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DESIGN, CONSTRUCTION, AND PERFORMANCE OF SULFUR-MODIFIED MIX IN THE WMA CERTIFICATION PROGRAM AT THE NCAT PAVEMENT TEST TRACK

Final Report

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DISCLAIMER

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EXECUTIVE SUMMARY

Based on the results of a nationwide survey, the National Center for Asphalt Technology (NCAT) established a national WMA Certification Program at the Pavement Test Track consisting of both field and laboratory performance evaluations to assist states with their WMA approval process. In this program, a WMA mix design and hot-mix asphalt (HMA) control, both blended with aggregates that have exhibited a high potential for stripping, are produced and paved as a surface lift in perpetual test cells on the NCAT Pavement Test Track to facilitate direct performance comparisons. A battery of laboratory tests is run on actual plant-produced material to evaluate mixes for moisture susceptibility, rutting potential, cracking resistance, stiffness, and bond strength in accordance with the responses to the national survey. Comprehensive surface performance on the Pavement Test Track is also compared, and NCAT certifies a WMA technology if its overall results are comparable to the control HMA.

This paper presents the results of the first WMA evaluation in the NCAT national WMA Certification Program. In this initial study, a sulfur-modified WMA (Shell Thiopave[1]) was produced along with a control HMA and paved as two adjacent test sections at the NCAT Pavement Test Track in May of 2010. No significant problems were encountered producing either mix. High densities were measured in both experimental pavements. In the laboratory, loaded wheel testing and flow number testing indicated that both mixes would provide acceptable rutting performance. Dynamic modulus testing on the plant-produced mixes showed the WMA would be stiffer than the HMA at warmer temperatures and slower loading frequencies (presumably as a result of the addition of sulfur). TSR, Hamburg Wheel-Track, and Boiling Water Testing on the plant-produced HMA and WMA indicated both mixes should be resistant to moisture damage. A critical temperature analysis on IDT test data showed the WMA was slightly more susceptible to low temperature cracking than the HMA; however, the difference in results was not enough to alter the required low PG grade.

Both mixes exhibited less than 6 mm (1/4 inch) of rutting after 1 year and 5 million equivalent single axle loadings (ESALs). Laboratory bond strength testing on field cores from the WMA and HMA test sections showed both mixes should have sufficient bond strength to their respective binder layers in the field. Roughness increased more in the HMA control section than it did in the WMA certification section. Change in surface macrotexture as a function of traffic was virtually identical for both mixes. This is an indication there is no difference in durability, which is supported by observations in cores. The HMA control section exhibited minor longitudinal cracking after approximately 2.9 million ESALs. Contrary to laboratory results from the overlay tester, which indicated the WMA mix would crack before the HMA mix, no cracking was observed in the WMA certification mix. Disagreement between lab and field results may be the result of the overlay tester's relatively high strain levels.

Based on a comprehensive assessment of construction, laboratory performance, and field performance, the use of Shell Thiopave as an alternative WMA technology in the manner it was used at the NCAT Pavement Test Track is recommended.

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[1] Shell Thiopave is a trade mark of the Shell Group of Companies

1. INTRODUCTION

The transition from traditional hot-mix asphalt (HMA) to warm-mix asphalt (WMA) in the United States market is expected to accelerate in coming years. More tonnage will increase the demand for WMA technology, which will in turn lead to an increase in the supply of technological options for WMA production. A rational and reliable process for evaluating emerging WMA technologies is needed to facilitate the rapid approval of those methods that offer performance comparable to traditional HMA and help prevent inferior technologies from incorrectly being placed on state-qualified products lists. Based on the results of a national survey, the National Center for Asphalt Technology (NCAT) has established a national WMA Certification Program at the Pavement Test Track consisting of both field and laboratory evaluation to assist states with their WMA approval process.

1.1 Program Development

In 2009, NCAT surveyed state agencies about the type of evaluation and documentation that should be included in such a national certification program. There were 31 responses to the survey. Ten of the respondents stated that performance data collected from the NCAT test track would be used for approving a WMA technology in their state. Twenty-one respondents stated that their state might accept the results, with many noting that acceptance would be dependent upon the scope and quality of the program. FIGURE 1 summarizes the responses to the question regarding acceptance of NCAT test track results to approve WMA technologies. FIGURE 2 summarizes the rankings of the mix properties that should be considered. FIGURE 3 summarizes the interest in collecting density, cracking, rutting, and smoothness measurements. FIGURE 4 summarizes the laboratory testing responses.

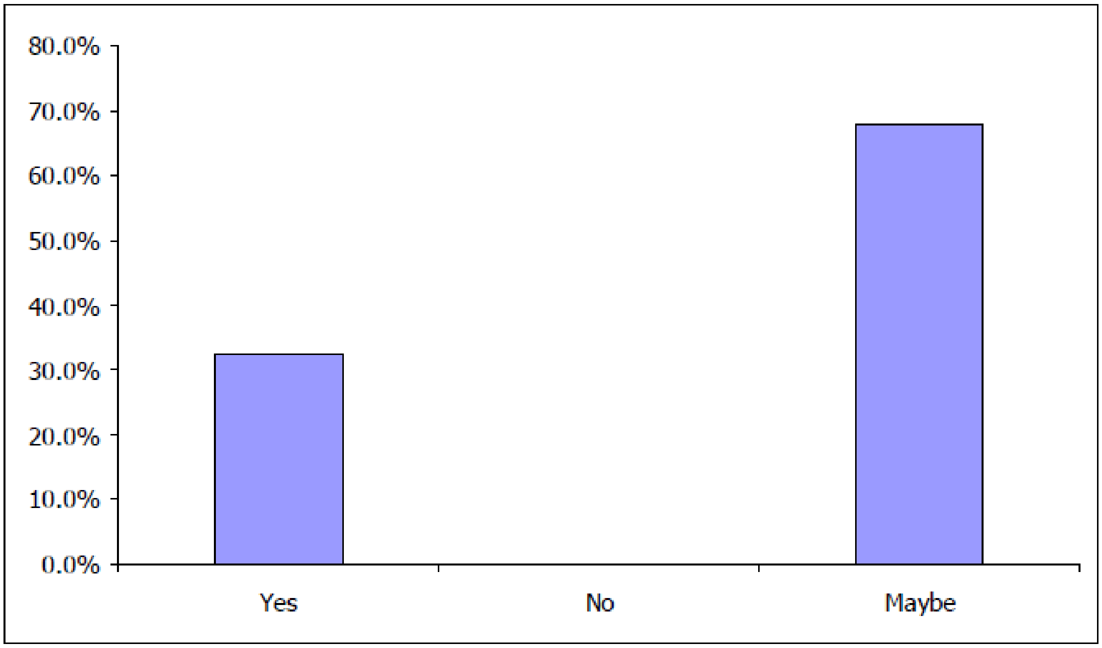

FIGURE 1 State Responses to Accepting Results from WMA Certification at the NCAT Pavement Test Track

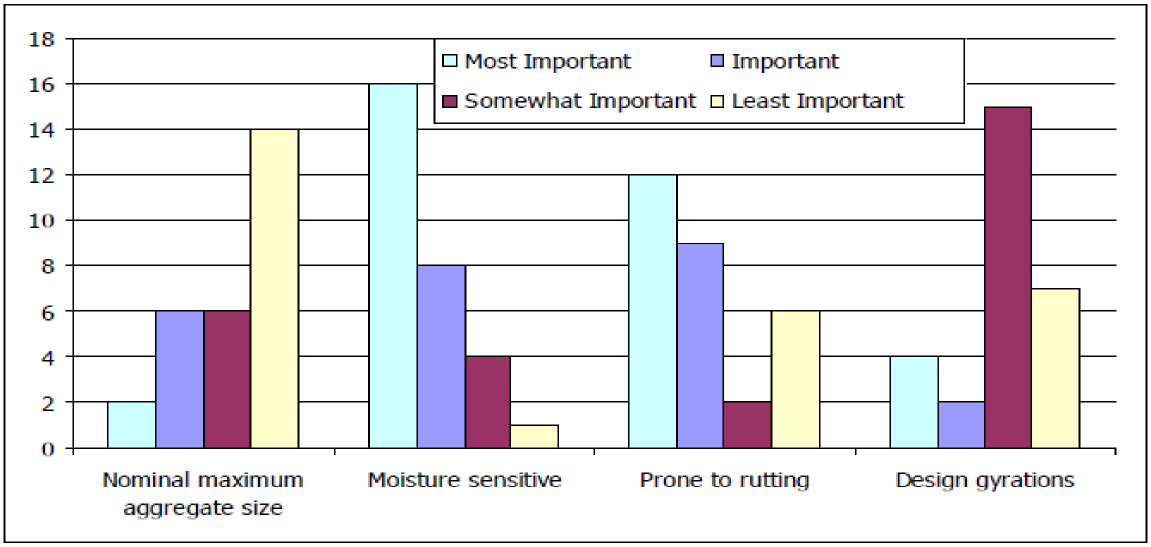

FIGURE 2 State Responses to Mix Property Concerns for WMA

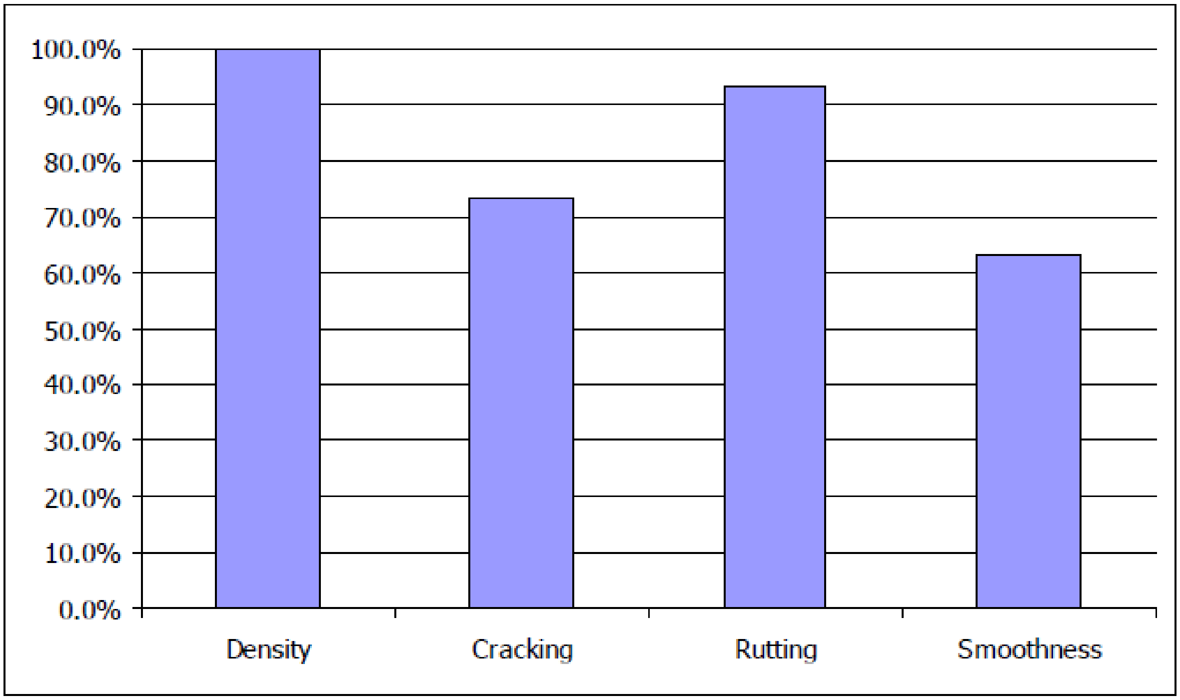

FIGURE 3 State Responses to Field Performance Concerns for WMA

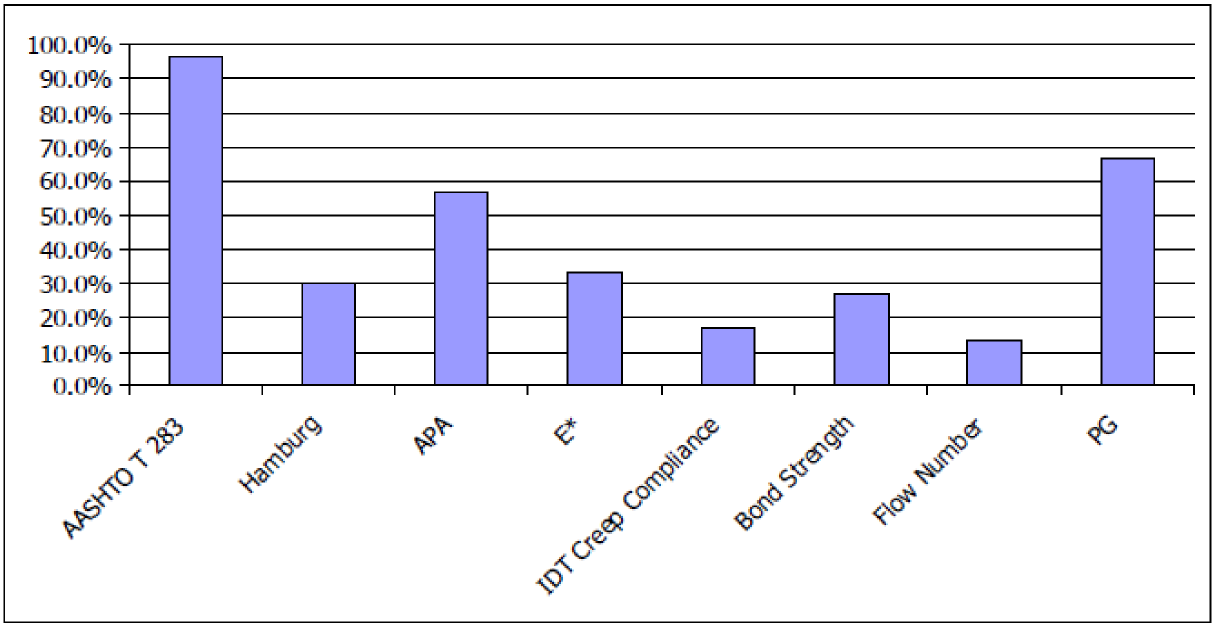

FIGURE 4 State Responses to Laboratory Performance Concerns for WMA

Based on these results, NCAT proposed that a certification program be established that would consist of a laboratory evaluation and accelerated field testing of WMA technologies at the NCAT Pavement Test Track. To date, 11 states have agreed to use the findings from the NCAT national WMA Certification Program to approve technologies. A sample commitment letter, specification package, and list of states endorsing the WMA certification program is included as APPENDIX A.

The WMA certification program begins with a Superpave mix design using the respective WMA technology followed by a one-year evaluation of field performance at NCAT's accelerated pavement-testing facility. The field-produced WMA is also sampled and tested with a range of laboratory performance tests as part of the evaluation. One year of traffic on the NCAT Pavement Test Track is the equivalent of one-half of a design lifetime of load-associated pavement damage. Pavement performance of each test section is evaluated weekly in order to document the relationship between changing pavement condition, traffic, and time. The pavement distresses that are included in the WMA Certification Program include rutting, cracking, roughness, and raveling.

The information collected from the NCAT Pavement Test Track is supplemented by laboratory testing of the plant-produced mix placed on the test section. The laboratory evaluation will assess the binder, aggregate, and mix properties. Mix testing includes moisture susceptibility, rutting potential, cracking resistance, stiffness, and bond strength. Field and laboratory data for the control and certification mixes are compared to determine if the WMA technology being evaluated results in pavement performance at least as good as the HMA control. If the comparison is favorable, NCAT certifies the WMA technology. If the WMA technology does not perform as well as the HMA control, NCAT recommends that the product undergo modifications to improve performance.

1.2 Objective

The purpose of this study was to determine if a test section paved with sulfur-modified warm mix performed equivalently to a test section paved with a control HMA at the NCAT Pavement Test Track.

1.3 Scope

Multiple data sets were used for this study to determine if the WMA test section performed equivalently to the HMA control test section. First, field performance data from both test sections were collected and compared. Secondly, the plant-produced mix used to pave both test sections was collected and evaluated using a variety of laboratory performance tests for engineering properties and resistance to common field distresses. The laboratory data for the WMA and HMA were compared for each of these tests, and conclusions about their relative performances were drawn based on visual comparison, practical performance limits, and statistical analyses.

2. EXPERIMENTAL SETUP

2.1 Mix Design

The mix design chosen for the certification program is a 9.5 mm (3/8 inch) nominal maximum aggregate size (NMAS), 65-gyration, dense Superpave blend containing only virgin materials. The mix was designed using a PG 67-22 binder, in accordance with AASHTO T323-07 and AASHTO R35-09. A crushed granite quarried in Lithia Springs, Georgia, was used as the virgin aggregate because mixtures using this aggregate source reportedly have been susceptible to moisture damage, which is a major concern for state DOTs according to the survey results shown in FIGURE 2. No hydrated lime or other mineral fillers or fibers were used. The gradation of the blend used for this design is presented in FIGURE 5. The aggregate consensus properties were measured and recorded in TABLE 1. The weighted average of these properties indicates this gradation is acceptable for a surface course designed for 10-30 million Equivalent Single Axle Loadings (ESALs), according to AASHTO T323-07.

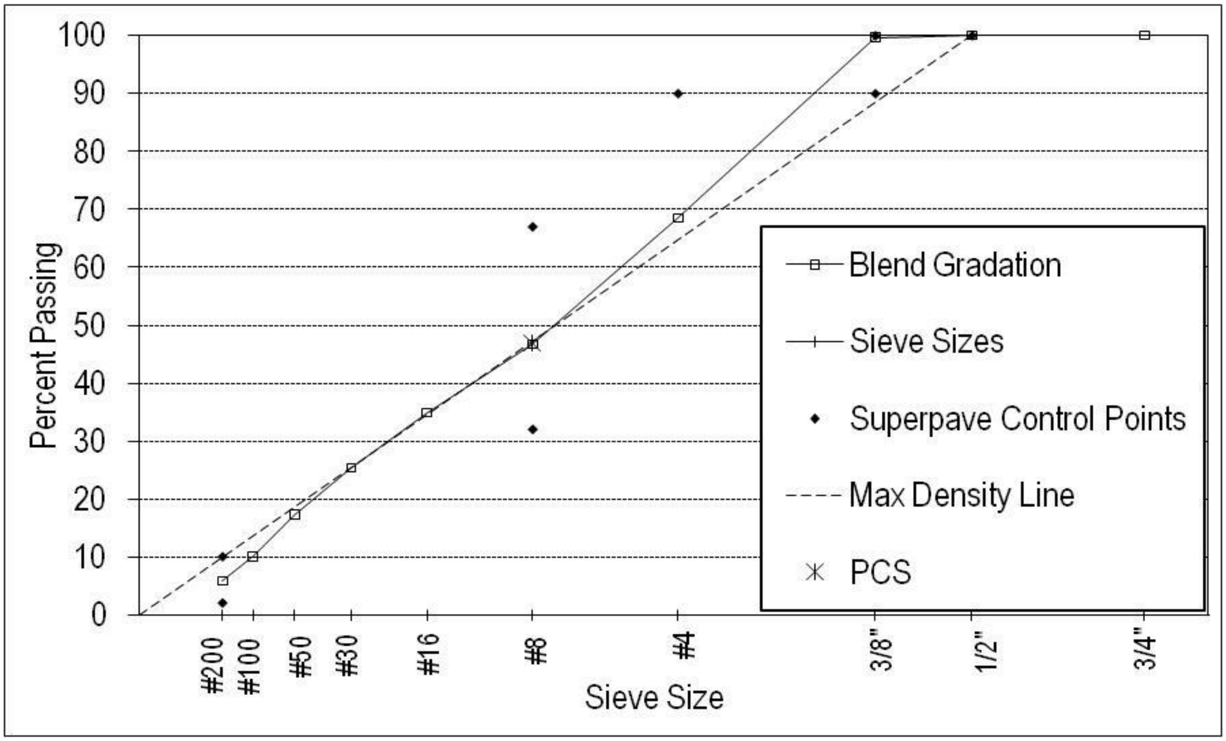

FIGURE 5 Design Aggregate Blend

TABLE 1 Mix Design Consensus Properties

Stockpile	Fractured Face Count (% 1 Crushed Face / % 2+ Crushed Faces)	5:1 Flat and Elongated Particles (%)	FAA (%)	Sand Equivalency
Lithia Springs 89s	100/100	0	n/a	n/a
Lithia Springs 810s	n/a	n/a	47.6	82.3
Lithia Springs W10s	n/a	n/a	45.9	92
Weighted Average	100/100	0	46.9	85.8
AASHTO M323*	95/90	<10	>45	>45

* = 10-30 Million ESAL Design, Less than 100 mm from the surface

2.2 WMA Certification Technology

Early attempts at utilizing sulfur as a binder replacement option in the 1970s consisted of adding molten liquid sulfur directly to the asphalt binder, which resulted in unacceptable levels of hydrogen sulfide (H_2S) to be emitted during production and construction (Strickland, et al. 2008). To address the environmental concerns associated with H_2S emissions, Shell Sulphur

Solutions has developed a pelletized sulfur formulation called Shell Thiopave[2] (FIGURE 6). The Thiopave system features sulfur pellets combined with a WMA additive that allows for production at temperatures around 135°C (275°F). At this temperature, H_2S emissions are reduced to an acceptably low level. Two structural Thiopave sections built for the 2009 NCAT Pavement Test Track have exhibited excellent performance, both in the laboratory and on the Track (Timm, Robbins, et al. 2011). As a result of this positive experience with construction and performance, Shell Sulphur Solutions elected to participate in NCAT's national WMA Certification Program.

