Title: Influence of Initial Aggregate Moisture Content and Production Temperature on Mixture Performance of Plant Produced Warm Mix Asphalt

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ABSTRACT

Although moisture damage potential is also possible in some hot mix asphalt (HMA) mixtures, due to its method of production, it may be more likely in WMA. Inadequately dried aggregates at lower production temperatures, and even the possible introduction of additional moisture to the WMA from the various WMA foaming technologies, may affect the binder to aggregate adhesion, moisture susceptibility and general mixture performance. Preliminary laboratory testing has shown that when producing warm mix asphalt (WMA), both the initial aggregate moisture content and mixing temperature can have a dramatic impact on the performance of the mixtures, especially with respect to the resistance to moisture damage. Unfortunately, it is often difficult to control these parameters outside the laboratory setting.

A research effort was conducted using plant produced hot mix and warm mix asphalt to evaluate their respective moisture damage sensitivity and rutting potential. Two different initial aggregate moisture contents (< 1.5% and >3.0%) were achieved by the use of covered stockpiles. Five different mixtures were produced at both moisture contents; 1) HMA (control), 2) WMA Foaming System, 3) WMA Foaming + Anti-Strip #1; 4) WMA Foaming + Anti-Strip #2, and 5) WMA Surfactant additive. Laboratory performance samples were sampled and compacted at the asphalt plant’s QC laboratory after similar conditioning periods. The paper presents the results of the moisture damage tests (Tensile Strength Ratio, Hamburg Wheel Tracking), permanent deformation (AMTP Flow Number and Asphalt Pavilion Analyzer), Dynamic Modulus and fatigue cracking via the Overlay Tester. The results of the study will hope to shed light on the potential for moisture damage with WMA and the possible benefit of anti-strip additives for WMA production.

BACKGROUND

The term warm mix asphalt (WMA) refers to technologies and systems that allow for the substantial reduction in production and compaction temperatures of hot mix asphalt. The original intent of utilizing WMA was to provide better workability and compaction of asphalt mixtures. In turn, a better compacted asphalt pavement should also enhance its general performance. It is well known that asphalt pavements compacted to better densities often have superior fatigue and rutting performance. A thorough analysis of this can be found in detail in NCHRP Report 567, Volumetric Requirements for Superpave Mix Design (Christensen and Bonaquist, 2006).

The implementation and use of WMA may create potential issues as well. The reduced oxidative aging of the asphalt binder during production may increase the asphalt’s susceptibility to rutting. However, mixture design/selection strategies, such as increasing the high temperature asphalt binder grade or selecting rut resistant mixtures like stone matrix asphalt, can commonly address these issues.

Another issue that will need to be addressed is the potential for moisture damage. Although moisture damage potential is also possible in some hot mix asphalt (HMA) mixtures, due to its method of production, it may be more likely in WMA. Inadequately dried aggregates at lower
production temperatures, and even the possible introduction of additional moisture to the WMA from the various WMA foaming technologies, may affect the binder to aggregate adhesion, moisture susceptibility and general mixture performance. The magnitude to which the different WMA technologies/additives affect the moisture sensitivity will vary and will depend on many regional (climate, aggregate type and asphalt binder source) and pavement specific conditions (traffic loading and general pavement integrity).

Information in the literature has indicated conflicting results with respect to laboratory and field moisture damage. The Texas Department of Transportation (TxDOT) (Rand, 2009) has acknowledged that WMA mixtures often fail the TxDOT Hamburg Wheel Tracking criteria, yet moisture damage has not been witnessed in the field. Similar results have also been reported when using the AASHTO T283 test procedure and comparing laboratory produced vs field compacted specimens (Bennert, 2007; Defiendorfer, 2009). This may indicate modifications to material preparation and/or test procedures are required when evaluating the moisture damage susceptibility of WMA mixtures in the laboratory so field conditions can be properly simulated.

