5	1.8	10,000
	77A	7.0			
	76A	7.1	0.2	0.7	10,000
	77B	7.6			
Polymer Modified	73A	7.8	0.1	0.3	10,000
	74A	8.0			
	58A	7.3	0.6	2.5	10,000
	58B	7.4			