A Cross-Cutting Comparison between Hot Mix Asphalt and Warm Mix Asphalt

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ABSTRACT

Warm Mix Asphalt (WMA), developed in Europe, has been used on paving projects in the United States since 2005. In an effort to answer questions during early implementation of WMA, the Federal Highway Administration (FHWA) conducted a variety of small-scale experiments comparing WMA and conventional Hot Mix Asphalt (HMA). The majority of tests on binders and mixtures were conducted on laboratory-created mixtures; but a portion of the experiments were conducted on plant-produced mixtures and one set of experimental results were based on field construction. The following aspects are summarized in this paper: binder stiffness and sensitivity to aging temperature, effect of wax additives on low temperature performance, effect of water-based foaming on mechanical properties, moisture damage and stripping sensitivity, laboratory and field compactability, evaluation of rutting potential from early opening of construction, and permanent deformation resistance. Overall, the results indicate there are no alarming indicators of poor performance or drastic difference with HMA, which is aligned with the positive field experience thus far.
INTRODUCTION

The primary driver of Warm Mix Asphalt (WMA) use in the United States (US) is the potential for improved compaction which leads to better pavement performance. WMA has seen widespread use across the US due to its ability to increase workability and, in some cases, reduce viscosity of asphalt mixtures allowing the binder to more readily coat aggregates at lower production temperatures (1). Increased workability has several benefits including improving compaction in cold weather, reducing compaction equipment needs, and mitigating against the risk of poor compaction when working with stiff mixtures containing polymers or high RAP contents (2). In addition, with proper production and construction best practices, WMA reduces fuel usage and emissions and improves worker comfort.

When WMA was first introduced to the US market, there were three technologies available; a wax additive, a zeolite additive, and an emulsion based product. Now, there are over thirty WMA technologies in the US market. One of the greatest challenges for highway agencies is determining which technologies to allow. Considering the lack of long-term performance information for WMA, demonstration projects and laboratory studies were essential during early implementation of WMA. The Federal Highway Administration’s Turner Fairbank Highway Research Center (FHWA TFHRC) conducted a variety of small-scale experiments comparing WMA and conventional Hot Mix Asphalt (HMA). The majority of tests on binders and mixtures were conducted on laboratory-created mixtures; but a portion of the experiments were conducted on plant-produced mixtures and one set of experimental results were based on field construction. For the first time, the results of these small-scale experiments are combined and discussed in this paper in order to document early lessons learned.

BACKGROUND

Development of WMA technologies began in Europe in the late 1990s, and, in the United States, the National Asphalt Pavement Association (NAPA) soon became interested in these technologies and began communicating with the European asphalt pavement industry about WMA. For their 2003 Annual Meeting, NAPA invited representatives from European companies to make presentations on WMA. The following year, NAPA and the Association of Equipment Manufacturers conducted a WMA demonstration project for the 2004 World of Asphalt Trade Show and Conference. That same year, FHWA, NAPA, and three warm-mix technology suppliers initiated a research project at Auburn University’s National Center for Asphalt Technology (NCAT) on methods for reducing asphalt mixture production and placement temperatures. FHWA and NAPA responded in 2005 by forming the Warm Mix Asphalt Technical Working Group (WMA TWG) and tasked it with proactively providing national guidance on investigating and implementing WMA technologies. The group includes multiple sectors of the asphalt pavement industry, such as State highway agencies, academia, and contractors. The group’s longstanding goal is to provide technical WMA guidance that will lead to a product with quality and performance at least equal to conventional HMA.

Although the original WMA technologies came out of Europe, documented performance data were limited. In 2007, FHWA conducted an International Technology Scanning Program tour in cooperation with AASHTO and NCHRP. A team of 13 asphalt pavement materials experts assembled to assess and evaluate European WMA experiences and pavement performance. FHWA published the results of the scan as Warm Mix Asphalt: European Practice
(3), which concluded: “The consensus among the scan team members was that WMA is a viable technology and that U.S. highway agencies and the HMA industry need to cooperatively pursue this path.” A number of implementation activities were identified and taken up by the WMA TWG to advance within the US. A number of the technical working group’s products are directly attributed to the scan team’s identified needs.

OBJECTIVES

The objective(s) of this paper is to summarize small-scale experiments conducted to answer early questions regarding WMA construction and performance such as:

- Is there increased rutting potential with WMA due to lower production and construction temperatures?
- Does WMA compact similar to HMA in the field?
- How does foaming affect performance, especially in regards to moisture sensitivity?
- What is the impact of wax additive on low temperature performance?

EXPERIMENTS

Maryland Interstate Case Study

One of the first public WMA projects in the US took place in Maryland where the Maryland State Highway Administration (MD SHA) milled and placed a 19 mm nominal size Stone Matrix Asphalt (SMA) base course on the Capitol Beltway (I-95/495) near Route 5 in August 2005. The base course was ultimately overlaid with a surface course, but was open to direct traffic for a period of time. The project used the WMA technology Sasobit and the objective was to determine the ability of Sasobit to increase workability of SMA mixtures at conventional SMA production and construction temperatures and determine any allowable temperature reduction in the process and still achieve field density. There were two concerns regarding the Sasobit additive: (1) premature rutting in the WMA Sasobit section upon opening to traffic in a “warm” state and (2) impact on long-term performance. A control HMA SMA was placed, as well as the Sasobit WMA SMA. The base binder was an SBS-modified PG76-22 used in both the control and WMA sections.