FIGURE 6 Thiopave Pellets and Compaction Aid (Timm, Tran, et al. 2009)

2.3 Test Section Construction

WMA certification cycles are intended to occur annually at the NCAT Pavement Test Track. One control HMA section is constructed for each cycle when the WMA section(s) is constructed. The goal of the field evaluation is to document constructability and performance of a WMA technology in comparison to a control HMA section. Plant emissions and fuel usage data are not collected since the production tonnage is too low to adequately evaluate these factors. The HMA control and WMA certification mixes for the current certification cycle are 38 mm milled inlays, placed in the curves of the NCAT Pavement Test Track in sections E8 (HMA) and E9 (WMA) as shown in FIGURE 7. The condition and structure of the underlying perpetual pavement was documented prior to placement of the inlays. As-built information on mix designs and mat placements for the HMA and WMA test sections are given in APPENDIX A. Similar construction quality was noted for both mixes. No coating, tenderness, or compaction issues were encountered.

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[2] Shell Thiopave is a trade mark of the Shell Group of Companies

FIGURE 7 Location of Study Sections on the NCAT Pavement Test Track

3. LABORATORY PERFORMANCE TESTING AND ANALYSIS

All the laboratory samples for this project were prepared from plant-produced mix sampled during construction of the test sections. The WMA was re-heated to 121°C (250°F), and the HMA was re-heated to 143°C (290°F) for compaction of test specimens in the laboratory. Additionally, the sulfur-modified performance testing specimens were allowed to rest at room temperature for a minimum of 14 days prior to conducting any laboratory performance testing on those specimens. Although the sulfur-modified WMA is typically as stable as HMA initially after construction, this additional curing time was to allow for the time-dependent improved strength properties of these mixes to become fully developed as the sulfur in those mixes crystallized. This methodology is consistent with laboratory testing previously performed at NCAT on sulfur-modified WMA (Timm, Robbins, et al. 2011) (Timm, Tran, et al. 2009). A summary of the laboratory testing plan for this project is provided as TABLE 2.

TABLE 2 Laboratory Testing Plan for Plant-Produced Mix

Test	Parameter Tested	Method
TSR	Moisture Susceptibility	AASHTO T 283-07
Hamburg Wheel-Tracking	Moisture Susceptibility and Rutting Using Unaged and Aged, Loose Mix Aged 4 hours at 135°C (275°F)	AASHTO T 324-04
Boiling Water Test	Moisture Susceptibility	TEX-530-C
APA	Rutting –Wheel Tracking	AASHTO TP 63-09
AMPT Flow Number	Rutting – Uni-axial Compression	AASHTO TP79-09
IDT	Thermal Cracking Resistance	AASHTO T 322-07
Bond Strength	Interface Bond Strength	ALDOT 430-08
AMPT Dynamic Modulus	Dynamic Modulus	AASHTO TP 79-09
Overlay Tester	Reflective Cracking Potential	TEX-248-F
Complex Shear Modulus, Phase Angle, Viscosity, Flexural Stiffness	Binder Performance Grade	AASHTO R 29-08

3.1 Asphalt Pavement Analyzer (APA)

The rutting susceptibility of each mix design was evaluated using the Asphalt Pavement Analyzer (APA) in accordance with AASHTO TP63-09 at a test temperature of 64°C (147°F), which is the 98% reliability high pavement temperature for the Opelika, Alabama, area according to LTPPBind v3.1. This was the test temperature selected for testing all mixes placed in the 2009 research cycle at the track. Six replicates were tested for each mix, each prepared to a height of 75 mm (3 inches) and an air void level of 7 ± 0.5 percent, per the specification. The specimens were loaded by a steel wheel supporting a 445 N (100 lbs) load resting on a pneumatic hose pressurized to 689 kPa (100 psi) for 8,000 cycles. Manual depth readings were taken at two locations on each specimen. This reading was taken after 25 conditioning cycles and after the loading was applied to determine the specimen rut depth. Automated rut depth measurements were also recorded by the testing software. Previous studies at the NCAT Test Track indicate that a rut depth of less than 5 mm (0.2 inches) in the APA would yield a rut-resistant mix in the field (Tran, et al. 2009).

The results of the APA testing are shown in FIGURE 8. The APA rut depths for the individual specimens are given in APPENDIX C. The results show that the WMA rutted about 1 mm (0.04 inches) less than the HMA; however, both mixes should have good resistance to rutting in the field based on the 5 mm (0.2 inch) APA criteria. There was a statistical difference between the two mixes using either the manual or automated measurement criteria (ANOVA $\alpha = 0.05$, p-value = 0.002). Less rutting was expected in the WMA certification mix given previous experience with sulfur-replacement mixes (Timm, Tran, et al. 2009).

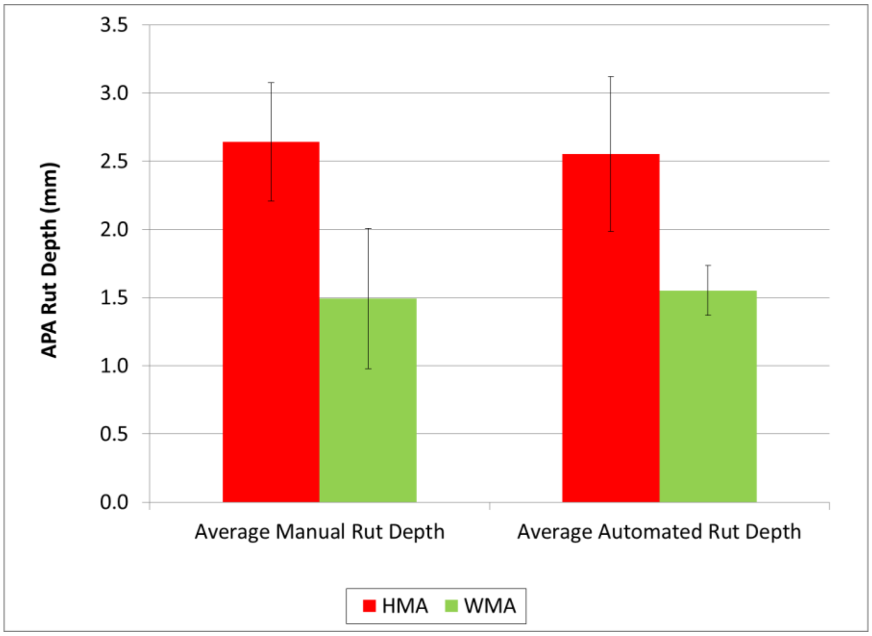


FIGURE 8 APA Test Results

3.2 Tensile Strength Ratio Testing

Tensile strength ratio (TSR) moisture susceptibility testing was performed for this project in accordance with AASHTO T283-07. The AASHTO T283-07 methodology uses 95 mm specimens compacted in a Superpave Gyratory Compactor to a target air void level of 7.0 ± 0.5%. A set of three specimens is then vacuum-saturated so that 70-80% of the internal voids are saturated with water. The specimens are then placed in a freezer for a minimum of 16 hours prior to being placed in a warm water bath (60^{o}C) for 24 hours. This process constitutes one ‘freeze-thaw’ cycle. These specimens, along with a control group of three specimens that had not been conditioned, are then tested for indirect tensile strength using a Marshall Press apparatus, which applies a load to the sample at a rate of 2 inches/minute. All specimens are placed in a 25^{o}C water bath for two hours to equilibrate their temperature prior to testing. The ratio of the indirect tensile strengths of the conditioned and unconditioned specimens is recorded as the tensile-strength ratio. This value is expected to be above 0.8 for moisture-resistant mixes (AASHTO R35-09), indicating less than a 20% reduction in splitting tensile strength given the above conditioning process, which is intended to be representative of moisture-induced damage.

The results of the TSR testing are summarized graphically in FIGURE 9 and in tabular form in TABLE 3. These data show that both the WMA and HMA had acceptable resistance to moisture damage, with TSR values above 0.8 for each mixture (0.95 for HMA and 0.92 for WMA). For both the WMA and HMA, there was no evidence of a statistical difference between the conditioned and unconditioned splitting tensile strengths (two sample *t*-test *p*-value less than $\alpha = 0.05$ for both). The data also shows a reduction (approximately 25%) in the splitting tensile strengths of the WMA versus the HMA, likely a consequence of reduced binder aging at the lower mixing and compaction temperatures. This reduction was statistically significant for both the conditioned and unconditioned splitting tensile strengths (two sample *t*-test $p = 0.00$ less than $\alpha = 0.05$ for both cases). While the splitting tensile strength of the WMA is reduced in relation to the HMA, the WMA splitting tensile strength is still above 100 psi, which is a commonly accepted benchmark for sufficient splitting tensile strength. The tensile strength data from the individual specimens are listed in APPENDIX C.

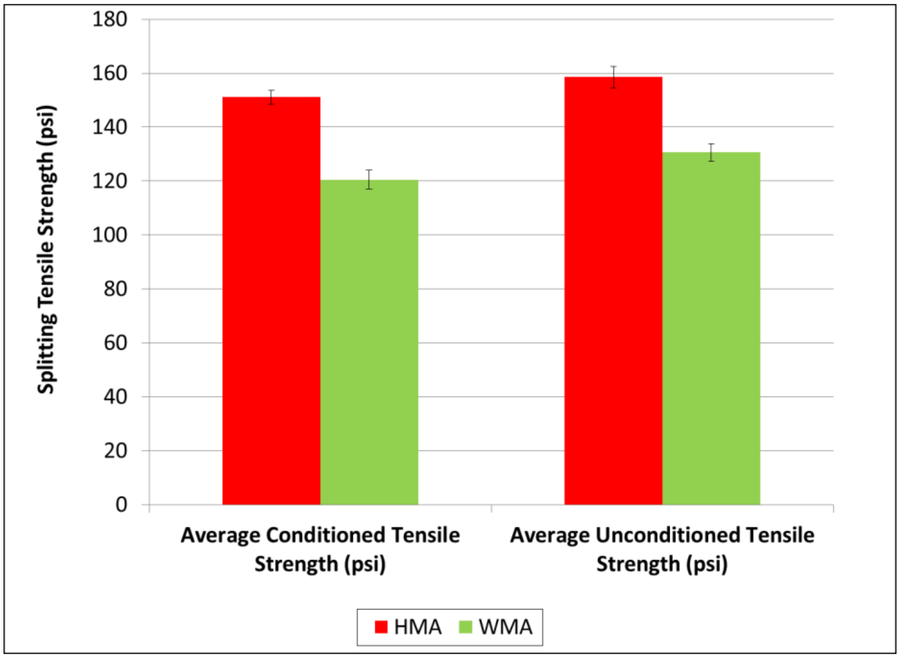


FIGURE 9 TSR Results

TABLE 3 Average Tensile Strengths and TSR

Mix ID	Average Conditioned Tensile Strength (psi)	Average Unconditioned Tensile Strength (psi)	TSR
HMA	151.1	158.5	0.95
WMA	120.5	130.6	0.92

3.3 Hamburg Wheel-Tracking Results

Hamburg wheel-track testing was performed to determine both the rutting and stripping susceptibility of the mixtures tested for this project. Testing was performed in accordance with AASHTO T 324-04. Three replicates were tested per mix. The specimens were originally compacted using an SGC to a diameter of 150 mm (6 inches) and a height of 95 mm (3.8 inches). These specimens were then trimmed so that two specimens, with a height between 38 mm (1.5 inches) and 50 mm (2 inches), were cut from the top and bottom of each gyratory-compacted specimen. The target air voids on these cut specimens were 7 ± 0.5 percent. Additionally, a set of WMA and HMA underwent short-term mechanical aging (4 hours at 135°C (275°F)) to determine the effect of the additional aging on these results. The data was analyzed to determine the average stripping inflection point (related to the moisture resistance of this mixture) and the average rut depth at 10,000 cycles or 20,000 passes (related to the deformation resistance of the mixture). Details on the data analysis can be found in the specification and have been documented elsewhere (Timm, Tran, et al. 2009). A stripping inflection point of greater than 5,000 cycles has been used to indicate a moisture resistant mix in the past, while an average rutting value of less than 10 mm (0.4 inches) has been used to indicate a deformation-resistant mix (Kvasnak, et al. 2010).

The average and standard deviation of the rutting and stripping measurements from the Hamburg test can be seen in tabular form in TABLE 4. The rutting results are shown graphically in FIGURE 10, and the stripping results are shown graphically in FIGURE 11. The individual specimen analysis results can be found in APPENDIX C. As seen in FIGURE 10 and FIGURE 11, the results of the Hamburg testing showed that both the WMA and HMA had acceptable moisture and deformation resistance by the previously listed criterion. The WMA had a lower average stripping inflection point than the HMA but still had acceptable moisture resistance. For the aged mixes, the WMA and HMA both had a high level of moisture resistance. The WMA and HMA showed similar rutting resistance regardless of the specimen aging. Additional specimen aging appeared to increase the average moisture resistance of the WMA in the Hamburg test.

To validate these results, a general linear model ANOVA ($\alpha = 0.05$) was performed to determine if the differences in the data points were statistically significant. For the total rut depth results, no statistical difference was seen between any of the four sample groupings (*p*-value = 0.091). A similar result was seen for the stripping inflection point results (*p*-value = 0.103). Therefore, the sulfur-modified WMA and HMA performed equivalently in terms of rutting and moisture resistance in the Hamburg test device.

TABLE 4 Tabular Hamburg Results

Mix ID	Average Total Rut Depth (Based on Rate) (mm)	Average Stripping Inflection Point (cycles)	Standard Deviation Rut Depth (mm)	Standard Deviation Stripping Inflection Point
HMA	4.193	8533	1.482	2540.3
WMA	4.455	6367	0.486	568.6
Aged HMA	3.001	9000	0.683	1732.1
Aged WMA	2.425	10000	0.860	0.0

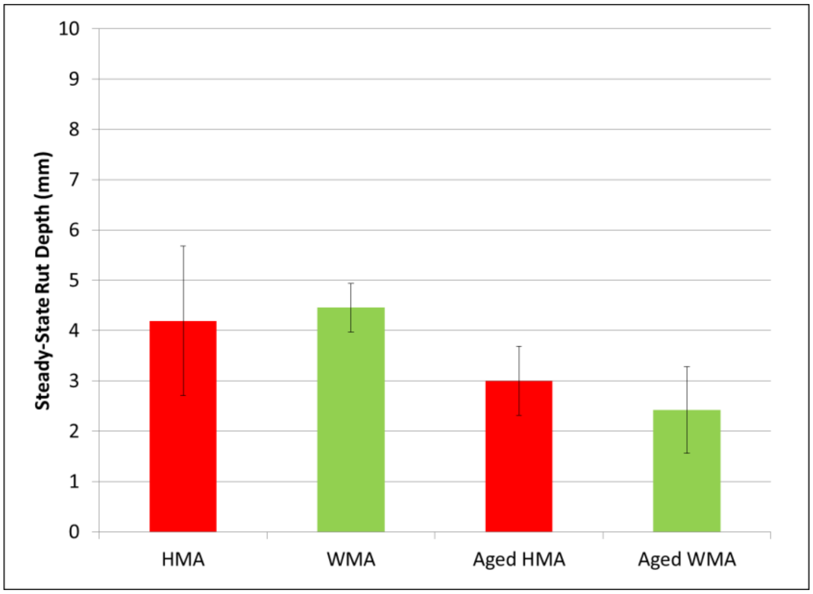


FIGURE 10 Hamburg Wheel-Tracking Rutting Results

FIGURE 11 Hamburg Wheel-Tracking Stripping Results

3.4 Boiling Water Test

The boiling water test was performed in accordance with TEX 530-C. For this test, a 200 gram (7 ounce) sample of asphalt mixture is placed in a stainless steel beaker filled with 2000 mL (1 quart) of distilled water that has been brought to a boil within an oil bath. Once the specimen has been spread evenly across the bottom of the beaker, the beaker is returned to the oil bath for 10 minutes before being removed. The degree of stripping is visually determined. The mass of the samples were also recorded both before and after boiling. The test data is shown in TABLE 5, while photos of the samples are shown in FIGURE 12. No evidence of stripping was seen in either sample, and no appreciable mass loss was determined in either sample from this test. The results of this test are in agreement with the TSR and Hamburg results.

TABLE 5 Boiling Water Test Results

Mix ID	Mass Loss After Testing (%)	Visual Evidence of Stripping
HMA	0.05	None
WMA	0.2	None

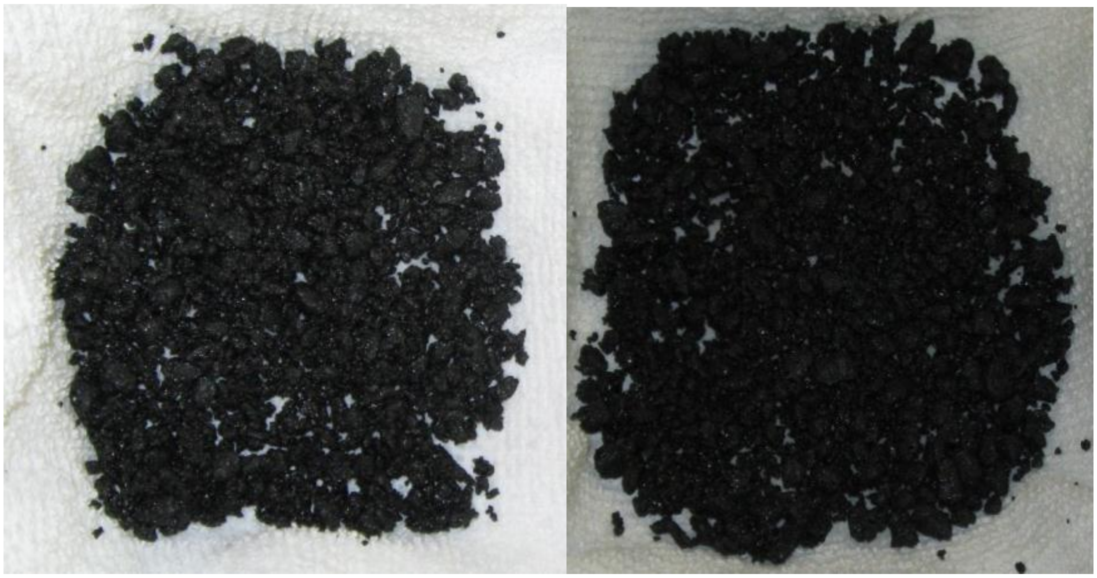


FIGURE 12 Loose Mix Samples Following Boiling Water Test - HMA (left) and WMA (right)

3.5 Binder Testing

Typically, binder performance grading would be performed as part of the WMA certification process. However, the sulfur-modified warm mixes are not appropriate for this type of testing. Sulfur is about twice as dense as asphalt binder; therefore the materials have a tendency to separate during the binder recovery and specimen-preparation process. Hence, prepared samples for the dynamic shear rheometer (DSR) and bending beam rheometer (BBR) tended to be very non-homogeneous. As a result of this effect, binder testing was not used to compare the performance of the sulfur-modified WMA binder to the HMA binder.