Recent work conducted by Bennert et al. (2011) has shown that when preparing asphalt mixtures in the laboratory using aggregates containing moisture, drastic decreases in both the Tensile Strength Ratio (TSR) and Hamburg Wheeling Tracking rutting performance occurs. The modified mixing procedure developed by the authors was to model the potential condition of residual moisture remaining in the aggregates prior to being coated with asphalt binder. It was clear from the moisture sensitivity test results that the combination of aggregates having initial moisture prior to mixing and reduced production temperatures created mixtures prone to moisture damage.

OBJECTIVE

The objective of the research study was to evaluate the influence of initial aggregate moisture content and reduced production temperature on the performance of hot mix asphalt (HMA) and warm mix asphalt (WMA) produced through an asphalt plant. Two different aggregate blend moisture contents were achieved in the field to evaluate this concept. Additionally, five different mixes produced at two different production temperatures were produced and evaluated in the study.

PLANT PRODUCTION AND MATERIAL

The production facility was located in Lewisburg, PA, approximately 50 miles north of Harrisburg, PA. The HMA and WMA produced on the project was placed approximately 30 miles from the asphalt plant on Pennsylvania state route 225 (SR225). The project was originally bid as a WMA project through the Pennsylvania Department of Transportation (PennDOT) resurfacing program.

The asphalt plant used to produce the HMA and WMA was a Cedarapids/Standard Havens Magnum counter-flow drum plant. The facility has 8 cold feed bins and 1 RAP bin. The fines removal system is automated in that the raw feed tests calculate the overall minus #200. In most cases, the targeted fines are accomplished by automatic changes in air flow while constant
monitoring of removal. Prior to delivery to the site, the loose mix was silo-ed for approximately 1 hour. This was consistent for all mixes to ensure differences in loose mix aging due to storage conditioning were minimal.

The base mixture produced was a 9.5mm Superpave mix designed for traffic levels of 0.3 to 3 million ESAL’s. The aggregate gradation and design volumetrics are shown in Figure 1. The plant produced mixture contained 15% RAP and a PG64-22 asphalt binder produced by NuStar Refinery, Paulsboro, NJ.

![Figure 1 – Mixture Design Volumetrics and Gradation](image)

<table>
<thead>
<tr>
<th>Sieve Size (mm)</th>
<th>Percent Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.00</td>
<td>100.0</td>
</tr>
<tr>
<td>12.50</td>
<td>100.0</td>
</tr>
<tr>
<td>9.50</td>
<td>96.0</td>
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<tr>
<td>4.75</td>
<td>64.0</td>
</tr>
<tr>
<td>2.36</td>
<td>41.0</td>
</tr>
<tr>
<td>1.18</td>
<td>26.0</td>
</tr>
<tr>
<td>0.60</td>
<td>17.0</td>
</tr>
<tr>
<td>0.30</td>
<td>11.0</td>
</tr>
<tr>
<td>0.15</td>
<td>8.0</td>
</tr>
<tr>
<td>0.075</td>
<td>5.0</td>
</tr>
</tbody>
</table>

During production, two initial aggregate blend moisture contents were initially targeted; 1) 1.5% and 3.0%. However, during production, it was determined that the actual moisture contents of the aggregate blends were 1.1% and 2.6%, respectively. Aggregate moisture contents were maintained by covering stockpiles until production occurred.

A total of 10 different asphalt mixtures were produced on the project over a two day period; 5 different mix types and two different initial aggregate moisture contents. Table 1 shows the mix types, production temperatures and truck loading temperatures. The foamed WMA was produced with a foaming system developed in-house by the asphalt plant and called SMARTFOAM. Details of the foaming system are proprietary and not available yet to be released, until the patents have been obtained. Two different anti-strip products were used in accordance with each of their respective manufacturer’s recommendations and were preblended in the asphalt binder tank prior to production. The Evotherm 3G was blended at a dosage rate of 0.5% per total weight of the asphalt binder.

