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

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ABSTRACT

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) 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.

In this program, each candidate WMA technology is utilized to produce a mixture with aggregates that have exhibited a high potential for stripping and paved as a surface lift on the NCAT Pavement Test Track. These test cells are supported by a robust perpetual foundation to ensure that any observed distresses are not caused or impacted by structural inadequacies. Trucking operations at the Track are used to compress half of a design lifetime of pavement damage (five million equivalent single axle loadings (ESAL)) into one accelerated performance year. Performance on the Track (measured in terms of rutting, roughness, raveling, cracking, etc.) is evaluated weekly in order to document all changes in pavement condition with increasing time and traffic. 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 priorities indicated by states’ responses in the national survey.

Measured data from WMA test sections is compared to that of an HMA control section placed at the same time using the same moisture susceptible aggregate blend. Based on this comparison, NCAT will certify 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 was produced along with a control HMA and paved as two adjacent test sections at the NCAT Pavement Test Track in May of 2010. Track performance data and the measured laboratory mixture results of this candidate WMA technology are discussed and compared to the control HMA.

Keywords: Accelerated Performance Testing, Laboratory Performance Testing, Mix Design, Production and Construction Processes, Sulfur-Modified Mixtures

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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.

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
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, eleven states have agreed to use the findings from the NCAT national WMA Certification Program to approve technologies. A sample commitment letter and specification package 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 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.

The mix design chosen for the certification program is a 9.5 mm (3/8 inch) 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, GA was used as the
virgin aggregate because it is known to have issues with moisture susceptibility. 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.

TABLE 1 Mix Design Consensus Properties

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

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

WMA CERTIFICATION TECHNOLOGY

Early attempts at utilizing sulfur as a binder replacement option in the 1970’s consisted of adding molten liquid sulfur directly to the asphalt binder, which caused unacceptable levels of hydrogen sulfide (H₂S) to be emitted during production and construction (Strickland et al., 2008). To address the environmental concerns associated with H₂O emissions, Shell Sulfur Solutions has developed a pelletized sulfur formulation called Thiopave© (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, hydrogen sulfide 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 et al., 2011). As a result of this positive experience with construction and performance, Shell Sulfur Solutions elected to participate in NCAT’s national WMA Certification Program.
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 are provided in TABLES 2 and 3. Similar construction quality was noted for both mixes. No coating, tenderness, or compaction issues were encountered.
TABLE 2 As-Built Properties of Hot-Mix Control Section E8

| Quadrant: | E |
| Section:  | 8 |
| Sublot:   | 1 |

**Laboratory Diary**

**General Description of Mix and Materials**

<table>
<thead>
<tr>
<th>Design Method:</th>
<th>Super</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compactive Effort:</td>
<td>65 gyrations</td>
</tr>
<tr>
<td>Binder Performance Grade:</td>
<td>67-22</td>
</tr>
<tr>
<td>Modifier Type:</td>
<td>NA</td>
</tr>
<tr>
<td>Aggregate Type:</td>
<td>Granite</td>
</tr>
<tr>
<td>Design Gradation Type:</td>
<td>Fine</td>
</tr>
</tbody>
</table>

**Construction Diary**

**Relevant Conditions for Construction**

<table>
<thead>
<tr>
<th>Completion Date:</th>
<th>May 11, 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 Hour High Temperature (F):</td>
<td>82</td>
</tr>
<tr>
<td>24 Hour Low Temperature (F):</td>
<td>59</td>
</tr>
<tr>
<td>24 Hour Rainfall (in):</td>
<td>0.00</td>
</tr>
<tr>
<td>Planned Sublot Lift Thickness (in):</td>
<td>1.5</td>
</tr>
<tr>
<td>Paving Machine:</td>
<td>Blaw Knox</td>
</tr>
</tbody>
</table>

**Avg. Lab Properties of Plant Produced Mix**

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Design</th>
<th>QC</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 mm (1&quot;):</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>19 mm (3/4&quot;):</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>12.5 mm (1/2&quot;):</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>9.5 mm (3/8&quot;):</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>4.75 mm (#4):</td>
<td>67</td>
<td>72</td>
</tr>
<tr>
<td>2.36 mm (#8):</td>
<td>47</td>
<td>46</td>
</tr>
<tr>
<td>1.18 mm (#16):</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>0.60 mm (#30):</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>0.30 mm (#50):</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>0.15 mm (#100):</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>0.075 mm (#200):</td>
<td>5.9</td>
<td>6.1</td>
</tr>
</tbody>
</table>

| Binder Content (Pb): | 5.7 | 5.5 |
| Eff. Binder Content (Peb): | 5.2 | 5.0 |
| Dust-In-Binder Ratio: | 1.1 | 1.2 |

| Rice Gravity (Cmm): | 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 | 79 |