3.6 Overlay Tester

Both mixes were tested in the Overlay Tester (OT) in accordance with Tex 248-F. The OT was originally designed to test the susceptibility of an asphalt mixture to reflection cracking when placed over a jointed concrete pavement. Three replicates of each mixture were tested with a target air void content of 7 ± 0.5% . Other research has indicated 700 cycles to failure being a good OT benchmark for a specialized crack-alleviating mixture (CAM) that is intended to be more resistant to reflection cracking (Chen 2008). This test is currently not intended for conventional mixes on perpetual foundations, which was the case in this study.

A comparison of the average and standard deviations of the cycles to failure in the OT is shown in FIGURE 13. The individual sample cycles to failure are given in APPENDIX C. A plot of the raw test data is also shown in FIGURE 14, which shows the load carried by the individual specimens versus the number of loading cycles in the OT. It can be seen that the HMA had significantly longer fatigue life than the WMA in the OT from both figures. A two-sample *t*-test confirmed the presence of a statistical difference ($\alpha = 0.05$, p-value = 0.001). This behavior was not unexpected given the stiffer nature of sulfur-modified materials, where a portion of the visco-elastic bitumen is replaced with a crystalline sulfur binder. Both mixes had less than the threshold 700 cycles to failure; however, it should be noted that in the field, the HMA section has exhibited surface cracking while the WMA section has not. This contrast in behavior indicates the lack of correlation between the laboratory fracture test results and the field cracking performance for this particular test. For future WMA certification projects, adjustments may be made to the relatively high strain in the Tex 248-F procedure so the results are more indicative of field performance.

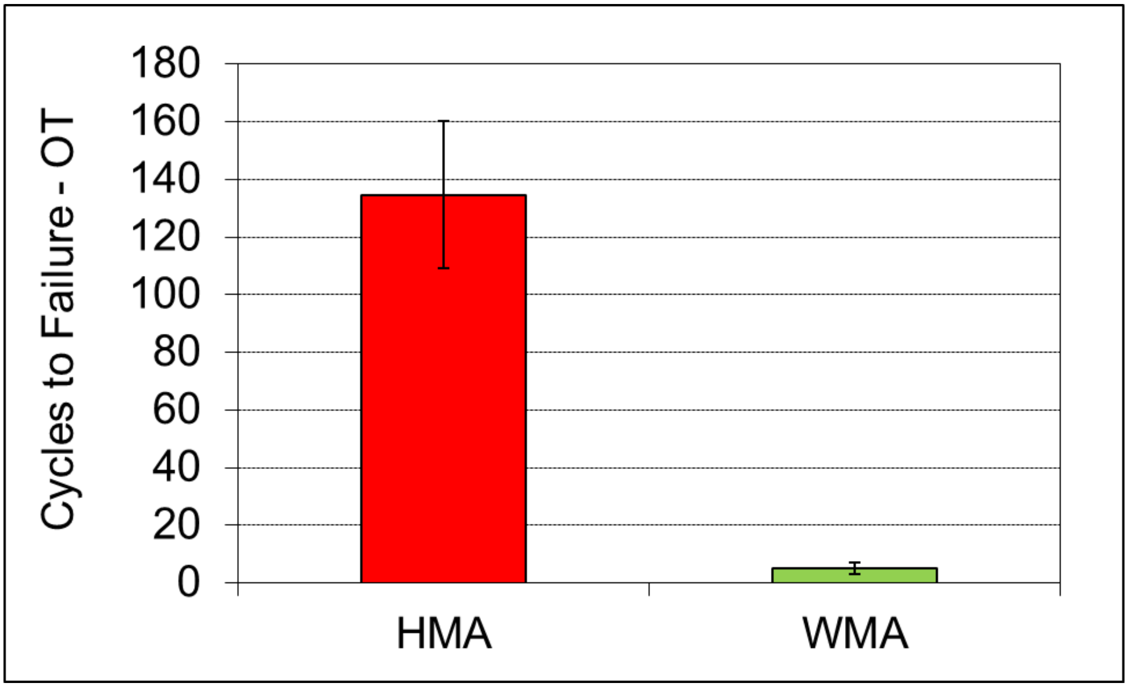


FIGURE 13 Overlay Tester - Cycles to Failure

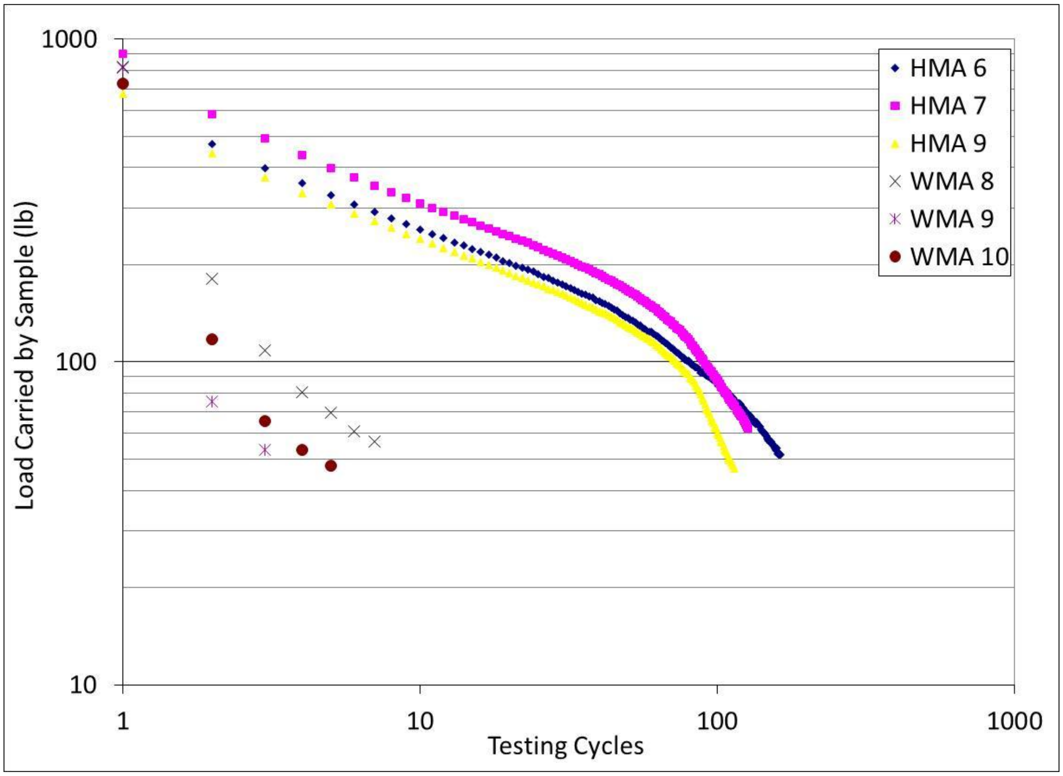


FIGURE 14 Overlay Tester - Load Carried by Specimen versus Number of Cycles

3.7 Dynamic Modulus

Dynamic modulus testing was performed for both mixes using an IPC Global Asphalt Mixture Performance Tester (AMPT). Three replicates of each mix were tested with 138 kPa (20 psi) confining pressure. Samples were prepared to 7 ± 0.5% percent air voids and prepared in accordance with AASHTO PP 60-09. The mixtures were tested in accordance with AASHTO PP79-09 with the temperatures and frequencies recommended by AASHTO PP61-09. Mastercurves were generated in accordance with the procedure outlined in AASHTO PP61-09. A detailed procedure regarding the dynamic modulus testing procedure and data analysis is well documented in these specifications as well as in previous studies conducted at NCAT (Timm, Robbins, et al. 2011).

The mastercurves generated for this study are shown in FIGURE 15. The regression coefficients of these mastercurves as well as the raw data collected to generate them are tabulated in APPENDIX C. The data in this figure shows the change in stiffness of the WMA and HMA across a full range of testing temperatures and loading frequencies. At the lower-temperature, faster frequency end of the curve (right-hand side) the WMA and HMA appear to have similar stiffnesses. As the temperatures increase and frequency of loading is reduced (left-hand side of the curve), the WMA becomes stiffer than the HMA. These results were expected given previous experience with the sulfur-modified material (Timm et al., 2009).

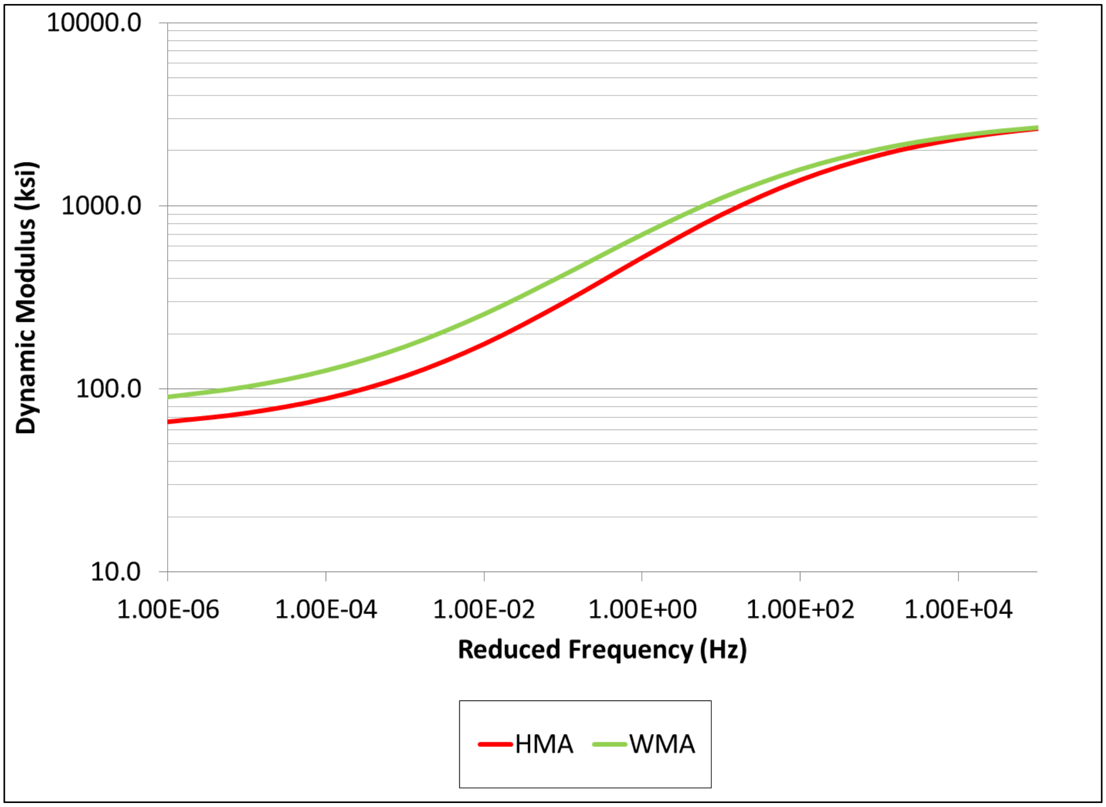


FIGURE 15 Dynamic Modulus MasterCurves

3.8 IDT Testing - Critical Cracking Temperature Analysis

In thermal cracking analysis, the temperature at which the estimated thermal stress in a pavement due to contraction exceeds the tested indirect tensile strength of a mixture is used to assess low-temperature cracking performance of asphalt mixtures. This type of analysis is referred to as a “critical temperature analysis.” A mixture exhibiting a lower critical cracking temperature than those of the other mixtures would have better resistance to thermal cracking. While thermal cracking is not of concern for the pavements at the NCAT test track (climate), this evaluation was conducted to determine if the sulfur-modified WMA had equivalent low-temperature cracking performance to that of a control HMA. Previous research has indicated this to be the case, albeit using a different laboratory test (thermal stress-restrained specimen testing) (Timm, Tran, et al. 2009).

Both the sulfur-modified WMA and HMA mixtures were evaluated using a critical temperature analysis for this study. To estimate the thermal stress and measure the tensile strength at failure, the indirect tensile creep compliance and strength tests were conducted as specified in AASHTO T 322-07. A thermal coefficient of each mixture was estimated based on its volumetric properties and typical values for the thermal coefficient of asphalt and aggregate. This computation is detailed below.

The testing was conducted using an indirect tensile testing (IDT) system with an MTS® load frame and an environmental chamber capable of maintaining the temperatures required for this test. Creep compliances at 0◦C, -10◦C, and -20◦C and a tensile strength at -10◦C were measured in accordance with AASHTO T 322-07. These temperatures are specified as a function of the low-temperature PG grade of the binder in AASHTO T322-07. The creep test applies a constant load to the asphalt specimen for 100 seconds while the horizontal and vertical strains are measured on each face of the specimen using on-specimen instrumentation.

Four specimens were prepared for each mix from hot-compacted plant-produced mix. The first specimen was used to find a suitable creep load for that particular mix at each testing temperature. The remaining three specimens were tested at this load for data analysis. Specimens used for the creep and strength tests were 38 to 50 mm thick and 150 mm in diameter. Specimens were prepared to 7 ± 0.5% air voids. FIGURE 16 shows a photo of the MTS load frame and the load guide device used for IDT testing.

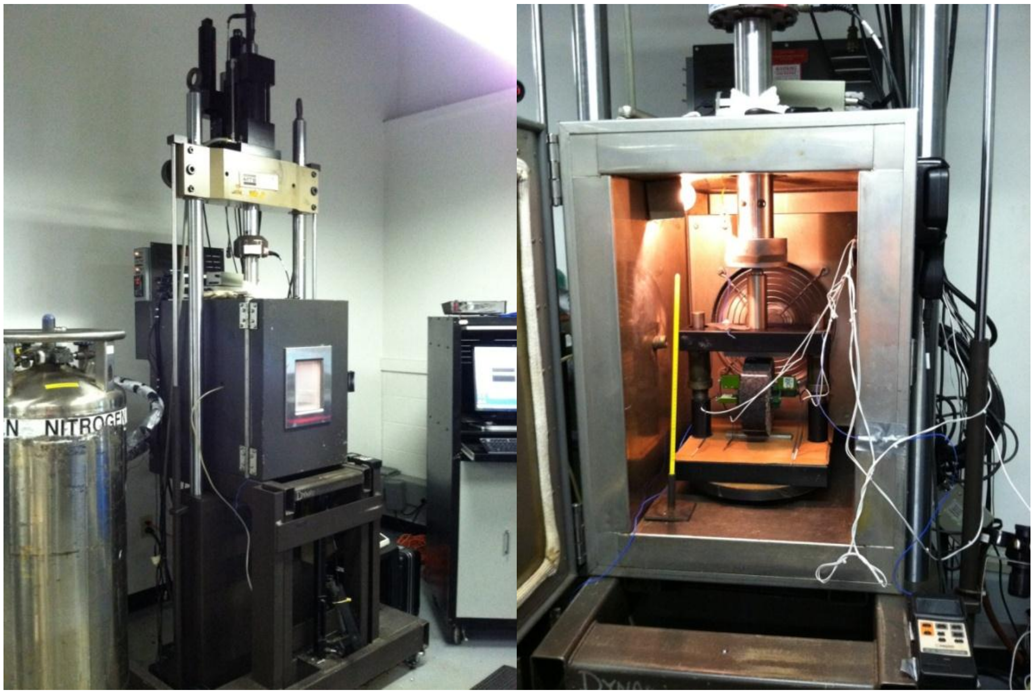


FIGURE 16 MTS® Testing Device used for IDT Testing

For linear visco-elastic materials, the effect of time and temperature can be combined into a single parameter through the use of the time-temperature superposition principle (similar to the dynamic modulus data discussed previously). From a proper set of creep compliance tests under different temperature levels, the creep compliance mastercurve can be generated by shifting the creep compliance data to a curve based on a reference temperature. This reference temperature is typically the lowest creep compliance test temperature (-20°C for this study). The relationship between real time t, reduced time ξ, and a shifting factor a_T are given as Equation 1.

$$\xi=t/a_T \tag{1}$$

An automated procedure to generate the mastercurve was developed as part of the Strategic Highway Research Program (SHRP) (Buttlar, Roque and Reid 1998). The system requires the measurement of creep compliance test data at three different test temperatures. The creep compliance data used for this generation of the creep compliance mastercurve are listed in APPENDIX C. The final products of the system are a generalized Maxwell model (or Prony series), which is several Maxwell elements connected in parallel, and temperature-shifting factors. The generalized Maxwell model and shifting factors are used for predicting thermal stress development of the asphalt mixture due to change in temperature. The Maxwell model elements and shift factors generated through the analysis system for this project are listed in APPENDIX C.

In addition to thermo-mechanical properties, it is required to estimate the coefficient of thermal contraction of the asphalt mixture for the critical temperature analysis. The linear thermal coefficients, α, of the given asphalt mixtures were estimated using the relationship below, which is a modified version of the relationship proposed by Jones et al. (Jones, Darter and Littlefield 1968) (Equation 2). The estimated thermal coefficients were $2.156\text{x}10^{-5}$ ($1/^{o}C$) for the WMA and $2.076\text{x}10^{-5}$ ($1/^{o}C$) for the HMA.

$$\alpha_{MIX} = \frac{VMA * B_{AC} + V_{AGG} * B_{AGG}}{3 * V_{TOTAL}} \tag{2}$$

Where: α_{MIX} = linear coefficient of thermal contraction of the asphalt mixture (1/°C)
B_{AC} = volumetric coefficient of thermal contraction of the asphalt cement in the solid state ($3.45 \text{ x } 10^{-4}/°C$)
B_{AGG} = volumetric coefficient of thermal contraction of the aggregate ($1\text{x}10^{-6}/°C$)
VMA = percent volume of voids in the mineral aggregate
V_{AGG} = percent volume of aggregate in the mixture
V_{TOTAL} = 100 percent

Based on the above parameters, the change in thermal stress for each mixture was estimated at the cooling rate of 10°C per hour starting at 20°C. The finite difference solution below developed by Soules et al. (Soules, et al. 1987) was used to estimate thermal stress development based on the Prony Series coefficients (Equations 3 and 4). This analysis was performed in a MATHCAD program developed at NCAT.

$$\sigma_i(t) = e^{-\Delta\xi/\lambda_i}\sigma_i(t-\Delta t) + \Delta\varepsilon\, E_i \frac{\lambda_i}{\Delta\xi}\left(1 - e^{-\Delta\xi/\lambda_i}\right) \tag{3}$$

$$\sigma(t) = \sum_{i=1}^{N+1}\sigma_i(t) \tag{4}$$

Where:

σ = thermal stress
ΔT and $\Delta\xi$ = changes in temperature and reduced time over the small time Δt

A complete description of the thermal stress analysis can be found in Hiltunen and Roque (Hiltunen and Roque 1994) and Kim et al. (Kim, Roque and Birgisson 2008). FIGURE 17 shows thermal stress development as a function of a reduction in temperature. This data shows the WMA to develop thermal stress at a higher rate than the HMA when pavement temperatures drop below -15^{o}C. Recall that the "critical" temperature is the temperature at which the predicted stresses exceed the measured tensile stress. The results of this analysis showed the WMA had a critical cracking temperature of -26.4°C (-15.5°F) while the HMA had a critical cracking temperature of -28.6°C (-19.5°F). However, the question then becomes whether this is a practically significant difference. The base binder grade of the virgin AC was a PG 67-22. Both the WMA and HMA satisfied the performance criteria of the base binder grade, with the HMA meeting the performance criteria of a lower grade of AC (i.e., a PG XX-28). Therefore, the results of the testing suggest the sulfur-modified WMA would be slightly more susceptible to thermal cracking than the control HMA, with the sulfur modification not negatively impacting the critical cracking temperature to the point where it would alter the required PG grade of the base binder.