**PERFORMANCE TESTING OF MIXTURES**

Samples fabricated for performance testing were compacted at the asphalt plant’s QC lab. Approximately 1,800 lbs of material were sampled from the trucks prior to leaving the plant and compacted to air voids ranging between 6 and 7% air voids.
Table 1 – Mix Types with Associated Production Temperatures

<table>
<thead>
<tr>
<th>Aggregate Blend Moisture Content (%)</th>
<th>Mix Type (ID)</th>
<th>Production Temp at Drag (F)</th>
<th>Temperature Before Leaving Plant (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1%</td>
<td>WMA - Foam (A1)</td>
<td>275</td>
<td>260</td>
</tr>
<tr>
<td></td>
<td>HMA (B1)</td>
<td>315</td>
<td>295</td>
</tr>
<tr>
<td></td>
<td>WMA - Foam + Anti-Strip #1 (C1)</td>
<td>270</td>
<td>255</td>
</tr>
<tr>
<td></td>
<td>WMA - Evotherm 3G (D1)</td>
<td>270</td>
<td>255</td>
</tr>
<tr>
<td></td>
<td>WMA - Foam + Anti-Strip #2 (E1)</td>
<td>270</td>
<td>250</td>
</tr>
<tr>
<td>2.6%</td>
<td>WMA - Foam (A2)</td>
<td>285</td>
<td>270</td>
</tr>
<tr>
<td></td>
<td>HMA (B2)</td>
<td>315</td>
<td>305</td>
</tr>
<tr>
<td></td>
<td>WMA - Foam + Anti-Strip #1 (C2)</td>
<td>285</td>
<td>270</td>
</tr>
<tr>
<td></td>
<td>WMA - Evotherm 3G (D2)</td>
<td>285</td>
<td>260</td>
</tr>
<tr>
<td></td>
<td>WMA - Foam + Anti-Strip #2 (E2)</td>
<td>285</td>
<td>260</td>
</tr>
</tbody>
</table>

Along with typical moisture sensitivity testing, the asphalt mixtures were also evaluated for their respective stiffness, rut resistance, and crack resistance properties. The testing program utilized was as follows:

1. Mixture Stiffness – Dynamic Modulus using AASHTO TP79
2. Permanent Deformation – Flow Number using AASHTO TP79 and test criteria established in NCHRP Project 9-33
3. Cracking Resistance – Overlay Tester using TxDOT TEX-248F
4. Moisture Damage
   a. Tensile Strength Ratio (TSR) using AASHTO T283
   b. Hamburg Wheel Tracking using AASHTO T324

**Dynamic Modulus (AASHTO TP79)**

Dynamic modulus and phase angle data were measured and collected in uniaxial compression using the Simple Performance Tester (SPT) following the method outlined in AASHTO TP79, *Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)*. The data was collected at three temperatures: 4, 20, and 35°C using loading frequencies of 25, 10, 5, 1, 0.5, 0.1, and 0.01 Hz.

The collected modulus values of the varying temperatures and loading frequencies were used to develop Dynamic Modulus master stiffness curves and temperature shift factors using numerical optimization of Equations 1 and 2. The reference temperature used for the generation of the master curves and the shift factors was 20°C.

\[
\log|E^*| = \delta + \frac{(Max - \delta)}{\beta + \gamma \left[ \log a + \frac{\Delta e}{19.14714 \left( \frac{1}{T_r} \right)} \right]} 
\]

where:
- \( E^* \) = dynamic modulus, psi
- \( \omega_r \) = reduced frequency, Hz
Max = limiting maximum modulus, psi
\( \delta, \beta, \) and \( \gamma \) = fitting parameters

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

(2)

where:
- \( a(T) \) = shift factor at temperature \( T \)
- \( T_r \) = reference temperature, °K
- \( T \) = test temperature, °K
- \( \Delta E_a \) = activation energy (treated as a fitting parameter)

Resultant master stiffness curves are shown in Figures 2 through 4. Figure 2 shows the dynamic modulus results for the WMA mixes. As the figure shows, there is minimal difference between the mixes at the two different aggregate moisture contents. There does seem to be a slight trend indicating that as the aggregate moisture content went from 1.1 to 2.6%, a slight increase in mixture stiffness resulted. However, this is believed to be due to the increase in production temperature that occurred at the 2.6% aggregate moisture content condition. On average, a 15°F increase in production temperature occurred at the plant. The increase in production temperature and resultant increase in mixture stiffness is consistent with results shown by others (Bennert et al., 2011).