**Plant Configuration and Placement Details**

<table>
<thead>
<tr>
<th>Component</th>
<th>% Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt Content (Plant Setting):</td>
<td>5.4</td>
</tr>
<tr>
<td>80 Lithia Springs Granite:</td>
<td>40.0</td>
</tr>
<tr>
<td>810 Lithia Springs Granite:</td>
<td>36.0</td>
</tr>
<tr>
<td>W10 Lithia Springs Granite:</td>
<td>23.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>% Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-Built Sublot Lift Thickness (in):</td>
<td>1.5</td>
</tr>
<tr>
<td>Total Thickness of All 3000 Sublots (in):</td>
<td>1.5</td>
</tr>
<tr>
<td>Approx. Underlying HMA Thickness (in):</td>
<td>22.5</td>
</tr>
<tr>
<td>Type of Tack Coat Utilized:</td>
<td>NTSS-HHM</td>
</tr>
<tr>
<td>Target Tack Application Rate (gal/yd²):</td>
<td>0.07</td>
</tr>
<tr>
<td>Approx. Avg. Temperature at Plant (F):</td>
<td>325</td>
</tr>
<tr>
<td>Avg. Measured Mat Compaction:</td>
<td>97.2%</td>
</tr>
</tbody>
</table>

**General Notes:**

1) Mixes are referenced by quadrant (E=East, N=North, W=West, and S=South), section # (sequential) and sublot (top=1);
2) The total HMA thickness of all structural study sections (H1-H11 and 58-612) ranges from 3.34 to 14 inches by design;
3) All non-structural sections are supplied by a uniform perpetual foundation in order to study surface mix performance;
4) SMA and OGFCC refer to store 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 3 As-Built Properties of WMA Test Section E9

<table>
<thead>
<tr>
<th>Quadrant:</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section:</td>
<td>9</td>
</tr>
<tr>
<td>Sublot:</td>
<td>1</td>
</tr>
</tbody>
</table>

#### Laboratory Diary

**General Description 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

#### Construction Diary

**Relevant Conditions for Construction**

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

#### Avg. Lab Properties of Plant Produced Mix

<table>
<thead>
<tr>
<th>Slab Size</th>
<th>Design</th>
<th>QC</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 mm (1&quot;)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>19 mm (3/4&quot;)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>12.5 mm (1/2&quot;)</td>
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<tr>
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<td>67</td>
<td>70</td>
</tr>
<tr>
<td>2.36 mm (#8)</td>
<td>47</td>
<td>43</td>
</tr>
<tr>
<td>1.18 mm (#16)</td>
<td>35</td>
<td>33</td>
</tr>
<tr>
<td>0.60 mm (#30)</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>0.30 mm (#60)</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>0.15 mm (#100)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>0.075 mm (#200)</td>
<td>5.9</td>
<td>6.0</td>
</tr>
</tbody>
</table>

- **Binder Content (Pb):** 6.5
- **Eff. Binder Content (Pee):** 6.2
- **Dust-to-Binder Ratio:** 1.0
- **Bulk Gravity (Gmm):** 2.441
- **Avg. Bulk Gravity (Gmb):** 2.356
- **Avg. Voids (V):** 3.5
- **Avg. Voids in Gso:** 2.614
- **Avg. VMA:** 15.8
- **Avg. VFA:** 78

#### Plant Configuration and Placement Details

- **As-Built Sublot Lift Thickness (in):** 1.3
- **Total Thickness of All 300G Sublots (in):** 1.3
- **Approx. Underlying HMA Thickness (in):** 22.7
- **Type of Tack Coat Utilized:** NT35-H1M
- **Target tack Application Rate (gal/sq yd):** 0.07
- **Approx. Avg. Temperature at Pave (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);  
2. The total HMA thickness of all structural study sections (H1-N11 and H8-H31) ranges from 5.3 to 14 inches by design;  
3. All non-structural sections are supported by a uniform perpetual foundation in order to study surface mix performance;  
4. SMA and OGFRC 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

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### LABORATORY PERFORMANCE

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. A summary of the laboratory testing plan is provided as TABLE 4.
TABLE 4 Laboratory Testing Plan for Plant Produced Mix

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

Asphalt Pavement Analyzer
The rutting susceptibility 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 high PG grade of the binder. 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 samples 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 results show that the WMA rutted about 1.0 mm (0.04 inches) less than the HMA; however, both mixes should have good resistance to rutting 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 et al., 2009).