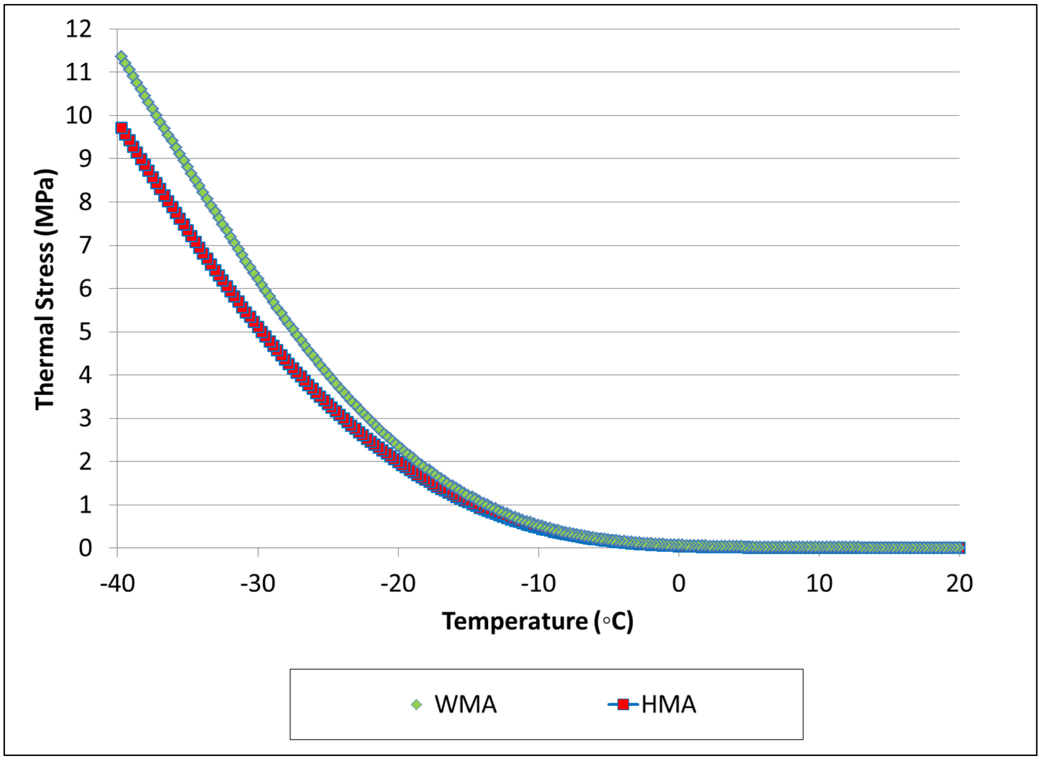


FIGURE 17 Thermal-Stress versus Temperature – IDT Testing

3.9 Flow Number Testing

Flow number testing was performed for both mixes using an IPC Global® AMPT device. Three replicates of each mix were tested. Specimens were prepared in accordance with AASHTO PP 60-09, and tested in accordance with AASHTO PP79-09. Testing temperature for all specimens was 59.5°C [139°F, which is the LTPPBind v3.1 50% reliability high pavement temperature for the Auburn-Opelika, AL area adjusted to a depth of 20 mm (0.8 inches)].

Both the WMA and HMA were tested using two sets of testing parameters. The first set of testing parameters was 689 kPa (100 psi) deviatoric stress and 69 kPa (10 psi) confinement. Specimens for this testing were prepared to 7 ± 0.5 percent air voids. Due to the confinement, these mixes did not exhibit tertiary flow. An example of the typical behavior for a confined flow number test is shown in FIGURE 18. Therefore, mix-to-mix comparisons were made using the level of specimen deformation at 20,000 cycles.

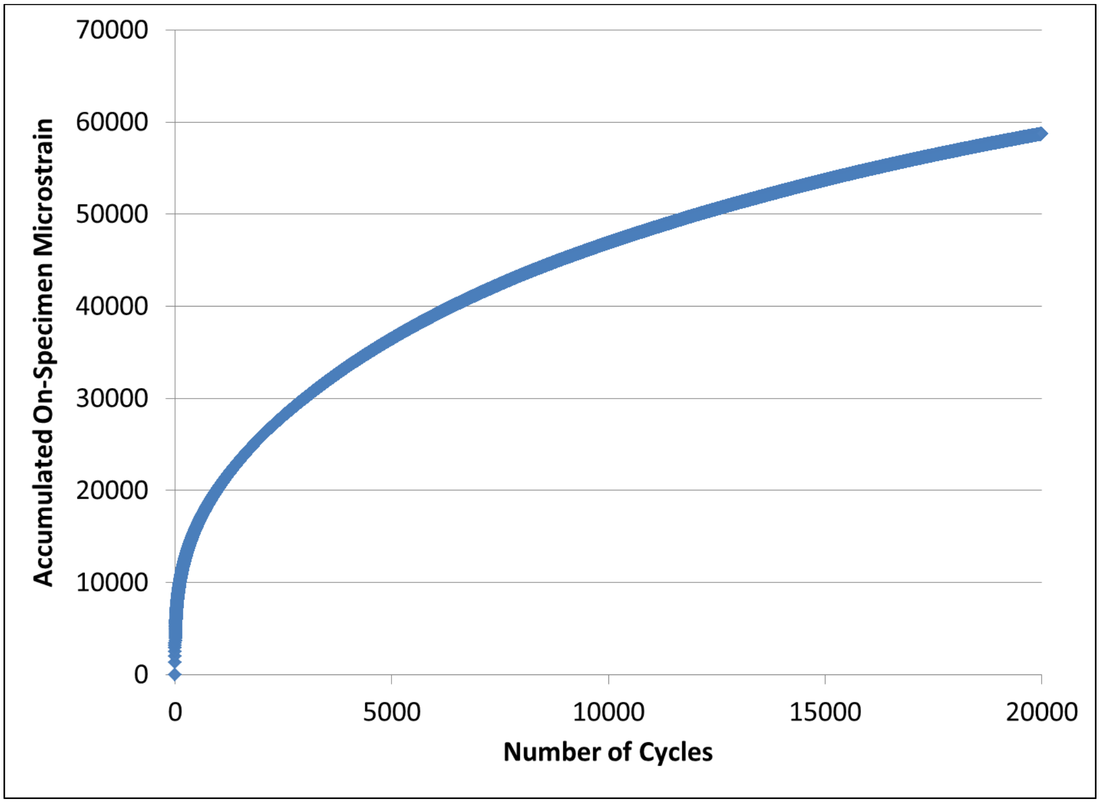


FIGURE 18 Typical Confined Flow Test Behavior

The second set of testing parameters was 600 kPa (87 psi) deviatoric stress and 0 kPa (0 psi) confinement. Specimens for this testing were prepared to 4 ± 0.5% air voids. Tertiary flow for these samples was determined using the Francken Model (Equation 5) (Biligiri, et al. 2007). The typical behavior for an unconfined flow number test is shown in FIGURE 19.

$$\varepsilon_p(N) = aN^b + c(e^{dN} - 1) \qquad (5)$$

Where: ε_p = Permanent Strain
a,b,c,d = Regression Coefficients
N = Number of Testing Cycles

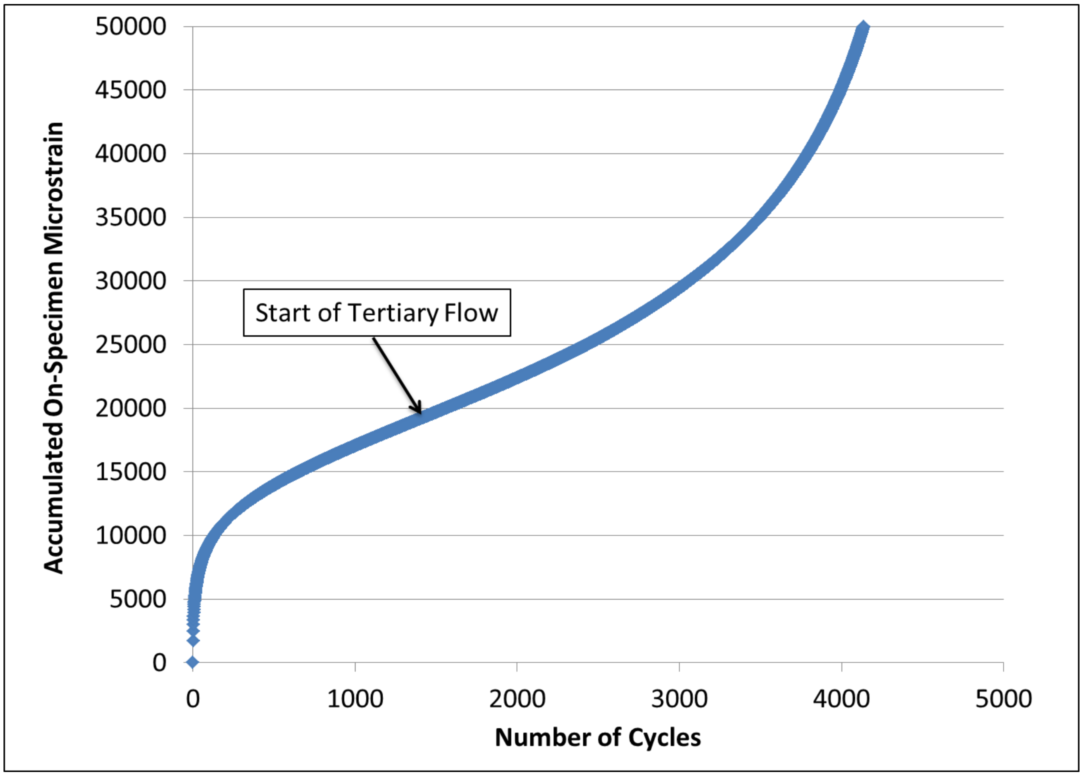


FIGURE 19 Typical Unconfined Flow Number Test Behavior

The results of the Flow Number testing are in TABLE 6. The graphical flow number results for the confined and unconfined testing are presented as FIGURE 20 and FIGURE 21, respectively. The individual flow number test results are given in APPENDIX C. These results show that the WMA showed more permanent deformation than the HMA in the confined flow number test; however, the difference in the results was not statistically significant (ANOVA $\alpha = 0.05$, *p*-value = 0.062). For the unconfined tests, the WMA had a lower average flow number than the HMA (approximately 300 versus approximately 1000); however, the difference in the results was again not statistically significant given the high variability of the HMA results (ANOVA $\alpha = 0.05$, *p*-value = 0.137). Therefore, the flow number testing showed the rutting resistance for these WMA and HMA mixtures to be comparable.

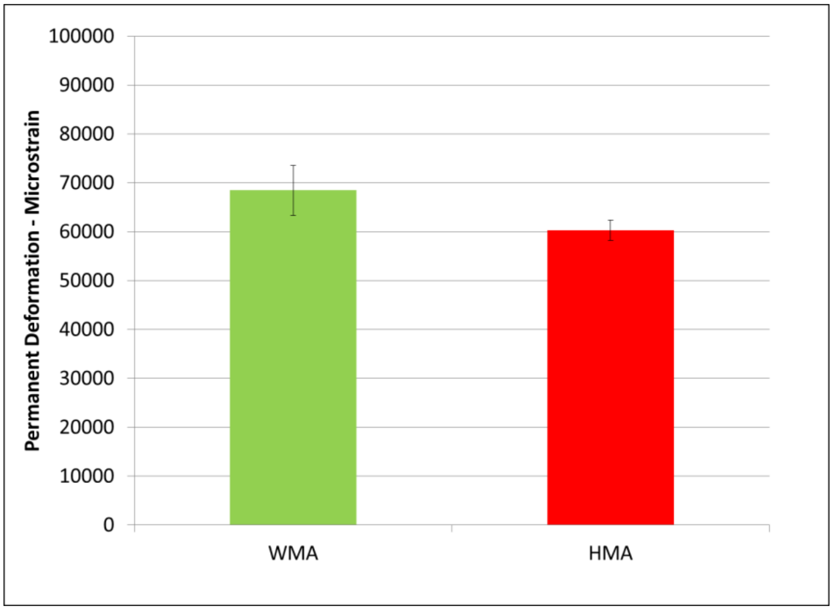


FIGURE 20 Confined Flow Number Test Results

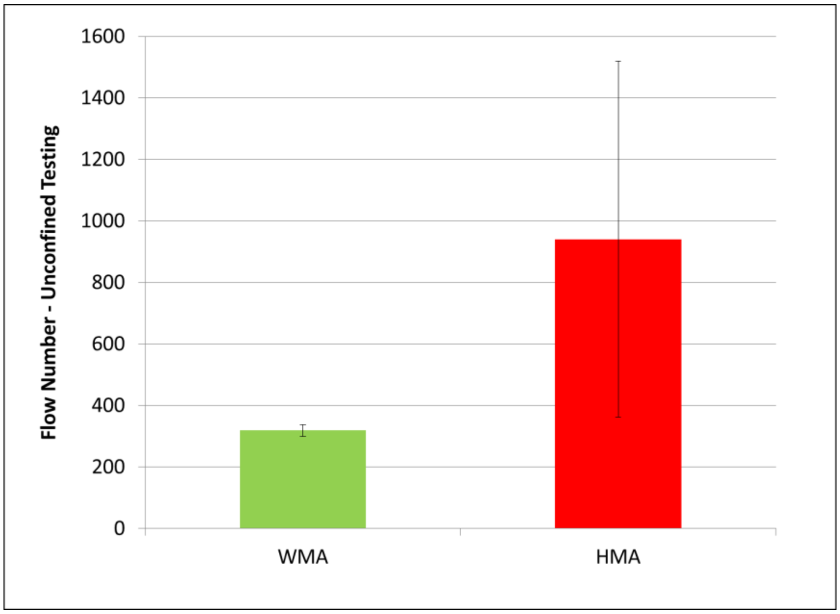


FIGURE 21 Unconfined Flow Number Results

TABLE 6 Average and Standard Deviation - Flow Number Results

Mix ID	Average Microstrain at 20,000 cycles – Confined Testing	Average Flow Number – Unconfined Testing	Standard Deviation of Microstrain at 20,000 cycles – Confined Testing	Standard Deviation Flow Number – Unconfined Testing
WMA	68438.3	319	5102.6	19.1
HMA	60279.0	940	2128.4	578.9

3.10 Bond Strength Testing

Bond strength testing was performed for this project to ensure similar quality of bond of the tested surface layers to their respective binder layers. For this testing, three field cores were taken from sections E8 and E9 after paving at the test track. The cores were tested in accordance with ALDOT procedure 430. This test procedure applies a monotonic shearing load to the interface between two asphalt layers using the Marshall Press apparatus. The load is applied at a rate of 50 mm (2 inches) per minute, and the testing is conducted on cores conditioned to 25°C (77°F). The shearing load is applied in the direction of traffic for this testing. The bond strength is calculated by dividing the maximum shear load by the cross-sectional area of the core. A photo of bond strength testing in progress is shown in FIGURE 22.

FIGURE 22 Bond Strength Testing In Progress

The results of the bond strength testing are shown in
TABLE 7. The individual sample bond strengths are tabulated in APPENDIX C. The data shows the WMA has a higher interface bond strength than the HMA; however, the difference was not statistically significant (ANOVA α = 0.05, *p*-value = 0.15). The bond strength values for both sections are well above 689 kPa (100 psi), which is a preliminary lower bound used to evaluate the quality of pavement layer bonding using this testing procedure. Practically, these results indicate that a slippage or de-bonding failure is unlikely to occur in the field given the strength of the interface.

TABLE 7 Results from Interface Bond Strength Testing - Field Cores

Mix ID	Average Bond Strength (psi)	Standard Deviation of Bond Strength (psi)
HMA	240.8	49.4
WMA	299.6	29.1

4. FIELD PERFORMANCE

The WMA and HMA test track sections are trafficked for one year. Pavement condition measurements were obtained and documented on a weekly basis. Rutting was evaluated using inertial profiler equipped with a laser for measuring ruts. The inertial profiler was also used to assess the roughness and macrotexture of the pavement. Crack maps were created to document cracking. Cores were taken each quarter for inspection of any signs of moisture damage. No signs of moisture damage were observed in any study cores.

4.1 Accelerated Loading

Test sections on the NCAT Pavement Test Track are loaded with heavy triple trailer trains (shown in FIGURE 23) with an average gross vehicle weight of 690 kN (155,000 lbs) driven by human drivers at a cruise speed of 70 km per hour (45 mph). Individual single axles are loaded to optimize the efficiency of pavement damage, which averages approximately 11.8 ESALs per truck pass. Each vehicle in the five-truck fleet laps the track approximately 400 times a day in order to induce damage in experimental pavements. Five million ESALs were applied to both experimental pavements between May 2010 and May 2011. Trucking was initiated on both the HMA control and WMA test mixes on May 12, 2010, as soon as construction was complete.

FIGURE 23 Application of Accelerated Damage on the NCAT Pavement Test Track

4.2 Rutting Performance

Every Monday, trucking operations are suspended on the NCAT track so that surface condition studies can be conducted to thoroughly document field performance of all experimental sections. Rutting is characterized using numerous methods (both contact and non-contact) to facilitate comparison of results for quality control purposes (Powell 2006). Results from periodic rut depth measurements in both sections are included as FIGURE 24. The tabulated raw data are given in APPENDIX D. These data reveal a steady increase in rut depth from the time the pavements were constructed in May 2010 until October 2010 when pavement temperatures decreased significantly. The difference in rutting between the sections occurred early in the performance history, with measured rut depths becoming parallel after the fall 2010. Although the HMA control section exhibited slightly less rutting than the WMA certification section, neither section rutted more than 6 mm (1/4 inch).