Figures 3 and 4 show the dynamic modulus test results for the 1.1% and 2.6% aggregate moisture content, respectively. At the 1.1% aggregate moisture content, there appears to be more separation between the different mixtures evaluated, with the Evotherm 3G mixture resulting in the lowest modulus while the HMA achieved the highest modulus. The general ranking appears to be a function of the production temperature; the HMA mixture was produced at 315°F while the Evotherm 3G mixture was produced at 270°F.

At the 2.6% aggregate moisture content, the modulus properties all seem to converge close to one another, showing minimal separation. This is again believed to be due to the effects of the production temperature than the actual moisture content of the aggregate blend. Review of the data shows that much of the test data converge together with the Foamed WMA (Mix A2) resulting in the lowest modulus values. This again is consistent with the production temperatures shown in Table 1 where most of the mixtures were produced between 315°F and 285°F, while the Foamed WMA (Mix A2) was produced at 275°F.

From the preliminary dynamic modulus data shown in this section, it would appear that production temperature, in the ranges shown in Table 1, have a greater influence on mixture stiffness than initial aggregate blend moisture contents of the range shown in Table 1.
Figure 2 – Dynamic Modulus Master Stiffness Curves for WMA Mixes
Figure 3 – Master Stiffness Curves for All Mixes – 1.1% Aggregate Moisture

Figure 4 – Master Stiffness Curves for All Mixes – 2.6% Aggregate Moisture
Repeated Load – Flow Number Test (AASHTO TP79)

Repeated load permanent deformation testing was measured and collected in uniaxial compression using the Asphalt Mixture Performance Tester (AMPT) following the method outlined in AASHTO TP79, *Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)*. The unconfined repeated load tests were conducted with a deviatoric stress of 600 kPa and a test temperature of 54.4°C, which corresponds to New Jersey’s average 50% reliability high pavement temperature at a depth of 25 mm according to the LTPPBind 3.1 software. These testing parameters (temperature and applied stress) conform to the recommendations currently proposed in NCHRP Project 9-33, *A Mix Design Manual for Hot Mix Asphalt*. Testing was conducted until a permanent vertical strain of 5% or 10,000 cycles was obtained.

Test results of the mixtures are shown in Figure 5. The test results show the same general trend as indicated with the dynamic modulus tests – as production temperature increased, so did the resistance to permanent deformation. On average, the Flow Number value increased 49.6% when the mixtures went from 1.1% to 2.6% aggregate blend moisture content. However, when looking at the production temperature, the increase in Flow Number is consistent with an increase in the production temperature (average increase of 10°F). In fact, the HMA mix (B1 and B2) were almost identical in Flow Number, which reflects the closeness in production temperature (310°F and 315°F), respectively.

![Figure 5 – Flow Number Test Results](image-url)
As mentioned earlier, the traffic level on Pennsylvania SR 225, where the mixtures were placed, contained traffic volumes on the order of 0.3 to 3 million ESAL’s. Based on the preliminary recommendations in NCHRP 9-33 (Christensen et al, 2010) shown in Table 2, all mixtures would be applicable for Pennsylvania SR 225.