FIGURE 8 APA Test Results
Tensile Strength Ratios

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 (3.8 inch) samples compacted in a Superpave Gyratory Compactor, with a target air void level of 7.0 ± 0.5%. One freeze-thaw cycle was used on the conditioned subset of samples. In accordance with AASHTO R35-09, the minimum TSR criterion is 0.8 for moisture-resistant mixes. The results of the TSR testing are summarized in FIGURE 9. These data show that both the WMA and HMA had acceptable resistance to moisture damage, with TSR values above 0.8 for each mixture. 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.

FIGURE 9 TSR Test Results

Hamburg

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 hrs 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 steady-state rut depth at 10,000 cycles (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 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 a steady-state rutting value of less than 10 mm (0.4 inches) has been used to indicate a deformation resistant mix (Kvasnak et al., 2010).

As seen in FIGURE 10, 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 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 sample aging. Additional sample aging appeared to increase the moisture resistance of the WMA in the Hamburg test.
Boil Test
The boil test was performed in accordance with TEX 530-C. For this test, a 200 gram (7 ounce) sample of asphalt is placed in a stainless steel beaker filled with 1000 mL (1 quart) of distilled water. The beaker is placed over an oil bath so that the water is boiling. The sample of asphalt is added to the beaker with boiling water, and then removed after 10 minutes. 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 11. No evidence of stripping was seen in either sample, and no appreciable mass loss was determined from this test in either sample. The results of this test are in agreement with the TSR and Hamburg results.

TABLE 5 Boil Test Results

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Mass Loss After Testing (%)</th>
<th>Visual Evidence of Stripping</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMA</td>
<td>0.05</td>
<td>None</td>
</tr>
<tr>
<td>WMA</td>
<td>0.2</td>
<td>None</td>
</tr>
</tbody>
</table>

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. This is because the specific gravities of the sulfur (specific gravity approximately 1.92) and the virgin binder (specific gravity approximately 1.03) are
appreciably different, and the materials have a tendency to separate during the binder recovery process. Therefore, prepared samples for the DSR and 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 to the HMA.

Overlay Tester

Both mixes were tested in the overlay tester in accordance with Tex 248-F. The overlay tester was originally designed to test the susceptibility of an asphalt mixture to reflective cracking that had been placed over a jointed concrete pavement. Three replicates of each mixture were tested with a target air void content of 7 ± 0.5 percent. Other research has indicated 700 cycles to failure being a good benchmark for a mixture that is resistant to fatigue cracking in the overlay tester (Chen, 2008).

The results of this testing is shown in FIGURE 12. It can be seen that the HMA had significantly longer fatigue life than the WMA in the overlay tester. This behavior was not unexpected given the more brittle nature of sulfur-modified materials. 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 indicates a disconnect between the laboratory test results and the field performance for this particular test. For future WMA certification projects, adjustments may be made to the relatively high strain Tex 248-F procedure so the results are more indicative of field performance.

Dynamic Modulus

Dynamic Modulus testing was performed for both mixes using an IPC Global Asphalt Mixture Performance Tester (AMPT) device. 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. These mastercurves are shown in FIGURE 13. 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 equivalent stiffness. However, as the temperatures increase and frequency of loading is reduced (left-hand side of the curve) the WMA appears stiffer than the HMA. These results were expected given previous experience with the sulfur-modified material (Timm et al., 2009).
Critical Cracking Temperature Analysis
For each mix, indirect tensile testing (IDT) was performed in accordance with AASHTO T322-07. Three replicates of each mix were prepared to 7 ± 0.5 percent air voids for this testing. The testing was performed using an MTS load frame and environmental chamber to determine the creep compliance at 0, -10, and -20°C as well as the splitting tensile strength at -10°C (32, 14, -4, and 14°F, respectively). This data was used to perform a critical temperature analysis. The critical temperature analysis determines the temperature at which the thermally developed tensile stresses in the asphalt mixture exceed the measured splitting tensile strength. This critical temperature indicates the lowest temperature a mix can withstand without undergoing thermal cracking. For this analysis, the creep compliance mastercurves were generated using an automated procedure developed under the SHRP program (Buttlar et al., 1998). The thermal stress analysis was performed in a MATHCAD program developed by Dr. Jaeseung Kim. A full description of the thermal stress development analysis is documented elsewhere (Hiltunen and Roque, 1994) (Kim et al., 2008). 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), which indicates the WMA is slightly more susceptible to thermal cracking.