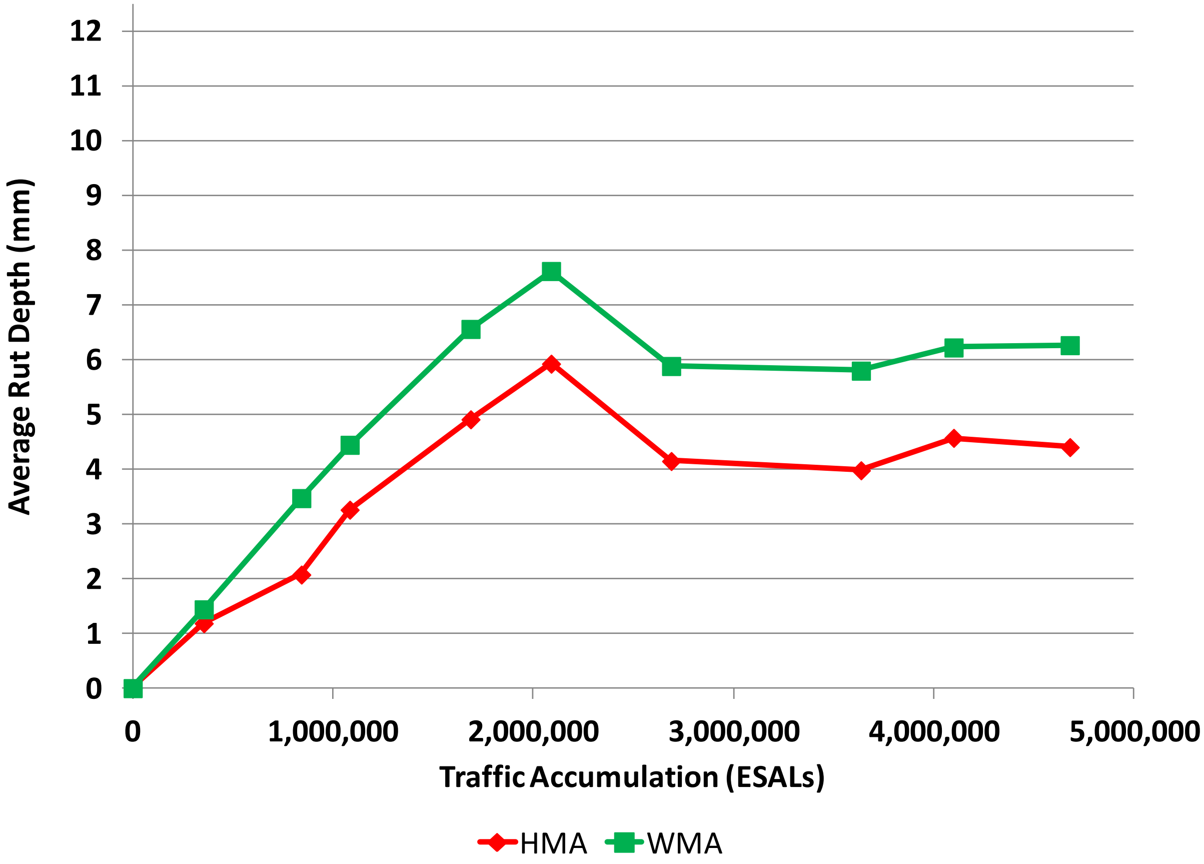


FIGURE 24 Field Rutting Performance Comparison

4.3 Roughness Performance

Automated roughness measurements are obtained using the Automatic Road Analyzer (ARAN) van. The ARAN van is equipped with inertially compensated precision distance lasers to normalize vehicle dynamics and produce profile-based roughness measurements for each section. As seen in FIGURE 25, slightly more changes in roughness were observed in the HMA control section than in the WMA certification section. Higher levels of roughness were measured in the HMA control section after the appearance of a rich spot near the end of the section, possibly because shear flow changed the surface profile. After the appearance of the rich spot (shown in FIGURE 26), changes in roughness for the two sections were similar. The tabulated roughness data are given in APPENDIX D.

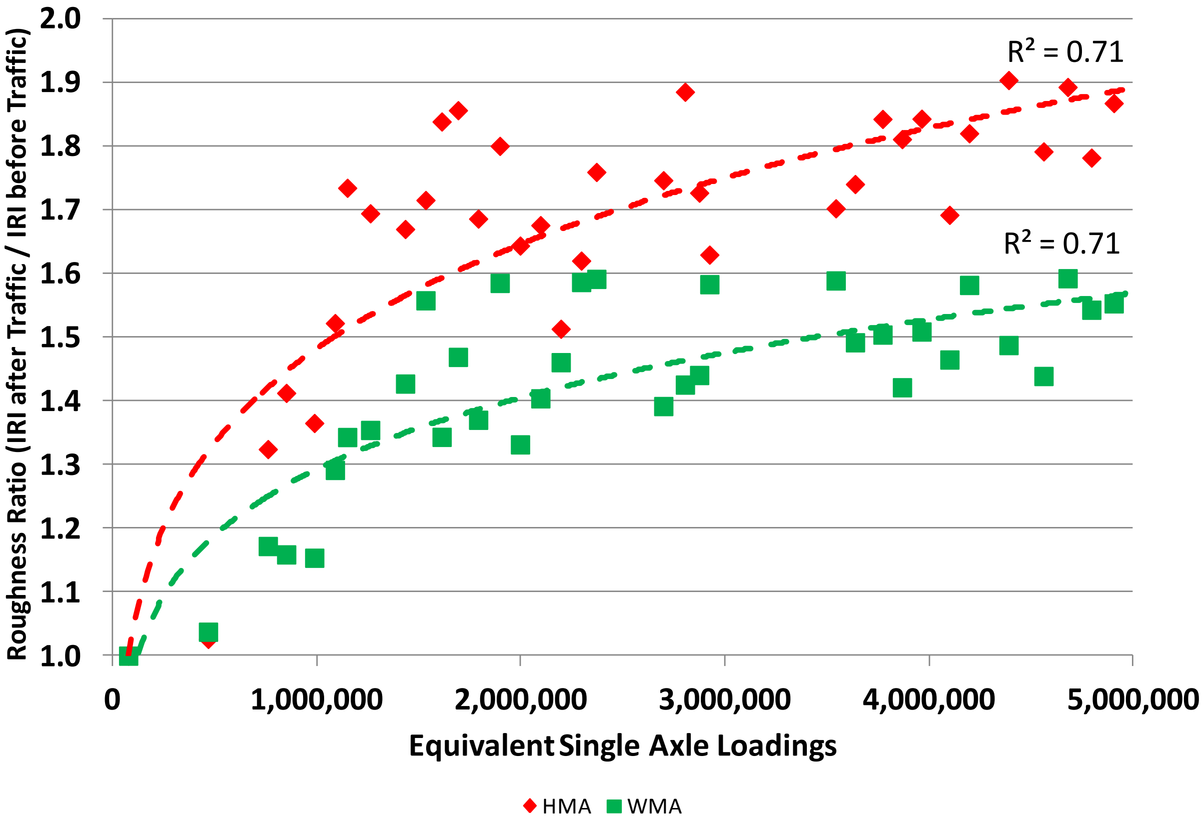


FIGURE 25 Roughness Performance Comparison

FIGURE 26 Rich Spot near the End of the HMA Control Test Section

4.4 Macrotexture Performance

The ARAN van also measures pavement macrotexture using a laser that samples data at a high frequency (64 kHz). Performance history at the track strongly suggests that macrotexture is related to pavement durability, where pavement macrotexture increases when aggregate particles are dislodged from the mat (leaving exposed surface voids in their place). This cumulative process is commonly referred to as raveling (Powell 2006).

Changes in macrotexture are considered a key performance measure in the WMA certification program. Macrotexture measurements as a function of traffic are presented in FIGURE 27. These data do not indicate significant differences between the HMA control section and the WMA certification section. The tabulated macrotexture data are given in APPENDIX D.

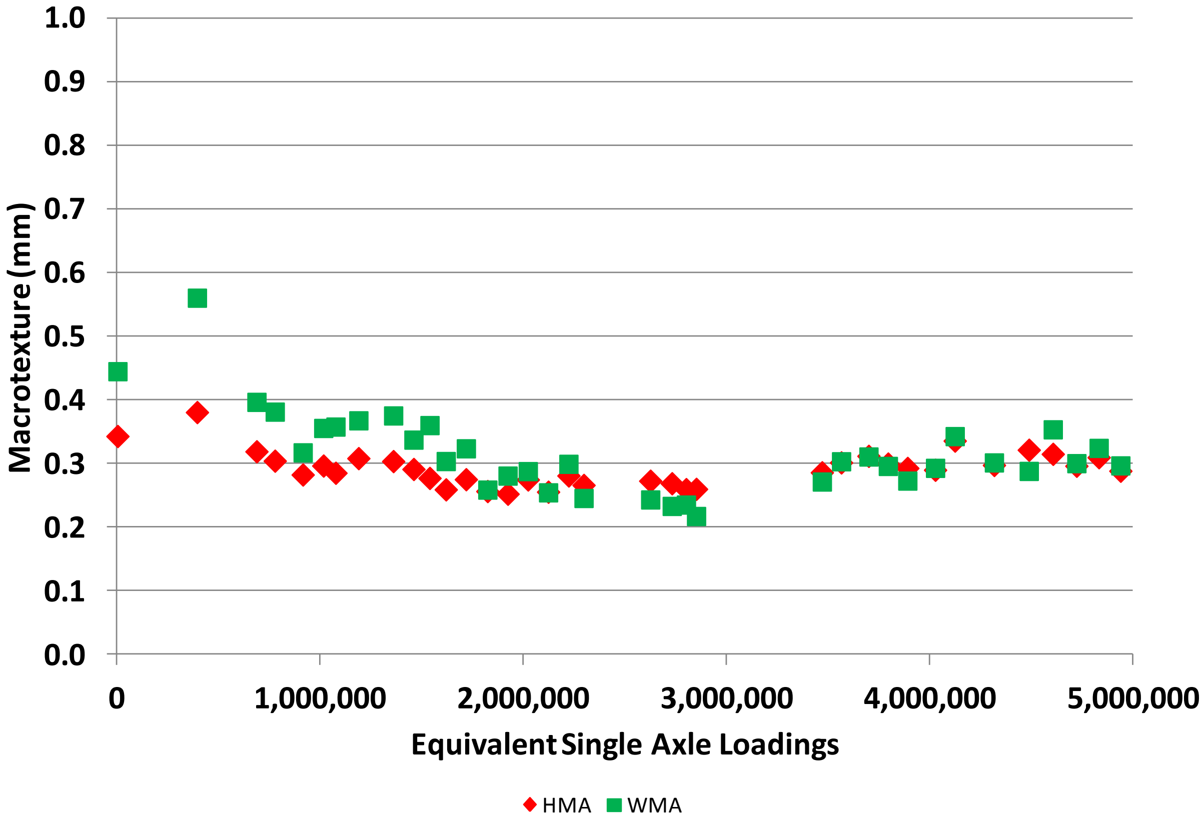


FIGURE 27 Macrotexture Performance Comparison

4.5 Cracking Performance

All experimental pavements are visually inspected for cracking on a weekly basis. Just over 4 meters (13 feet) of low-severity longitudinal cracking was observed in the HMA control section, while no cracking was observed in the WMA certification section. Cracks maps for both sections after 5 million ESALs are presented in FIGURE 28, and a picture of the cracking observed in the HMA control section is exhibited in FIGURE 29.

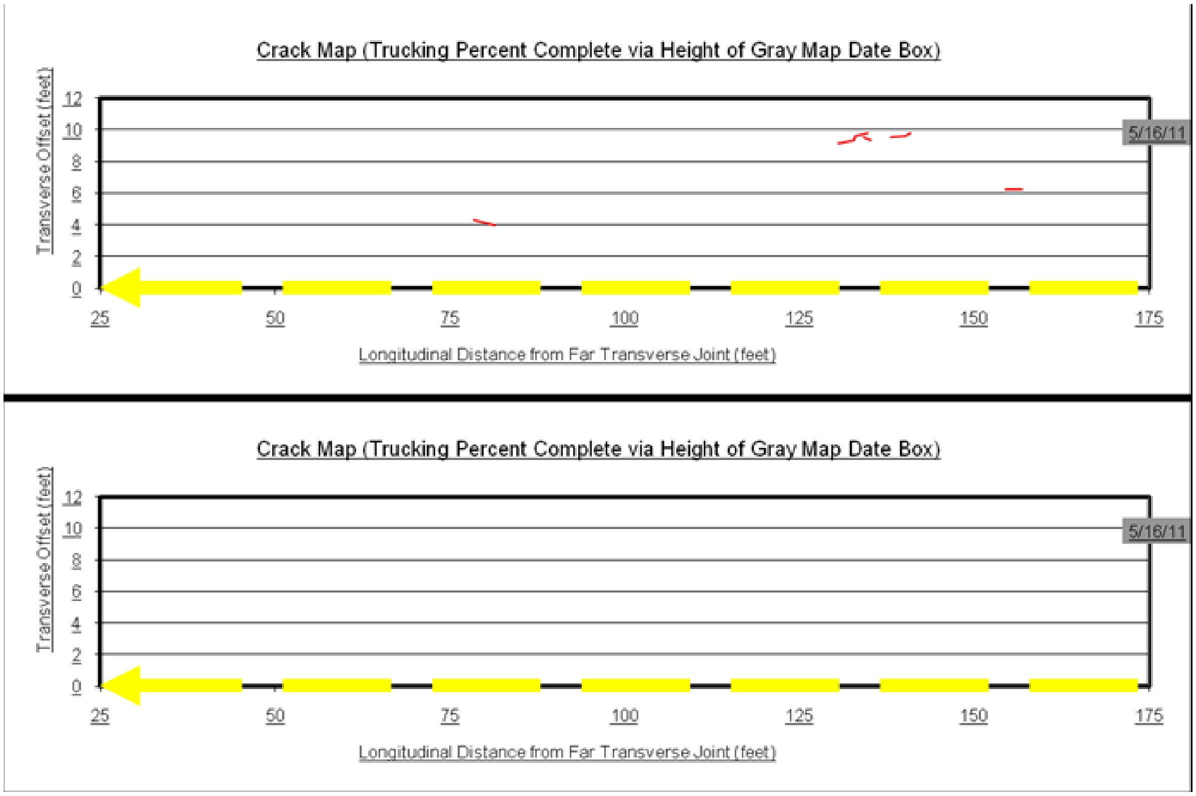


FIGURE 28 Crack Maps of Control HMA (top) and WMA (bottom) Test Sections

FIGURE 29 Cracking Observed in the Control HMA Test Section

5. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be made based on the results of this study comparing mix produced using Shell Thiopave sulfur-modified WMA technology and a conventional HMA control mix:

1) No significant problems were encountered producing either mix. A rich spot near the end of the HMA section is an indication that the design gradation is subject to segregation during placement. High densities were measured in both experimental pavements.
2) Although slightly more rutting was observed in the WMA certification section, both mixes exhibited less than 6 mm (1/4 inch) of rutting on the track. In the laboratory, the APA test predicted the HMA would rut less than the WMA, with both mixes having an acceptable level of rutting. The Hamburg wheel-tracking and flow number tests predicted the WMA and HMA would have a similar level of rutting resistance. Hence, the results of the laboratory rutting-susceptibility tests were in agreement with the measured rut depths in the field.
3) Dynamic modulus testing on the plant-produced mixes showed the WMA would be stiffer than the HMA at warmer temperatures and slower loading frequencies.
4) TSR, Hamburg wheel-tracking, and boiling water testing on the plant-produced HMA and WMA showed both mixes should be resistant to moisture damage in the field.
5) A critical temperature analysis on IDT (AASHTO T 322-07) test data showed the WMA was slightly more susceptible to low-temperature cracking than the HMA (WMA would crack at 2˚ warmer than the HMA). However, the difference in results was not enough to alter the required low PG grade of the binder.
6) Laboratory bond strength testing (ALDOT Procedure 430) on field cores from the WMA and HMA test sections showed both mixtures should have sufficient bond strength to their respective binder layers in the field.
7) Roughness increased more in the HMA control section than it did in the WMA certification section.
8) The change in surface macrotexture as a function of traffic was virtually identical for both mixes. This is indicative of no differences in durability, which is supported by observations of the cores.
9) The HMA control section exhibited minor longitudinal cracking after approximately 2.9 million ESALs. No cracking was observed in the WMA certification section through 5 million ESALs.
10) Although crack-susceptibility testing as measured with the overlay tester, created some concern over how the WMA certification mix would perform, the HMA control section was the only one that actually cracked on the track.

Based on a comprehensive assessment of construction, laboratory performance, and field performance, acceptance of Shell Thiopave as an alternative WMA technology in the manner in which it was used at the NCAT Pavement Test Track is recommended.

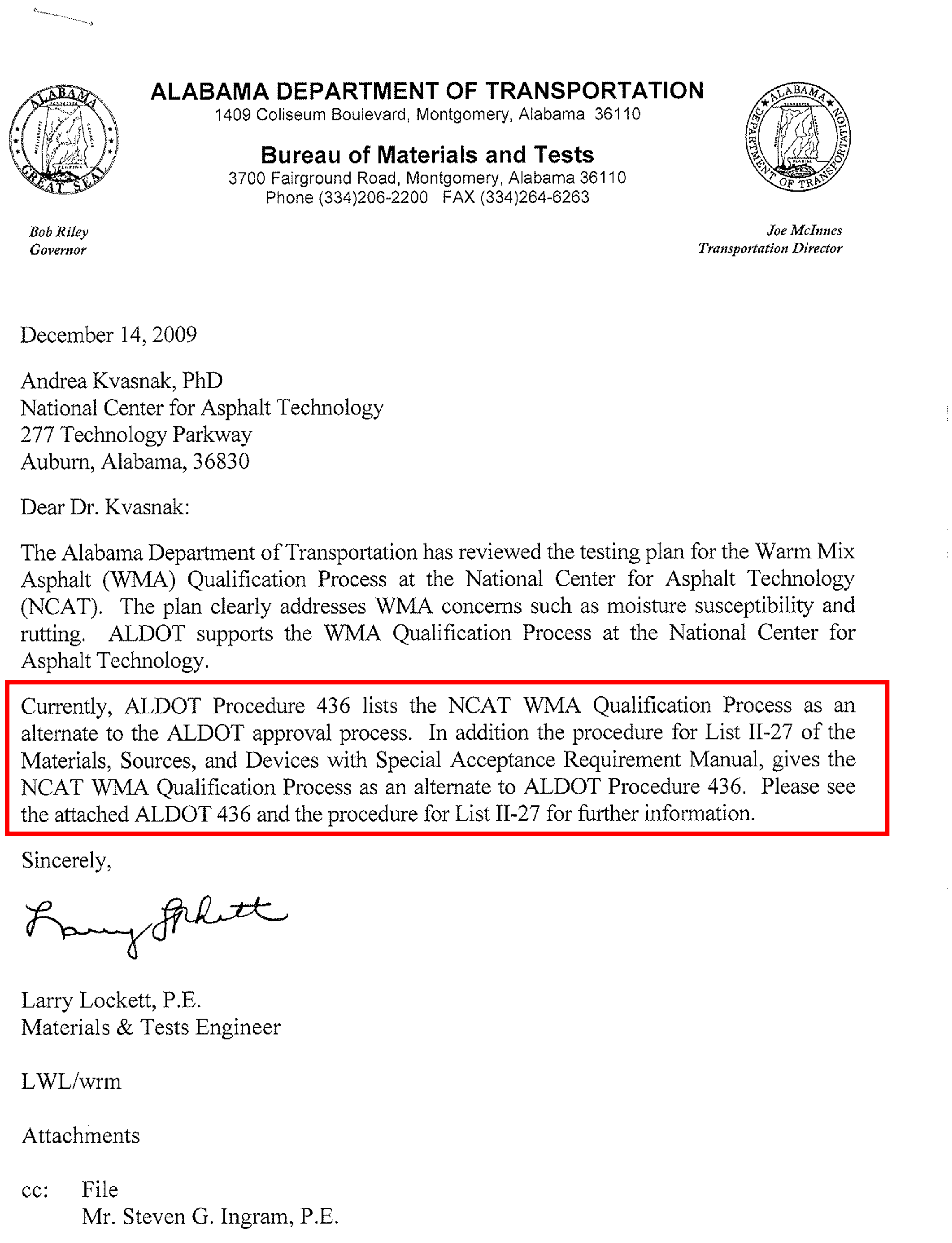
REFERENCES

1) National Center for Asphalt Technology - Asphalt Technology News, Fall 2009: Volume 21, No. 2.
2) Biligiri, K. P., K. E. Kaloush, M. S. Mamlouk, and M. W. Witczak. Rational Modeling of Tertiary Flow for Asphalt Mixtures. *Transportation Research Record: Journal of the Transportation Research Baord*, 2007, pp. 63-72.
3) Buttlar, W. G., R. Roque, and B. Reid. Automated Procedure for Generation of Creep Compliance Master Curve for Asphalt Mixtures. *Transportation Research Record 1630*, 1998: pp. 28-36.
4) Chen, Dar-Hao. Field Experiences with RDD and Overlay Tester for Concrete Pavement Rehabilitation. *ASCE Journal of Transportation Engineering*, 2008: pp. 24-33.
5) Hiltunen, D. R., and R. Roque. A Mechanics-Based Prediction Model for Thermal Cracking of Asphaltic Concrete Pavements. *Journal of the Association of Asphalt Paving Technologists*, 1994, pp. 81-117.
6) Jones, G. M., M. I. Darter, and G. Littlefield. Thermal Expansion-Contraction of Asphaltic Concrete. *Journal of the Association of Asphalt Paving Technologists*, 1968: pp. 56-97.
7) Kim, J., R. Roque, and B. Birgisson. Integration of Thermal Fracture in the HMA Fracture Model. *Journal of the Association of Asphalt Paving Technologists,* 2008: pp. 631-662.
8) Kvasnak, A.N., J. R. Moore, A.J. Taylor, and B. D. Prowell. Preliminary Evaluation of Warm Mix Asphalt Field Demonstration: Franklin, Tennessee. NCAT Report 10-01, National Center for Asphalt Technology, Auburn, AL, 2010.
9) Powell, R. B.. *Predicting Field Performance on the NCAT Pavement Test Track.* Ph.D. Dissertation, Auburn, AL: Auburn University, 2006.
10) Soules, T. F., R. F. Busbey, S. M. Rekhson, A. Markovsky, and M. A. Burke. "Finite-Element Calculation of Stresses in Glass Parts Undergoing Viscous Relaxation." *Journal of the American Ceramic Society*, 1987: pp. 90-95.
11) Strickland, D., J. Colange, M. Martin, and I. Deme. Performance Properties of Sulphur Extended Asphalt Mixtures with Modified Sulphur Pellets. *ISAP*, 2008.
12) Timm, D. H., M. M. Robbins, J. R. Willis, N. H. Tran, and A. J. Taylor. Evaluation of Mixture Performance and Structural Capacity of Pavements Utilizing Shell Thiopave - Phase II: Construction, Laboratory Evaluation and Full-Scale Testing of Thiopave Test Sections - One Year Report. Draft Final Report, National Center for Asphalt Technology, Auburn University, AL, 2011.
13) Timm, D. H., N. H. Tran, A. J. Taylor, M. M. Robbins, and R. Powell. Evaluation of Mixture Performance and Structural Capacity of Pavements Using Shell Thiopave. NCAT Report No. 09-05, National Center for Asphalt Technology, Auburn University, AL, 2009.
14) Tran, N. H., R.C. West, R. B. Powell, and A. Kvasnak. Evaluation of AASHTO Rut Test Procedure Using the Asphalt Pavement Analyzer. *Journal of the Association of Asphalt Paving Technologists, Volume 78,* 2009: pp. 1-24.