Table 2 – NCHRP 9-33 Minimum Flow Number Criteria (Christensen et al., 2010)

<table>
<thead>
<tr>
<th>Traffic Level, Million ESALs</th>
<th>Minimum Flow Number, Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 3</td>
<td>---</td>
</tr>
<tr>
<td>3 to &lt; 10</td>
<td>53</td>
</tr>
<tr>
<td>10 to &lt; 30</td>
<td>190</td>
</tr>
<tr>
<td>&gt; 30</td>
<td>740</td>
</tr>
</tbody>
</table>

Overlay Tester (TxDOT TEX-248F)

The Overlay Tester, described by Zhou and Scullion (2007), has shown to provide an excellent correlation to field cracking for both composite pavements (Zhou and Scullion, 2007; Bennert et al., 2009) as well as flexible pavements (Zhou et al., 2007). Figure 6 shows a picture of the Overlay Tester used in this study. Sample preparation and test parameters used in this study followed that of TxDOT TEX 248F, Test Procedure for Overlay Test. These included:

- 25°C (77°F) test temperature;
- Opening width of 0.025 inches;
- Cycle time of 10 seconds (5 seconds loading, 5 seconds unloading); and
- Specimen failure defined as 93% reduction in Initial Load.

Figure 6 – Picture of the Overlay Tester (Chamber Door Open)
The Overlay Tester test results for the mixtures are shown in Figure 7. The data shows a general decrease in the fatigue life, with an average decrease of approximately 44% when comparing the 1.1% and 2.6% aggregate blend moisture content mixes. At this time, since there is limited data pertaining to the effects of aggregate moisture and production temperature on fatigue resistance, it is not clear why the reduction in fatigue life occurred. Bennert et al. (2011) did show that as production temperature decreases, an increase in the fatigue life as measured by the Overlay Tester occurred. However, at this time, it is not known whether the aggregate moisture was detrimental to the mixture intermediate temperature fatigue life.

Resistance to Moisture-Induced Damage (Tensile Strength Ratio, TSR)

Tensile strengths of dry and conditioned asphalt samples were measured in accordance with AASHTO T283, *Resistance of Compacted Asphalt Mixtures to Moisture Induced Damage*. All samples were prepared to air voids levels between 6.5% and 7%. Since the mixture was produced through the asphalt plant, the loose mix was not additionally conditioned, as specified in AASHTO T283, Section 7.4. All conditioned specimens were subjected to one freeze-thaw cycle, in accordance to AASHTO T283, Section 10.

The resultant TSR and wet (conditioned) indirect tensile strengths are shown in Figures 8 and 9. The test results indicate that a 8.3% decrease in TSR and 7.5% decrease in wet indirect tensile
Figure 8 – Tensile Strength Ratio (TSR) Values

Figure 9 – Wet (Conditioned) Indirect Tensile Strengths
strength were observed when comparing the 1.1% and 2.6% aggregate blend moisture contents. In general, indirect tensile strengths commonly increase as mixture stiffness increases. Therefore, the reason for the decrease in wet indirect tensile strength is most likely due to the additional moisture in the aggregate blend.

The TSR results also indicate that not all anti-strips will help in increasing the resistance to moisture damage in the mixtures. Anti-strip #2 did not significantly change the TSR values of the baseline HMA or foamed WMA mixture, and actually lowered the TSR value at the 2.6% moisture content condition. Meanwhile, both anti-strip #1 and the Evotherm 3G generally improved or maintained the TSR values of the HMA mix at both aggregate moisture contents. This was also the case with wet indirect tensile strengths. It is also interesting to note that the foamed WMA (Mix A1 and A2) was able to achieve higher TSR and wet indirect tensile strengths than the baseline HMA mixture (Mix B1 and B2).

**Hamburg Wheel Track Test (AASHTO T324)**

Hamburg Wheel Track tests were conducted in accordance with AASHTO T324, *Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)*. Test specimens, compacted between 6.0 to 7.0% air voids, were tested at a test temperature (water) of 50°C. Since PennDOT does not utilize the Hamburg Wheel Tracking test, nor does it have established criteria, the number of loading cycles until 12.5mm of rutting was used for comparison purposes, as is commonly done by TxDOT.

Figure 10 shows the results of the wet Hamburg Wheel Tracking tests. The results for the 1.1% aggregate blend moisture content are relatively close to one another with the results having a range of 355 cycles. Although a precision and bias statement does not exist for this test method, the narrow range of results would suggest the performance among the mixes is relatively the same. It should also be noted that the HMA baseline mixture achieved the lowest number of cycles to 12.5mm rutting at the 1.1% aggregate blend moisture content.