Flow Number Testing
Flow number testing was performed for both mixes using an IPC Global AMPT device. Three replicates of each mix were tested. Samples were prepared in accordance with AASHTO PP 60-09, and tested in accordance with AASHTO PP79-09. Testing temperature for all samples was 59.5°C (139°F, which is the LTPPBind v3.1 50% Reliability high pavement temperature for the Auburn-Opelika 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 with 689 kPa (100 psi) deviatoric stress and 69 kPa (10 psi) confinement. Samples for this testing were prepared to 7 ± 0.5 percent air voids. Due to the confinement, these mixes did not exhibit tertiary flow. Therefore, mix to mix comparisons were made using the level of sample deformation at 20,000 cycles. The second set of testing parameters was with 600 kPa (87 psi) deviatoric stress and 0kPa (0 psi) confinement. Samples for this testing were prepared to 4 ± 0.5 percent air voids. Tertiary flow for these samples was determined using the Francken Model.

The results of the Flow Number testing are shown in FIGURE 14. 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 much 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).

**FIGURE 14 Flow Number Test Results**

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 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 15.

**FIGURE 15 Photo of Bond Strength Testing in Progress**
The results of the bond strength testing are shown in TABLE 6. The data shows the WMA has a higher interface bond strength than the HMA; however, the difference was not statistically significant (ANOVA $\alpha = 0.05$, 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 (http://www.eng.auburn.edu/research/centers/ncat/newsroom/bond-strength-testing.html).

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Average Bond Strength (psi)</th>
<th>Standard Deviation of Bond Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMA</td>
<td>240.8</td>
<td>49.4</td>
</tr>
<tr>
<td>WMA</td>
<td>299.6</td>
<td>29.1</td>
</tr>
</tbody>
</table>

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 by use of an 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.

Accelerated Loading

Test sections on the NCAT Pavement Test Track are loaded with heavy triple trailer trains (shown in FIGURE 16) 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 of 2010 and May of 2011. Trucking was initiated on both the HMA control and WMA test mixes as soon as construction was completed.

FIGURE 16 Application of Accelerated Damage on the NCAT Pavement Test Track
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 over time. 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 17. These data reveal a steady increase in rut depth from the time the pavements were constructed in May of 2010 until October of 2010 when pavement service 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 of 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 17 Rutting Performance Comparison

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 18, slightly more change in roughness was 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 19), changes in roughness for the two sections were similar.
FIGURE 18 Roughness Performance Comparison

![Roughness Performance Comparison Graph](image1)

FIGURE 19 Rich Spot Near End of HMA Control Section

![Rich Spot Near End of HMA Control Section](image2)
Macrotexture Performance
The ARAN van also measures pavement macrotexture using a laser which samples data at a relatively 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 20. These data do not indicate significant differences between the HMA control section and the WMA certification section.

FIGURE 20 Macrotexture Performance Comparison

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 21, and a picture of the cracking observed in the HMA control section is included as FIGURE 22.
FIGURE 21 Cracking in Control HMA (Top) and Certification WMA (Bottom) Test Sections

FIGURE 22 Cracking Observed in the Control HMA Test Section
CONCLUSIONS AND RECOMMENDATIONS
The following conclusions can be made based on the results of this study comparing mix produced using Thiopave WMA technology to 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. The opposite trend was observed in the laboratory;

3) Roughness increased more in the HMA control section that it did in the WMA certification section;

4) 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;

5) The HMA control section exhibited minor longitudinal cracking after approximately 2.9 million ESALs. No cracking was observed in the WMA certification section;

6) Although brittleness and crack susceptibility testing 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; and

7) Based on a comprehensive assessment of construction, laboratory performance, and field performance, acceptance of Thiopave as an alternative WMA technology in the manner in which it was used at the NCAT Pavement Test Track is recommended.
ACKNOWLEDGEMENT
The Pavement Test Track is managed by NCAT, who is responsible for daily operations and the completion of associated research. Funding for the NCAT track is provided under a cooperative agreement by the following entities:

- Alabama Department of Transportation
- Florida Department of Transportation
- Georgia Department of Transportation
- Mississippi Department of Transportation
- Missouri Department of Transportation
- North Carolina Department of Transportation
- Oklahoma Department of Transportation
- South Carolina Department of Transportation
- Tennessee Department of Transportation
- Federal Highway Administration
- Kraton Polymers
- Old Castle Materials
- Polycon
- Shell Sulfur Solutions
- Lake Asphalt of Trinidad and Tobago

The authors are solely responsible for the contents of this paper, and the views expressed do not necessarily reflect the views of the researchers or the research sponsors.
REFERENCES


APPENDIX A Sample Commitment Letter and Specification Package for the WMA Certification Program
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.
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
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.
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.
• 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 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.
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