APPENDIX A
WMA Certification Documentation

Table A1 List of States Currently Endorsing the NCAT WMA Certification Program

Alabama
Arizona
Colorado
Delaware
Florida
Indiana
New Hampshire
South Carolina
Tennessee
Texas
Washington



ALABAMA DEPARTMENT OF TRANSPORTATION
1409 Coliseum Boulevard, Montgomery, Alabama 36110

Bureau of Materials and Tests
3700 Fairground Road, Montgomery, Alabama 36110
Phone (334)206-2200 FAX (334)264-6263

Bob Riley
Governor

Joe McInnes
Transportation Director

December 14, 2009

Andrea Kvasnak, PhD
National Center for Asphalt Technology
277 Technology Parkway
Auburn, Alabama, 36830

Dear Dr. Kvasnak:

The Alabama Department of Transportation has reviewed the testing plan for the Warm Mix Asphalt (WMA) Qualification Process at the National Center for Asphalt Technology (NCAT). The plan clearly addresses WMA concerns such as moisture susceptibility and rutting. ALDOT supports the WMA Qualification Process at the National Center for Asphalt Technology.

Currently, ALDOT Procedure 436 lists the NCAT WMA Qualification Process as an alternate to the ALDOT approval process. In addition the procedure for List II-27 of the Materials, Sources, and Devices with Special Acceptance Requirement Manual, gives the NCAT WMA Qualification Process as an alternate to ALDOT Procedure 436. Please see the attached ALDOT 436 and the procedure for List II-27 for further information.

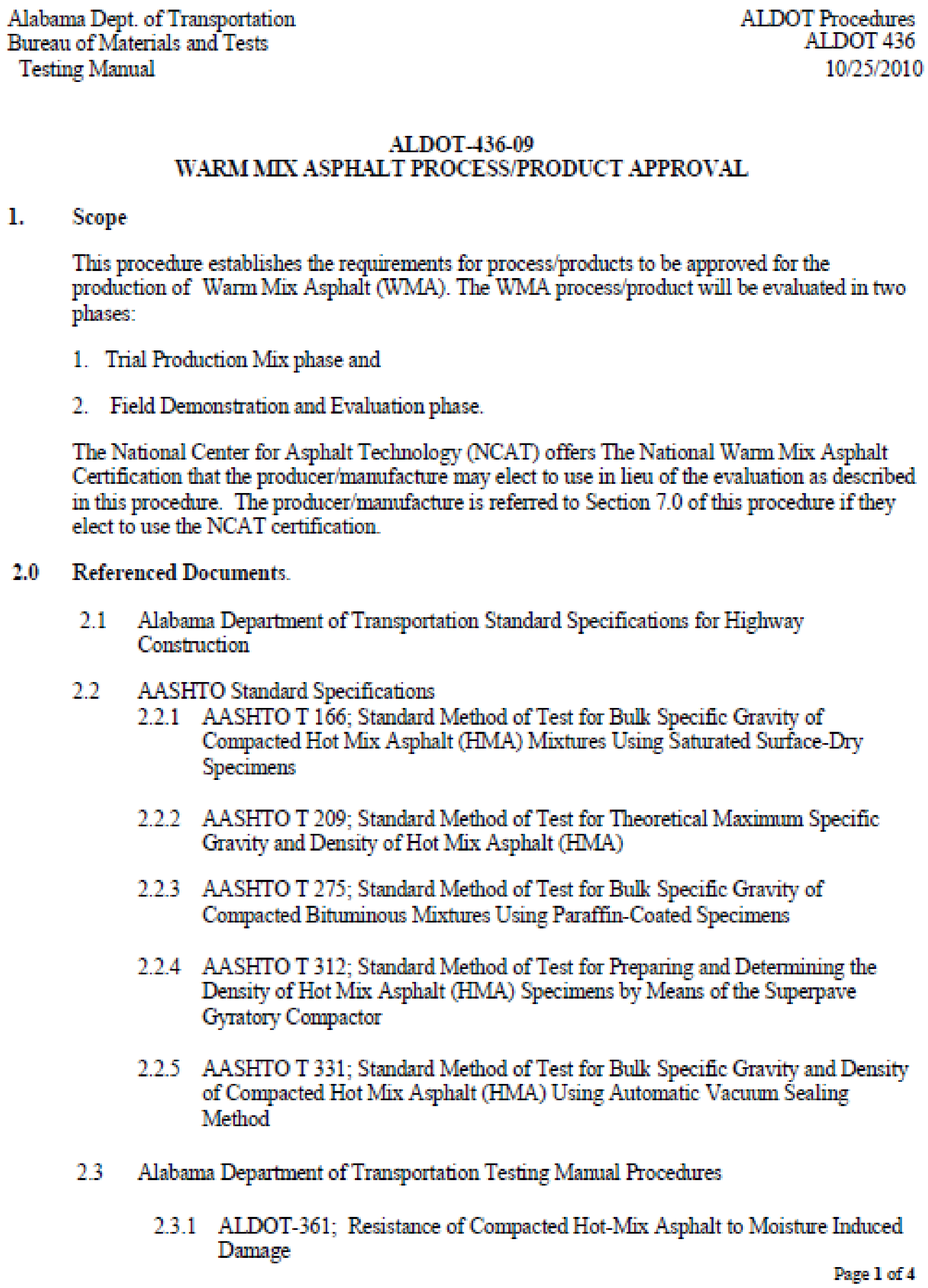
Sincerely,

Larry Lockett, P.E.
Materials & Tests Engineer

LWL/wrm

Attachments

cc: File
Mr. Steven G. Ingram, P.E.



Alabama Dept. of Transportation
Bureau of Materials and Tests
Testing Manual

ALDOT Procedures
ALDOT 436
10/25/2010

ALDOT-436-09
WARM MIX ASPHALT PROCESS/PRODUCT APPROVAL

1. Scope

This procedure establishes the requirements for process/products to be approved for the production of Warm Mix Asphalt (WMA). The WMA process/product will be evaluated in two phases:

1. Trial Production Mix phase and
2. Field Demonstration and Evaluation phase.

The National Center for Asphalt Technology (NCAT) offers The National Warm Mix Asphalt Certification that the producer/manufacture may elect to use in lieu of the evaluation as described in this procedure. The producer/manufacture is referred to Section 7.0 of this procedure if they elect to use the NCAT certification.

2.0 Referenced Documents.

2.1 Alabama Department of Transportation Standard Specifications for Highway Construction

2.2 AASHTO Standard Specifications

2.2.1 AASHTO T 166; Standard Method of Test for Bulk Specific Gravity of Compacted Hot Mix Asphalt (HMA) Mixtures Using Saturated Surface-Dry Specimens

2.2.2 AASHTO T 209; Standard Method of Test for Theoretical Maximum Specific Gravity and Density of Hot Mix Asphalt (HMA)

2.2.3 AASHTO T 275; Standard Method of Test for Bulk Specific Gravity of Compacted Bituminous Mixtures Using Paraffin-Coated Specimens

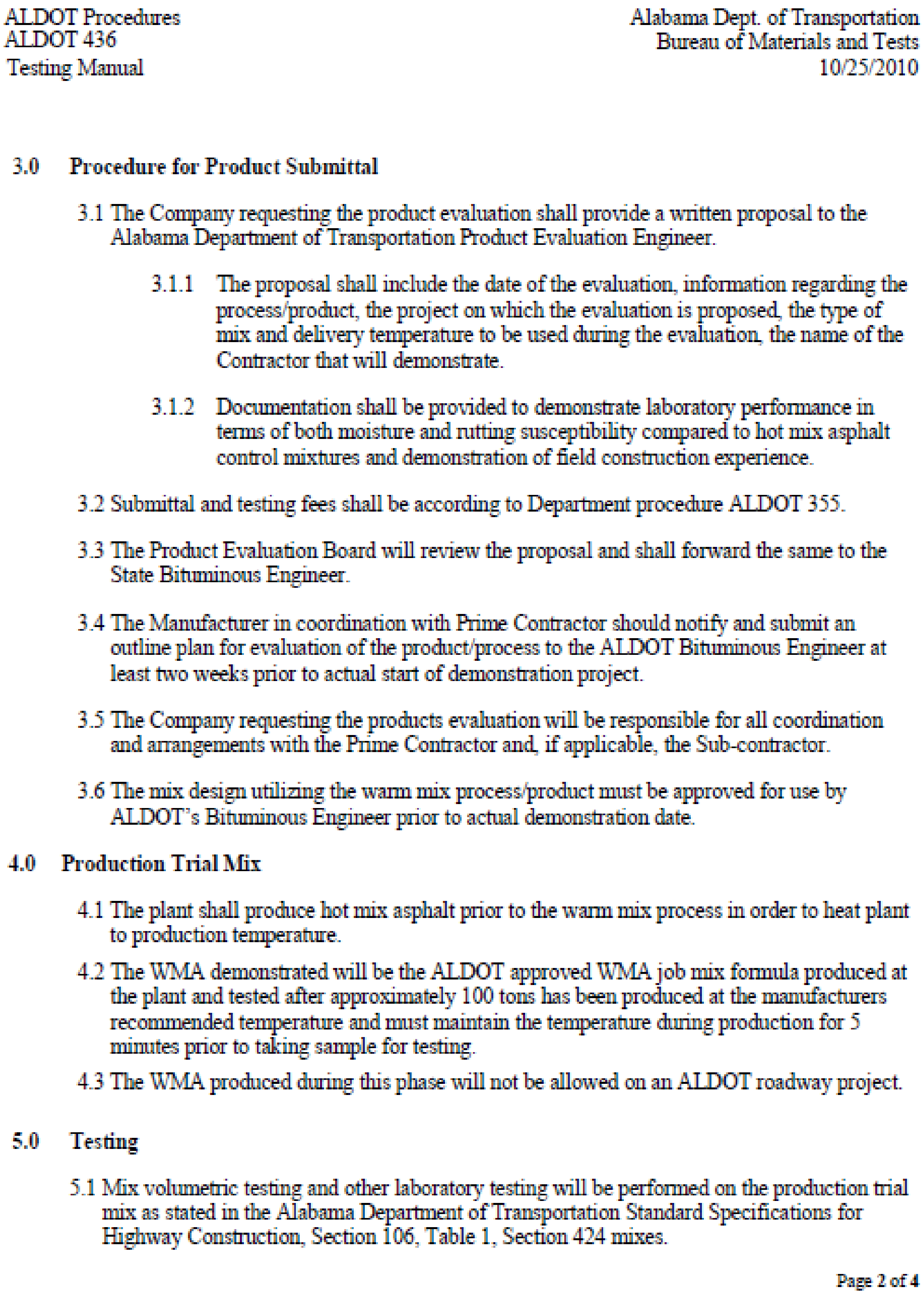
2.2.4 AASHTO T 312; Standard Method of Test for Preparing and Determining the Density of Hot Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor

2.2.5 AASHTO T 331; Standard Method of Test for Bulk Specific Gravity and Density of Compacted Hot Mix Asphalt (HMA) Using Automatic Vacuum Sealing Method

2.3 Alabama Department of Transportation Testing Manual Procedures

2.3.1 ALDOT-361; Resistance of Compacted Hot-Mix Asphalt to Moisture Induced Damage

Page 1 of 4



3.0 Procedure for Product Submittal

3.1 The Company requesting the product evaluation shall provide a written proposal to the Alabama Department of Transportation Product Evaluation Engineer.

3.1.1 The proposal shall include the date of the evaluation, information regarding the process/product, the project on which the evaluation is proposed, the type of mix and delivery temperature to be used during the evaluation, the name of the Contractor that will demonstrate.

3.1.2 Documentation shall be provided to demonstrate laboratory performance in terms of both moisture and rutting susceptibility compared to hot mix asphalt control mixtures and demonstration of field construction experience.

3.2 Submittal and testing fees shall be according to Department procedure ALDOT 355.

3.3 The Product Evaluation Board will review the proposal and shall forward the same to the State Bituminous Engineer.

3.4 The Manufacturer in coordination with Prime Contractor should notify and submit an outline plan for evaluation of the product/process to the ALDOT Bituminous Engineer at least two weeks prior to actual start of demonstration project.

3.5 The Company requesting the products evaluation will be responsible for all coordination and arrangements with the Prime Contractor and, if applicable, the Sub-contractor.

3.6 The mix design utilizing the warm mix process/product must be approved for use by ALDOT's Bituminous Engineer prior to actual demonstration date.

4.0 Production Trial Mix

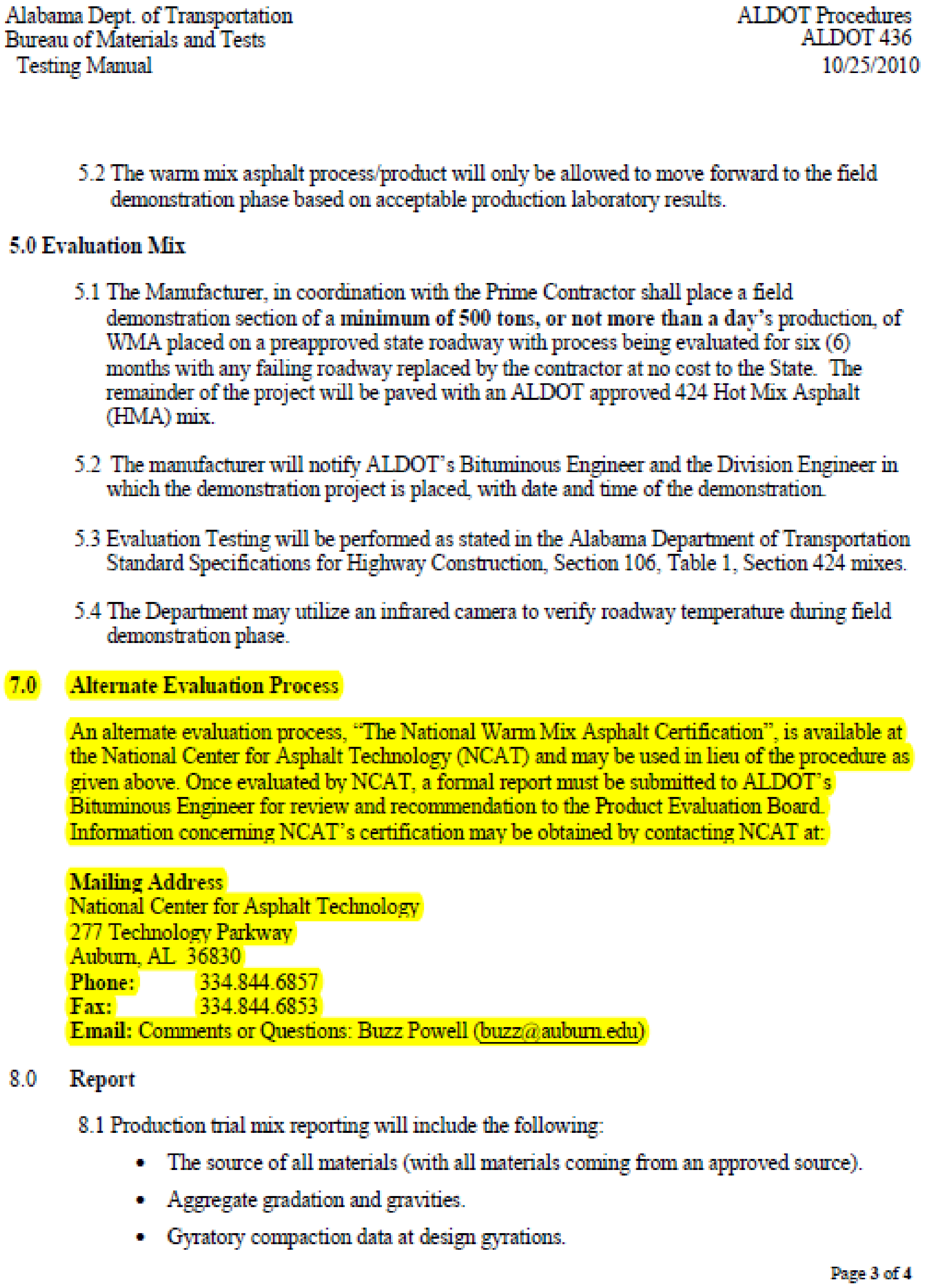
4.1 The plant shall produce hot mix asphalt prior to the warm mix process in order to heat plant to production temperature.

4.2 The WMA demonstrated will be the ALDOT approved WMA job mix formula produced at the plant and tested after approximately 100 tons has been produced at the manufacturers recommended temperature and must maintain the temperature during production for 5 minutes prior to taking sample for testing.

4.3 The WMA produced during this phase will not be allowed on an ALDOT roadway project.

5.0 Testing

5.1 Mix volumetric testing and other laboratory testing will be performed on the production trial mix as stated in the Alabama Department of Transportation Standard Specifications for Highway Construction, Section 106, Table 1, Section 424 mixes.



Alabama Dept. of Transportation
Bureau of Materials and Tests
Testing Manual

ALDOT Procedures
ALDOT 436
10/25/2010

5.2 The warm mix asphalt process/product will only be allowed to move forward to the field demonstration phase based on acceptable production laboratory results.

5.0 Evaluation Mix

5.1 The Manufacturer, in coordination with the Prime Contractor shall place a field demonstration section of a **minimum of 500 tons, or not more than a day's** production, of WMA placed on a preapproved state roadway with process being evaluated for six (6) months with any failing roadway replaced by the contractor at no cost to the State. The remainder of the project will be paved with an ALDOT approved 424 Hot Mix Asphalt (HMA) mix.

5.2 The manufacturer will notify ALDOT's Bituminous Engineer and the Division Engineer in which the demonstration project is placed, with date and time of the demonstration.