At the 2.6% aggregate blend moisture content, the number of cycles to achieve 12.5mm of Hamburg rutting slightly increased for each mix (showing better rutting resistance), except the foamed WMA with anti-strip #2. As the initial moisture content of the aggregate blend increased, the number of loading cycles to 12.5mm Hamburg rutting actually increased, which many would interpret as having a higher resistance to moisture damage. This is counterintuitive to what is commonly assumed where residual moisture in the aggregate may initiate moisture damage in asphalt mixtures. Therefore, it may be concluded that the increase in production temperature of the asphalt mixtures may have more of an impact on the general performance of the Hamburg test results than the increase in aggregate moisture content.
CONCLUSIONS

A research study was conducted to evaluate the performance of hot mix asphalt (HMA) and warm mix asphalt (WMA) at planned, different aggregate blend moisture contents, as well as production temperatures. Various asphalt mixture performance tests were conducted to assess how these parameters influence the mixture performance. Based on the materials in this study and range of test temperatures and aggregate moisture contents, the following conclusions can be drawn:

- The dynamic modulus properties of the mixtures appeared to be more influenced by the production temperature as opposed to the aggregate moisture content. The master stiffness curves appeared to all be comparable when production temperatures were relatively close to one another. Also, at the lower production temperatures, larger differences appeared between the dynamic modulus properties of the mixtures, which may mean that the properties of the WMA technology/additive began to supersede the influence of the production temperature and resultant stiffening. Larger differences were found at the high test temperatures with minimal to no noticeable difference found at low temperatures.
- Repeated Load/Flow Number testing showed that rutting resistance actually increased when the aggregate moisture content increased from 1.1% to 2.6%. However, based on the production temperatures, it is hypothesized that the additional stiffening resulting
from the increased production temperatures may have actually increased the rutting resistance of the mixtures, as noted previously and in Figure 2, where the dynamic modulus at the higher test temperatures were larger in the higher production temperature mixtures.

- The fatigue properties, as measured in the Overlay Tester, indicated that the fatigue resistance of the mixtures decreased as the aggregate moisture content increased from 1.1% to 2.6%, but also as production temperature increased 10°F. Previous work has indicated that asphalt mixtures produced at higher production temperatures do exhibit lower fatigue resistance when measured in the Overlay Tester (Bennert et al., 2011). Therefore, it is hypothesized that the reduced fatigue life may be more due to the higher production temperature than the higher aggregate moisture content.

- The moisture damage potential was assessed using the Tensile Strength Ratio (AASHTO T283) and the wet Hamburg Wheel Tracking test. The TSR results indicated that as aggregate blend moisture content increases, both the wet tensile strength and tensile strength ratio (TSR) decreased. This is believed to have occurred due to the possibility of residual moisture trapped in the aggregate breaking and causing cohesive/adhesive failure from the freeze-thaw cycle applied to the conditioned mixtures. The TSR value or the wet tensile strength did not increase with the increase in production temperatures, which is normally expected as the production temperature increases and stiffens the asphalt mixtures. This was the case in the wet Hamburg testing as the number of cycles to 12.5mm of Hamburg rutting increased as production temperature and aggregate blend moisture content increased. Normally, it would be assumed that higher aggregate moisture content would promote stripping potential, but this was not the case with the wet Hamburg test.

- Overall, the testing indicated that the changes in production temperature used in this study had a greater influence on the stiffness, rutting potential and fatigue cracking potential than the range in aggregate blend moisture content. The TSR test was found to be sensitive to possibly trapped moisture in the aggregate as was witnessed with lower TSR and wet tensile strengths. However, the wet Hamburg test appeared to be more sensitive to mixture stiffness (i.e. – production temperature) than the possibility of residual moisture in the aggregate blend.

ACKNOWLEDGEMENTS

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