5.3 Evaluation Testing will be performed as stated in the Alabama Department of Transportation Standard Specifications for Highway Construction, Section 106, Table 1, Section 424 mixes.

5.4 The Department may utilize an infrared camera to verify roadway temperature during field demonstration phase.

7.0 Alternate Evaluation Process

An alternate evaluation process, "The National Warm Mix Asphalt Certification", is available at the National Center for Asphalt Technology (NCAT) and may be used in lieu of the procedure as given above. Once evaluated by NCAT, a formal report must be submitted to ALDOT's Bituminous Engineer for review and recommendation to the Product Evaluation Board. Information concerning NCAT's certification may be obtained by contacting NCAT at:

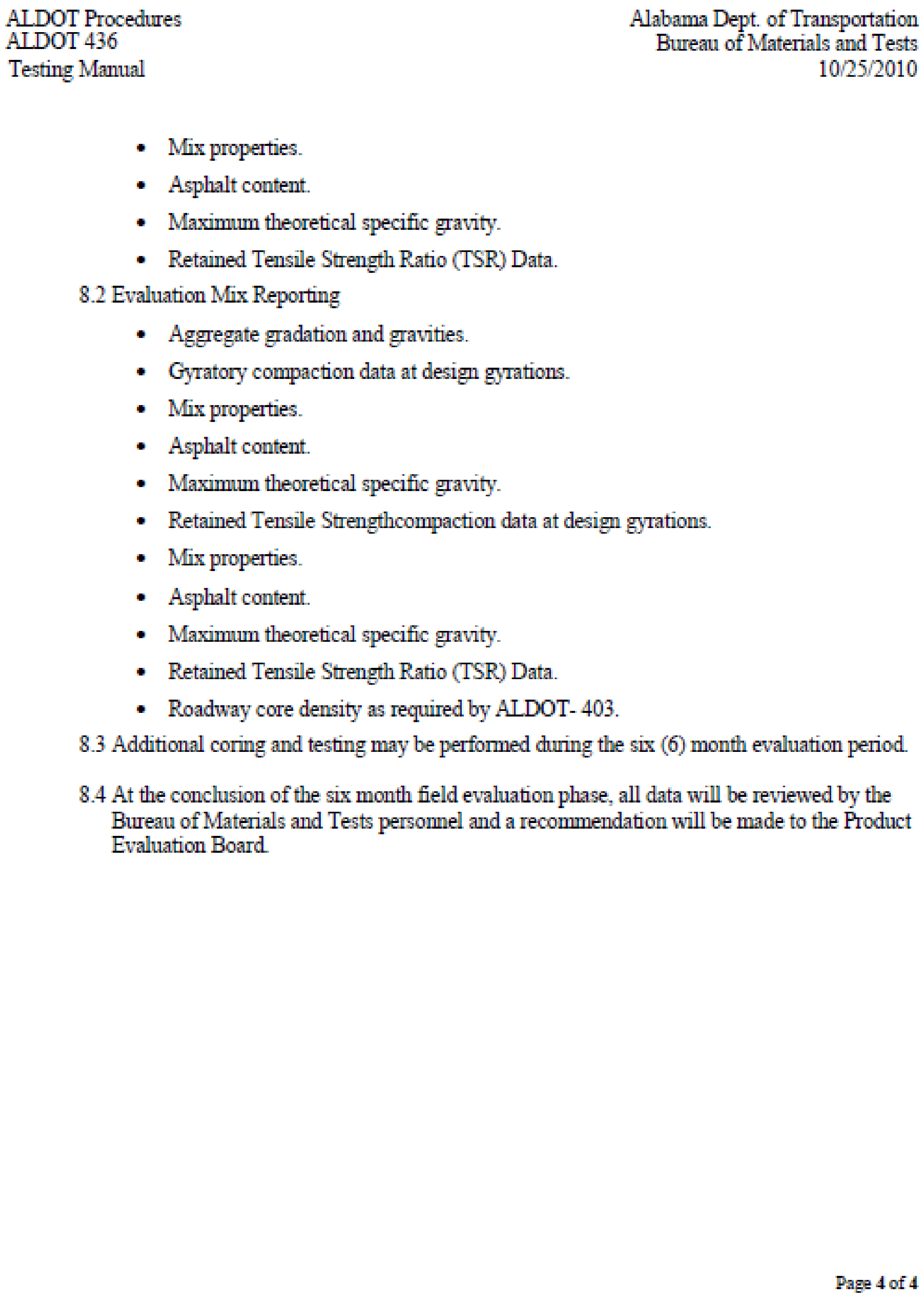
Mailing Address
National Center for Asphalt Technology
277 Technology Parkway
Auburn, AL 36830
Phone: 334.844.6857
Fax: 334.844.6853
Email: Comments or Questions: Buzz Powell (buzz@auburn.edu)

8.0 Report

8.1 Production trial mix reporting will include the following:

- The source of all materials (with all materials coming from an approved source).
- Aggregate gradation and gravities.
- Gyratory compaction data at design gyrations.

Page 3 of 4



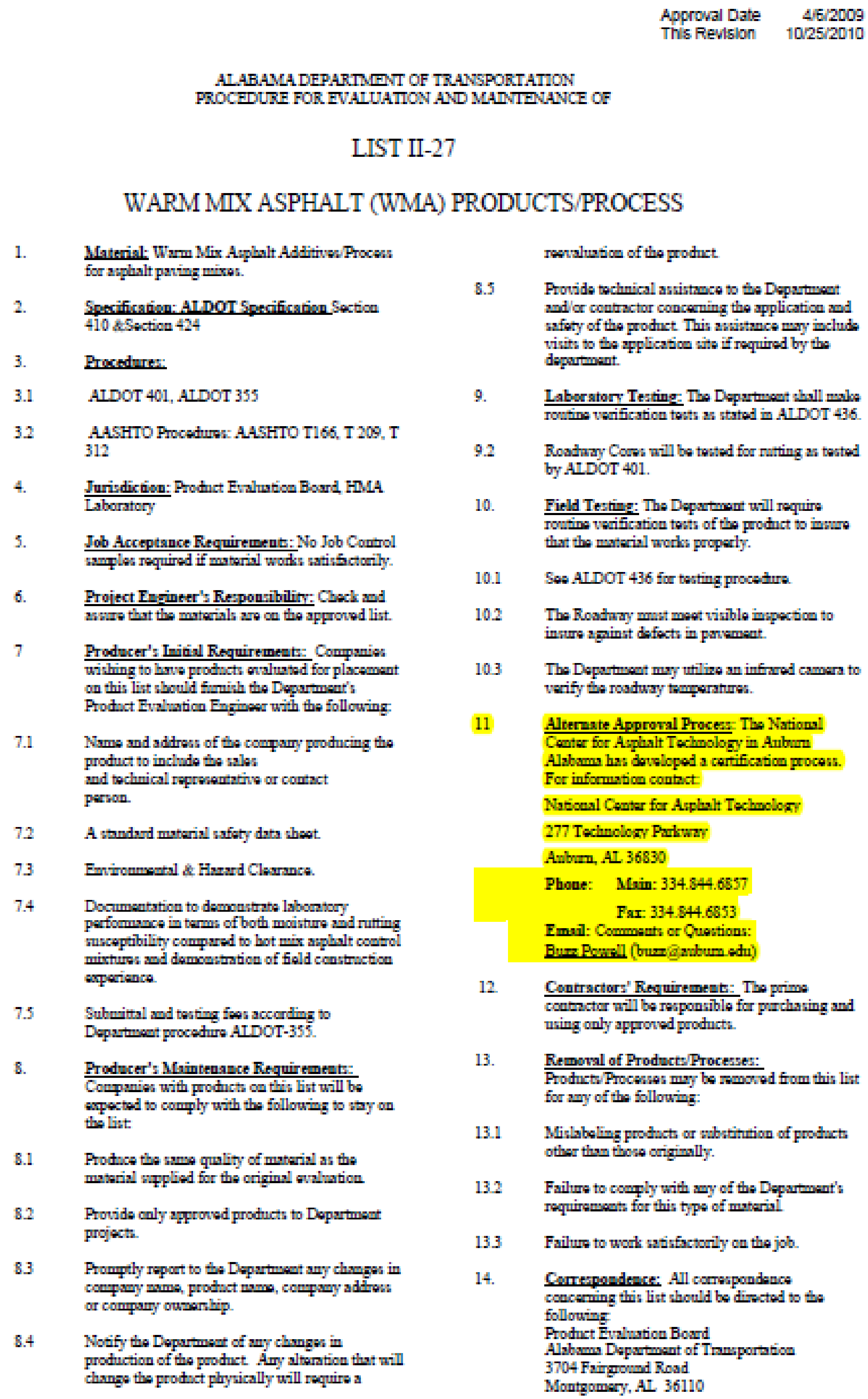
- Mix properties.
- Asphalt content.
- Maximum theoretical specific gravity.
- Retained Tensile Strength Ratio (TSR) Data.

8.2 Evaluation Mix Reporting

- Aggregate gradation and gravities.
- Gyratory compaction data at design gyrations.
- Mix properties.
- Asphalt content.
- Maximum theoretical specific gravity.
- Retained Tensile Strengthcompaction data at design gyrations.
- Mix properties.
- Asphalt content.
- Maximum theoretical specific gravity.
- Retained Tensile Strength Ratio (TSR) Data.
- Roadway core density as required by ALDOT- 403.

8.3 Additional coring and testing may be performed during the six (6) month evaluation period.

8.4 At the conclusion of the six month field evaluation phase, all data will be reviewed by the Bureau of Materials and Tests personnel and a recommendation will be made to the Product Evaluation Board.



Approval Date 4/6/2009
This Revision 10/25/2010

ALABAMA DEPARTMENT OF TRANSPORTATION
PROCEDURE FOR EVALUATION AND MAINTENANCE OF

LIST II-27

WARM MIX ASPHALT (WMA) PRODUCTS/PROCESS

1. **Material:** Warm Mix Asphalt Additives/Process for asphalt paving mixes.

2. **Specification: ALDOT Specification** Section 410 &Section 424

3. **Procedures:**

3.1 ALDOT 401, ALDOT 355

3.2 AASHTO Procedures: AASHTO T166, T 209, T 312

4. **Jurisdiction:** Product Evaluation Board, HMA Laboratory

5. **Job Acceptance Requirements:** No Job Control samples required if material works satisfactorily.

6. **Project Engineer's Responsibility:** Check and assure that the materials are on the approved list.

7 **Producer's Initial Requirements:** Companies wishing to have products evaluated for placement on this list should furnish the Department's Product Evaluation Engineer with the following:

7.1 Name and address of the company producing the product to include the sales and technical representative or contact person.

7.2 A standard material safety data sheet.

7.3 Environmental & Hazard Clearance.

7.4 Documentation to demonstrate laboratory performance in terms of both moisture and rutting susceptibility compared to hot mix asphalt control mixtures and demonstration of field construction experience.

7.5 Submittal and testing fees according to Department procedure ALDOT-355.

8. **Producer's Maintenance Requirements:** Companies with products on this list will be expected to comply with the following to stay on the list:

8.1 Produce the same quality of material as the material supplied for the original evaluation.

8.2 Provide only approved products to Department projects.

8.3 Promptly report to the Department any changes in company name, product name, company address or company ownership.

8.4 Notify the Department of any changes in production of the product. Any alteration that will change the product physically will require a reevaluation of the product.

8.5 Provide technical assistance to the Department and/or contractor concerning the application and safety of the product. This assistance may include visits to the application site if required by the department.

9. **Laboratory Testing:** The Department shall make routine verification tests as stated in ALDOT 436.

9.2 Roadway Cores will be tested for rutting as tested by ALDOT 401.

10. **Field Testing:** The Department will require routine verification tests of the product to insure that the material works properly.

10.1 See ALDOT 436 for testing procedure.

10.2 The Roadway must meet visible inspection to insure against defects in pavement.

10.3 The Department may utilize an infrared camera to verify the roadway temperatures.

11 **Alternate Approval Process:** The National Center for Asphalt Technology in Auburn Alabama has developed a certification process. For information contact:

National Center for Asphalt Technology

277 Technology Parkway

Auburn, AL 36830

Phone: **Main:** 334.844.6857

Fax: 334.844.6853

Email: Comments or Questions:
Buzz Powell (buzz@auburn.edu)

12. **Contractors' Requirements:** The prime contractor will be responsible for purchasing and using only approved products.

13. **Removal of Products/Processes:** Products/Processes may be removed from this list for any of the following:

13.1 Mislabeling products or substitution of products other than those originally.

13.2 Failure to comply with any of the Department's requirements for this type of material.

13.3 Failure to work satisfactorily on the job.

14. **Correspondence:** All correspondence concerning this list should be directed to the following:
Product Evaluation Board
Alabama Department of Transportation
3704 Fairground Road
Montgomery, AL 36110

APPENDIX B
As-Built Test Section Properties

Table B1 As-Built Properties of Hot-Mix Control Section (E8)

Quadrant: E
Section: 8
Sublot: 1

Laboratory Diary

General Desccription of Mix and Materials

Design Method:	Super
Compactive Effort:	65 gyrations
Binder Performance Grade:	67-22
Modifier Type:	NA
Aggregate Type:	Granite
Design Gradation Type:	Fine

Avg. Lab Properties of Plant Produced Mix

Sieve Size	Design	QC
25 mm (1"):	100	100
19 mm (3/4"):	100	100
12.5 mm (1/2"):	100	100
9.5 mm (3/8"):	100	100
4.75 mm (#4):	67	72
2.36 mm (#8):	47	46
1.18 mm (#16):	35	35
0.60 mm (#30):	25	26
0.30 mm (#50):	17	18
0.15 mm (#100):	10	11
0.075 mm (#200):	5.9	6.1
Binder Content (Pb):	5.7	5.5
Eff. Binder Content (Pbe):	5.2	5.0
Dust-to-Binder Ratio:	1.1	1.2
Rice Gravity (Gmm):	2.431	2.447
Avg. Bulk Gravity (Gmb):	2.334	2.368
Avg Air Voids (Va):	4.0	3.2
Agg. Bulk Gravity (Gsb):	2.614	2.624
Avg VMA:	15.8	14.7
Avg. VFA:	75	78

Construction Diary

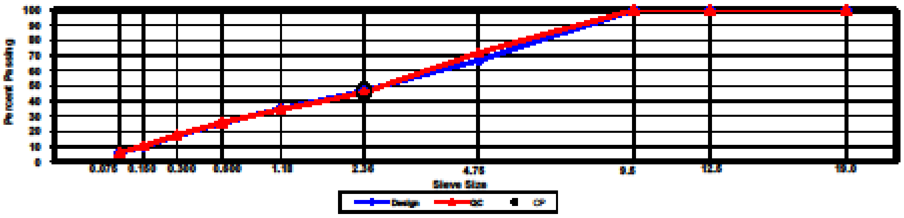
Relevant Conditions for Construction

Completion Date:	May 11, 2010
24 Hour High Temperature (F):	82
24 Hour Low Temperature (F):	59
24 Hour Rainfall (in):	0.00
Planned Subot Lift Thickness (in):	1.5
Paving Machine:	Blaw Knox

Plant Configuration and Placement Details

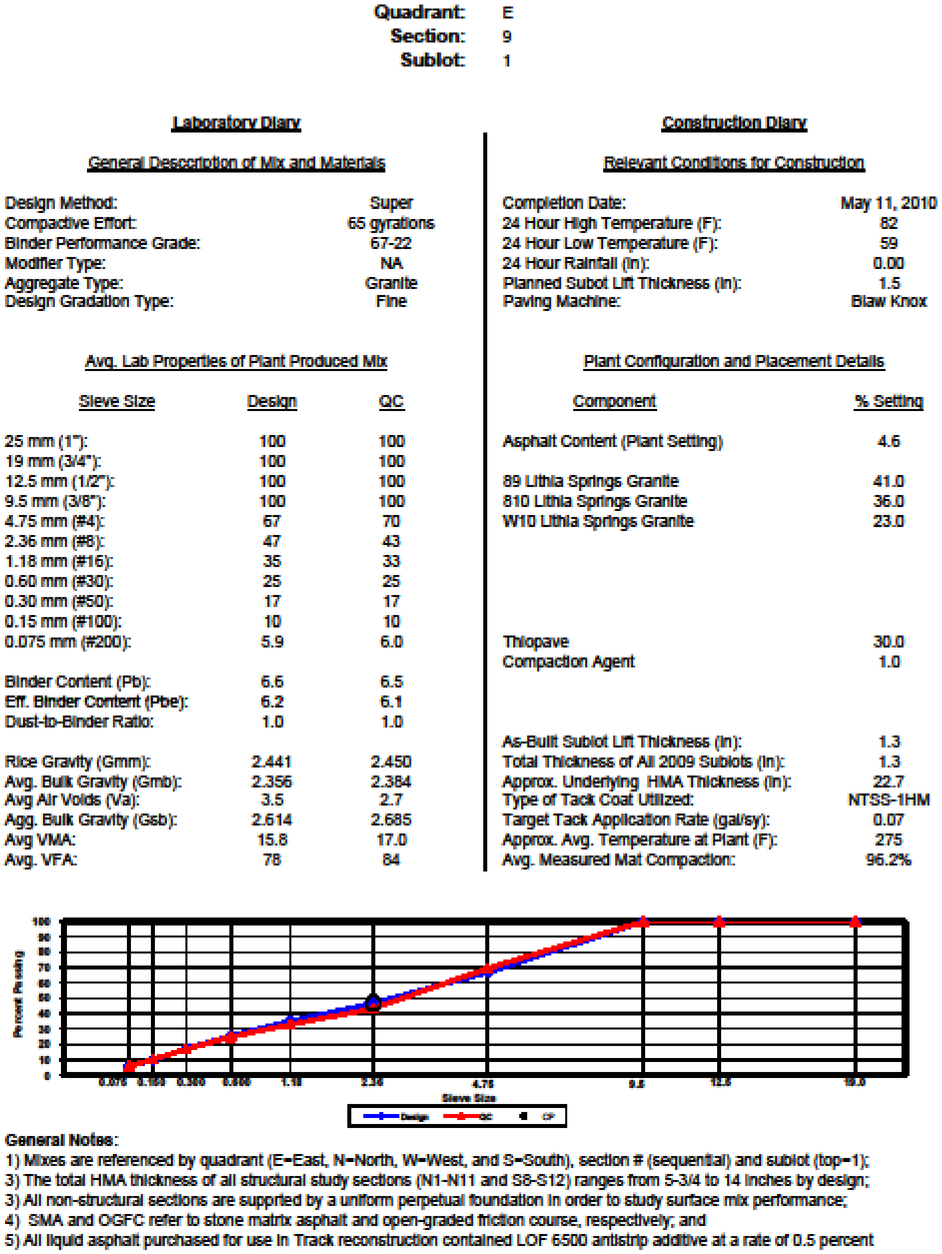
Component	% Setting
Asphalt Content (Plant Setting)	5.4
89 Lithia Springs Granite	41.0
810 Lithia Springs Granite	36.0
W10 Lithia Springs Granite	23.0

As-Built Sublot Lift Thickness (in):	1.5
Total Thickness of All 2009 Sublots (in):	1.5
Approx. Underlying HMA Thickness (in):	22.5
Type of Tack Coat Utilized:	NTSS-1HM
Target Tack Application Rate (gal/sy):	0.07
Approx. Avg. Temperature at Plant (F):	325
Avg. Measured Mat Compaction:	97.2%



General Notes:
1) Mixes are referenced by quadrant (E=East, N=North, W=West, and S=South), section # (sequential) and sublot (top=1);
3) The total HMA thickness of all structural study sections (N1-N11 and S8-S12) ranges from 5-3/4 to 14 inches by design;
3) All non-structural sections are suppried by a uniform perpetual foundation in order to study surface mix performance;
4) SMA and OGFC refer to stone matrix asphalt and open-graded friction course, respectively; and
5) All liquid asphalt purchased for use in Track reconstruction contained LOF 6500 antistrip additive at a rate of 0.5 percent

Table B2 As-Built Properties of WMA Test Section (E9)



Quadrant: E
Section: 9
Sublot: 1

Laboratory Diary

General Desccription of Mix and Materials

Design Method:	Super
Compactive Effort:	65 gyrations
Binder Performance Grade:	67-22
Modifier Type:	NA
Aggregate Type:	Granite
Design Gradation Type:	Fine

Avg. Lab Properties of Plant Produced Mix

Sieve Size	Design	QC
25 mm (1"):	100	100
19 mm (3/4"):	100	100
12.5 mm (1/2"):	100	100
9.5 mm (3/8"):	100	100
4.75 mm (#4):	67	70
2.36 mm (#8):	47	43
1.18 mm (#16):	35	33
0.60 mm (#30):	25	25
0.30 mm (#50):	17	17
0.15 mm (#100):	10	10
0.075 mm (#200):	5.9	6.0
Binder Content (Pb):	6.6	6.5
Eff. Binder Content (Pbe):	6.2	6.1
Dust-to-Binder Ratio:	1.0	1.0
Rice Gravity (Gmm):	2.441	2.450
Avg. Bulk Gravity (Gmb):	2.356	2.384
Avg Air Voids (Va):	3.5	2.7
Agg. Bulk Gravity (Gsb):	2.614	2.685
Avg VMA:	15.8	17.0
Avg. VFA:	78	84

Construction Diary

Relevant Conditions for Construction

Completion Date:	May 11, 2010
24 Hour High Temperature (F):	82
24 Hour Low Temperature (F):	59
24 Hour Rainfall (in):	0.00
Planned Subot Lift Thickness (in):	1.5
Paving Machine:	Blaw Knox

Plant Configuration and Placement Details

Component	% Setting
Asphalt Content (Plant Setting)	4.6
89 Lithia Springs Granite	41.0
810 Lithia Springs Granite	36.0
W10 Lithia Springs Granite	23.0
Thiopave	30.0
Compaction Agent	1.0
As-Built Sublot Lift Thickness (in):	1.3
Total Thickness of All 2009 Sublots (in):	1.3
Approx. Underlying HMA Thickness (in):	22.7
Type of Tack Coat Utilized:	NTSS-1HM
Target Tack Application Rate (gal/sy):	0.07
Approx. Avg. Temperature at Plant (F):	275
Avg. Measured Mat Compaction:	96.2%

General Notes:
1) Mixes are referenced by quadrant (E=East, N=North, W=West, and S=South), section # (sequential) and sublot (top=1);
3) The total HMA thickness of all structural study sections (N1-N11 and S8-S12) ranges from 5-3/4 to 14 inches by design;
3) All non-structural sections are suppried by a uniform perpetual foundation in order to study surface mix performance;
4) SMA and OGFC refer to stone matrix asphalt and open-graded friction course, respectively; and
5) All liquid asphalt purchased for use in Track reconstruction contained LOF 6500 antistrip additive at a rate of 0.5 percent

APPENDIX C
Laboratory Performance Testing Data

Table C1 Analyzed APA Data – Individual Samples

Mix ID	Sample ID	Sample Air Voids (%)	Manual Rut Depth (mm)	Automated Rut Depth (mm)
HMA	3	7.3	1.98	1.95
HMA	8	7.3	2.51	2.60
HMA	4	7.3	3.24	3.19
HMA	5	7.3	2.62	1.95
HMA	6	7.4	2.53	2.40
HMA	7	7.2	2.98	3.23
WMA	6	7.0	0.72	1.26
WMA	8	7.1	1.91	1.75
WMA	7	7.1	1.47	1.70
WMA	5	7.0	1.05	1.57
WMA	3	7.2	1.92	1.61
WMA	4	7.0	1.90	1.42

Table C2 Analyzed TSR Data – Individual Samples

Mix ID	Compaction Temp (F)	Freeze-Thaw Cycles	Sample ID	Va	Saturation (%)	Failure Load (lb)	Flow (0.01 in)	Splitting Tensile Strength (psi)
HMA	280	1	3	7.0	72.2	5175	15.0	149.6
HMA	280	1	4	6.9	71.5	5325	14.5	154.1
HMA	280	1	5	7.1	72.1	5175	15.0	149.7
HMA	280	0	6	6.9	N/A	5600	13.0	162.0
HMA	280	0	7	7.2	N/A	5510	13.0	159.5
HMA	280	0	8	7.1	N/A	5325	13.5	154.1
WMA	250	1	2	7.0	72.4	4300	11.0	124.3
WMA	250	1	3	7.0	72.7	4050	10.5	117.2
WMA	250	1	4	7.0	72.4	4150	12.0	120.0
WMA	250	0	6	7.0	N/A	4525	10.0	130.8
WMA	250	0	7	7.0	N/A	4400	11.0	127.3
WMA	250	0	8	7.0	N/A	4625	10.0	133.8

Table C3 Analyzed Hamburg Data – Individual Samples

Sample ID	Average Sample Air Voids (%)	Slope of Steady-State Rutting Curve	Rutting Rate (mm/hr)	Total Rut Depth (mm) (Based on Rate)	Stripping Inflection Point (cycles)
HMA #1	7.3	0.000255	0.643	2.550	10000*
HMA #2	7.4	0.000543	1.368	5.430	5600
HMA #4	6.7	0.000460	1.159	4.600	10000*
WMA #1	7.3	0.000430	1.084	4.300	5900
WMA #2	7.5	0.000500	1.260	5.000	6200
WMA #3	7.3	0.000407	1.025	4.067	7000
Aged HMA #1	7.4	0.000290	0.731	2.900	10000*
Aged HMA #3	7.4	0.000373	0.940	3.730	7000
Aged HMA #4	7.3	0.000238	0.599	2.375	10000*
Aged WMA #2	7.3	0.000220	0.554	2.200	10000*
Aged WMA #3	7.5	0.000338	0.851	3.375	10000*
Aged WMA #4	7.2	0.000170	0.428	1.700	10000*

* = Indicates no visible stripping inflection point after 10,000 testing cycles

Table C4 Overlay Tester Individual Sample Results

Sample ID	Sample Air Voids (%)	Peak Load (lb)	Cycles to Failure
HMA-6	7.2	738.2	163
HMA-7	6.5	898.6	127
HMA-9	6.9	676.0	114
WMA-8	6.8	820.2	7
WMA-9	6.6	817.2	3
WMA-10	7.3	726.2	5

Table C5 Dynamic Modulus Master Curve Coefficients (AASHTO TP 61-09)

Mix ID	Confinement (psi)	Max E* (Ksi)	Delta	Beta	Gamma	ΔE_A	R^2	S_e/S_y
HMA	20	3155.11	56.63	-0.209	-0.572	176869.7	0.998	0.032
WMA	20	3110.75	74.63	-0.400	-0.553	179504.0	0.998	0.035

Table C6 Raw Dynamic Modulus Test Data

Mix ID	Sample ID	Sample Air Voids (%)	Temperature (◦C)	Frequency (Hz)	Dynamic Modulus (ksi)	Phase Angle (deg)
WMA	9	7.1	4	10	1868.4	10.79
WMA	9	7.1	4	1	1401.9	13.38
WMA	9	7.1	4	0.1	996.8	16.69
WMA	9	7.1	20	10	981.8	18.35
WMA	9	7.1	20	1	629.3	22.09
WMA	9	7.1	20	0.1	385.5	24.91
WMA	9	7.1	40	10	518.9	24.60
WMA	9	7.1	40	1	303.1	25.24
WMA	9	7.1	40	0.1	188.4	24.06
WMA	9	7.1	40	0.01	125.4	20.89
WMA	10	7.4	4	10	2079.0	10.31
WMA	10	7.4	4	1	1560.8	12.97
WMA	10	7.4	4	0.1	1112.0	16.31
WMA	10	7.4	20	10	1080.1	17.96
WMA	10	7.4	20	1	688.1	21.68
WMA	10	7.4	20	0.1	415.4	24.75
WMA	10	7.4	40	10	366.2	26.24
WMA	10	7.4	40	1	219.4	23.80
WMA	10	7.4	40	0.1	152.6	21.10
WMA	10	7.4	40	0.01	122.8	17.58
WMA	11	7.3	4	10	2090.6	10.41
WMA	11	7.3	4	1	1559.9	12.95
WMA	11	7.3	4	0.1	1112.4	16.35
WMA	11	7.3	20	10	1102.7	17.56
WMA	11	7.3	20	1	706.9	21.12
WMA	11	7.3	20	0.1	433.2	24.08
WMA	11	7.3	40	10	390.9	25.38
WMA	11	7.3	40	1	234.1	23.45
WMA	11	7.3	40	0.1	160.1	21.13
WMA	11	7.3	40	0.01	125.3	18.36
HMA	10	7	4	10	1611.5	12.62
HMA	10	7	4	1	1142.9	16.15
HMA	10	7	4	0.1	758.7	20.41
HMA	10	7	20	10	825.0	20.73
HMA	10	7	20	1	488.5	24.75
HMA	10	7	20	0.1	269.6	27.59
HMA	10	7	40	10	284.6	27.17

Mix ID	**Sample ID**	**Sample Air Voids (%)**	**Temperature (◦C)**	**Frequency (Hz)**	**Dynamic Modulus (ksi)**	**Phase Angle (deg)**
HMA	10	7	40	1	163.2	24.03
HMA	10	7	40	0.1	106.6	21.50
HMA	10	7	40	0.01	81.3	17.29
HMA	11	7.2	4	10	1889.1	12.32
HMA	11	7.2	4	1	1344.8	15.60
HMA	11	7.2	4	0.1	892.4	19.76
HMA	11	7.2	20	10	867.0	20.92
HMA	11	7.2	20	1	508.5	24.63
HMA	11	7.2	20	0.1	274.4	27.53
HMA	11	7.2	40	10	313.3	26.89
HMA	11	7.2	40	1	180.7	24.20
HMA	11	7.2	40	0.1	117.2	21.90
HMA	11	7.2	40	0.01	87.0	17.75
HMA	12	7	4	10	1893.5	11.82
HMA	12	7	4	1	1366.1	15.02
HMA	12	7	4	0.1	917.9	19.02
HMA	12	7	20	10	901.8	20.15
HMA	12	7	20	1	541.3	23.97
HMA	12	7	20	0.1	306.2	26.80
HMA	12	7	40	10	311.7	25.73
HMA	12	7	40	1	184.8	22.59
HMA	12	7	40	0.1	125.4	19.72
HMA	12	7	40	0.01	96.9	15.43

Table C7 Calculated Creep Compliance and Indirect Tensile Strength (IDT Test)

Test Temperature (deg C)	**Loading Time (sec)**	**Creep Compliance (1/GPa)**	
		WMA	**HMA**
-20	1	0.04	0.04
-20	2	0.042	0.042
-20	5	0.044	0.045
-20	10	0.047	0.048
-20	20	0.049	0.051
-20	50	0.054	0.057
-20	100	0.058	0.063
-10	1	0.054	0.056
-10	2	0.059	0.06
-10	5	0.065	0.068
-10	10	0.071	0.076
-10	20	0.079	0.085
-10	50	0.092	0.1
-10	100	0.107	0.115
0	1	0.077	0.084
0	2	0.085	0.098
0	5	0.099	0.12
0	10	0.115	0.138
0	20	0.134	0.166
0	50	0.169	0.215
0	100	0.206	0.267
Indirect Tensile Strength at -10◦C (MPa)		**WMA**	**HMA**
		4.47	4.46

Table C8 Maxwell Elements and Shift Factors for Critical Temperature Analysis

<table>
<tr><th colspan="5">Maxwell Elements for Critical Temperature Analysis</th></tr>
<tr><th rowspan="2">Index, i</th><th colspan="2">WMA</th><th colspan="2">HMA</th></tr>
<tr><th>λ_i (sec)</th><th>E_i (MPa)</th><th>λ_i (sec)</th><th>E_i (MPa)</th></tr>
<tr><td>1</td><td>8.054</td><td>4.541*10^3</td><td>7.701</td><td>5.077*10^3</td></tr>
<tr><td>2</td><td>76.899</td><td>4.081*10^3</td><td>67.026</td><td>5.413*10^3</td></tr>
<tr><td>3</td><td>703.916</td><td>4.215*10^3</td><td>660.176</td><td>3.757*10^3</td></tr>
<tr><td>4</td><td>5.591*10^3</td><td>4.819*10^3</td><td>4.519*10^3</td><td>5.067*10^3</td></tr>
<tr><td>5</td><td>1.414*10^5</td><td>7.508*10^3</td><td>1.156*10^5</td><td>5.941*10^3</td></tr>
<tr><th colspan="5">Shift Factors for Creep Compliance Master Curve (1/◦C)</th></tr>
<tr><th>Temp (◦C)</th><th colspan="2">WMA</th><th colspan="2">HMA</th></tr>
<tr><td>-20</td><td colspan="2">1</td><td colspan="2">1</td></tr>
<tr><td>-10</td><td colspan="2">56.23</td><td colspan="2">35.48</td></tr>
<tr><td>0</td><td colspan="2">891.25</td><td colspan="2">794.330</td></tr>
</table>

Table C9 Individual Flow Number Test Results

Mix ID	Sample ID	Sample Air Voids (%)	Accumulated Microstrain – On-Specimen	Francken Flow Number	Microstrain at Flow (Francken)
WMA	6	7.3	70390	N/A	N/A
WMA	7	6.9	62648	N/A	N/A
WMA	8	7.3	72277	N/A	N/A
HMA	7	7.2	58689	N/A	N/A
HMA	8	7.3	62697	N/A	N/A
HMA	9	7	59451	N/A	N/A
WMA	5	3.8	103168	301	16529
WMA	12	3.8	101382	339	12960
WMA	13	3.8	104675	317	14668
HMA	13	3.9	100177	321	16306
HMA	14	3.9	100860	1031	16447
HMA	15	3.9	101036	1468	19506

Table C10 Individual Bond Strength Results – Field Cores

Mix ID	Core ID	Upper Lift Thickness (in)	Lower Lift Thickness (in)	Diameter (in)	Area (in^2)	Failure Load (lbf)	Bond Strength (psi)
HMA	1	1.48	2.10	5.93	27.60	6800	246.38
HMA	2	1.65	2.19	5.92	27.52	7900	287.10
HMA	3	1.66	2.27	5.92	27.53	5200	188.92
WMA	1	1.61	2.40	5.92	27.48	9150	332.98
WMA	2	1.49	2.42	5.90	27.35	7800	285.20
WMA	3	1.51	2.37	5.89	27.27	7650	280.48

APPENDIX D

Test Section Raw Performance Data

Table D1 ARAN Rutting Data – Test Track

Date of Data Collection	Applied ESALs	HMA ARAN Rutting (mm)	WMA ARAN Rutting (mm)
5/11/2010	0	0.00	0.00
6/7/2010	354,854	1.19	1.44
7/12/2010	842,003	2.07	3.47
7/26/2010	1,083,585	3.26	4.45
9/13/2010	1,687,238	4.91	6.56
10/11/2010	2,089,168	5.93	7.62
11/29/2010	2,688,948	4.15	5.88
2/21/2011	3,636,631	3.98	5.80
3/19/2011	4,099,363	4.57	6.22
4/25/2011	4,679,741	4.40	6.27

Table D2 Raw Rougness (IRI) Data – Test Track

Date of Data Collection	Applied ESALs	HMA Roughness (IRI)	WMA Roughness (IRI)
5/12/2010	0		
5/17/2010	74,763	53.91	61.51
5/24/2010	172,022		
5/31/2010	250,143		
6/14/2010	466,148	55.33	63.82
6/21/2010	564,840		
7/6/2010	759,189	71.40	72.09
7/12/2010	849,267	76.15	71.28
7/19/2010	986,829	73.61	70.96
7/26/2010	1,088,103	82.06	79.44
8/2/2010	1,148,253	93.51	82.61
8/10/2010	1,260,949	91.35	83.30
8/16/2010	1,361,624		
8/18/2010	1,361,624		
8/23/2010	1,432,247	90.02	87.77
8/30/2010	1,532,143	92.48	95.81
9/7/2010	1,611,209	99.12	82.63
9/13/2010	1,691,217	100.08	90.35
9/20/2010	1,790,215	90.90	84.28
9/27/2010	1,895,954	97.06	97.49
10/4/2010	1,995,520	88.62	81.90
10/9/2010	2,095,156	90.35	86.35

Date of Data Collection	Applied ESALs	HMA Roughness (IRI)	WMA Roughness (IRI)
10/16/2010	2,195,048	81.58	89.84
10/23/2010	2,295,099	87.35	97.58
10/30/2010	2,369,622	94.85	97.88
11/15/2010	2,558,286	90.27	72.08
11/29/2010	2,697,736	94.15	85.60
12/6/2010	2,803,895	101.64	87.68
12/13/2010	2,873,704	93.10	88.60
12/30/2010	2,923,567	87.85	97.37
2/14/2011	3,542,852	91.78	97.73
2/21/2011	3,637,486	93.83	91.76
2/28/2011	3,772,277	99.34	92.51
3/5/2011	3,867,894	97.63	87.42
3/12/2011	3,963,607	99.36	92.80
3/19/2011	4,100,274	91.22	90.10
3/26/2011	4,196,935	98.13	97.30
4/4/2011	4,293,688		
4/11/2011	4,390,062	102.63	91.49
4/18/2011	4,561,577	96.59	88.51
4/25/2011	4,679,741	102.05	97.95
5/2/2011	4,795,967	96.07	94.91
5/9/2011	4,905,708	100.68	95.52
5/16/2011	5,012,475	90.62	92.81

Table D3 Raw Macrotexture Data – Test Track

Date of Data Collection	Applied ESALs	HMA Macrotexture (mm)	WMA Macrotexture (mm)
5/12/2010	0		
5/17/2010	74,763	0.34	0.45
5/24/2010	172,022		
5/31/2010	250,143		
6/14/2010	466,148	0.38	0.56
6/21/2010	564,840		
7/6/2010	759,189	0.32	0.40
7/12/2010	849,267	0.30	0.38
7/19/2010	986,829	0.28	0.32
7/26/2010	1,088,103	0.30	0.36
8/2/2010	1,148,253	0.29	0.36
8/10/2010	1,260,949	0.31	0.37
8/16/2010	1,361,624		

Date of Data Collection	Applied ESALs	HMA Macrotexture (mm)	WMA Macrotexture (mm)
8/18/2010	1,361,624		
8/23/2010	1,432,247	0.30	0.38
8/30/2010	1,532,143	0.29	0.34
9/7/2010	1,611,209	0.28	0.36
9/13/2010	1,691,217	0.26	0.30
9/20/2010	1,790,215	0.28	0.32
9/27/2010	1,895,954	0.26	0.26
10/4/2010	1,995,520	0.25	0.28
10/9/2010	2,095,156	0.28	0.29
10/16/2010	2,195,048	0.26	0.25
10/23/2010	2,295,099	0.28	0.30
10/30/2010	2,369,622	0.27	0.25
11/15/2010	2,558,286		
11/29/2010	2,697,736	0.27	0.24
12/6/2010	2,803,895	0.27	0.23
12/13/2010	2,873,704	0.26	0.24
12/30/2010	2,923,567	0.26	0.22
2/14/2011	3,542,852	0.29	0.27
2/21/2011	3,637,486	0.30	0.30
2/28/2011	3,772,277	0.31	0.31
3/5/2011	3,867,894	0.30	0.30
3/12/2011	3,963,607	0.29	0.27
3/19/2011	4,100,274	0.29	0.29
3/26/2011	4,196,935	0.34	0.34
4/4/2011	4,293,688		
4/11/2011	4,390,062	0.30	0.30
4/18/2011	4,561,577	0.32	0.29
4/25/2011	4,679,741	0.32	0.35
5/2/2011	4,795,967	0.30	0.30
5/9/2011	4,905,708	0.31	0.32
5/16/2011	5,012,475	0.29	0.30