Sasobit is a synthetic fischer-tropsch wax used to lower the viscosity of asphalt at temperatures below HMA production temperatures but above the wax’s melting point. In this project, the granulated Sasobit was added to the drum by means of blowing with a modified fiber delivery system at 1.5% by weight of binder or approximately 2 pounds per ton. Changes in volumetric properties between the control and Sasobit mixtures were negligible; an extra 0.08% of liquid (melted Sasobit plus binder) was effectively added to the mixture which was within specification tolerances. The Sasobit wax will impact the high and low temperature performance grade of the asphalt due to its stiffening effect on the binder and mixture at in service temperatures. The amount of increase in the low and high PG temperature depends on the dosage rate and asphalt source. Historically, and more recently in the U.S., producers are relying on the binder supplier to blend the wax into the binder before delivery and certify the dosage rate and the asphalt’s performance grade with the wax included.
**Early Permanent Deformation Concerns with WMA**

TFHRC asphalt laboratories in cooperation with MD SHA designed a small experimental plan to simulate opening to traffic to evaluate potential “tenderness” and early permanent deformation of Sasobit WMA mixtures before the I-95/495 project. The French Pavement Rut Tester (PRT), a laboratory wheel-tracking device that accelerates rutting in a compacted asphalt mixture, has been used to evaluate mixtures with materials that may lead to rutting and mixtures with no performance history making it an applicable laboratory test for this experiment. The French PRT was developed by the Laboratoire Central des Ponts et Chaussees (LCPC) and used for over 25 years in France to evaluate permanent deformation behavior of asphalt mixtures. The French PRT applies a pneumatic wheel to compacted slabs to simulate pavement response under traffic and has been used to differentiate between good and poor field rut performance in France and the US (4; 5). Details on the French PRT may be found on Turner Fairbank’s Bituminous Mixtures Laboratory web page (6).

A direct comparison between a mixture with and without Sasobit was tested by making a slab of each to load in the PRT and compact by means of a reciprocating pneumatic wheel inflated to about 600 kPa. The slab dimensions were 100 mm thick x 500 mm length x 180 mm wide. The 100 mm thick slab offered the best representation of the SMA section field thickness. For this laboratory test strip, a dense graded mixture with 7% target air voids was used. It is believed this gradation offers a more conservative characterization of the potential premature rutting than an SMA where more stone-on-stone contact occurs. The actual SMA mix design may be tested after any final changes to the design are made. The pre-compacted slabs were loaded in the steel test molds and reheated in the oven to 115°C (above the 104°C Sasobit melting point). A thermocouple was placed in the center of the slab to monitor temperature. The slabs were then installed in the PRT. Normally the PRT test is controlled at 60°C. In this case, the PRT was not heated and loading began when the slab thermocouple reached 93°C (about 200°F). Preconditioning consisted of loading the slab for 40 cycles to seat the mix. Preconditioning was done partly because of a premature start of the loading at 109°C instead of 93°C on the control sample, but it was repeated on the Sasobit sample to be consistent. The loading was stopped and started again when the internal slab thermocouple reached 93°C as planned, approximately 10 minutes. The test slab was allowed to cool at room temperature while rut depths and temperature were logged at cycles of 300, 1000, 3000, 10000, etc. The heating and cooling temperature profile is provided in FIGURE 1. The temperature reduction is almost identical between the control and Sasobit modified slabs. The focus of the test was to compare deformation between the Sasobit modified and control mixes during early load cycles (i.e. after opening to traffic) where the Sasobit has the highest probability to be without the beneficial crystallization that supposedly contributes to decreased rutting potential.
FIGURE 1 Temperature profile of French Pavement Rut Tester slabs during heating and cooling.

Deformation profiles in the PRT are measured by taking 15 measurements: five locations along the length of the sample and three vertical deformations are measured across the width. The points are averaged for a reduced measurement. Three types of rutting were measured in the PRT: the average rut depth in mm, the average vertical rut strain in % to account for differences in slab thickness, and the post-preconditioning loading rutting. These rutting results for the control HMA mix and the Sasobit WMA mixture are shown in FIGURE 2. Part of the large amount of rutting in these tests may be due to the typical high amount of initial rutting seen in all permanent deformation tests on asphalt concrete when the aggregates are seating; and less due to the actual effect of binder temperature.
FIGURE 2 Rut measurements and center slab temperature versus load cycles from the French Pavement Rut Tester.
It must be noted that these tests are based on one replicate. A coefficient of variation less than 20% is remarkably low for PRT testing, but this is for a constant temperature test around 60°C. When comparing either the total rut depth or strain, the control mixture without Sasobit has a larger accumulation. This could be expected based on the fact that Sasobit has been shown in TFHRC Binder Rheology Laboratory to increase the high temperature performance grade by one PG Grade. For the laboratory experiment, the binder was a PG64-22 (rather than the SBS-modified PG76-22 binder used in the field) and 1.5% Sasobit by weight of binder increased the high temperature grade to 70.8. Regarding the cumulative rutting after the preconditioning, the Sasobit mixture had a slight increase in rutting of about 0.25 over 10,000 cycles to the point where the cooled mixtures no longer rut in the PRT. Based on this experiment, Sasobit WMA in mixtures not allowed to fully crystallize and cure over 24 hours does not appear to cause a largely softer and grossly rut susceptible mixture at pavement temperatures typical to traffic opening.

*Does WMA Compact Similar to HMA in Field?*

In addition to demonstrating WMA, this project also demonstrated Intelligent Compaction (IC) (7). The IC roller, supplied by Bomag Americas, Inc. was a smooth drum roller outfitted with mechanical components and software capable of vectoring the compactive effort. The IC roller was utilized for breakdown and intermediate compaction using four passes (forward, reverse, forward, reverse) enabling significant density changes to be observed. IC rollers are able to measure the surface temperature and stiffness of the mat during each roller pass. This project provided a unique opportunity to compare the field compaction of Sasobit WMA with control HMA.

The surface temperature at each roller pass was measured from an infrared device mounted underneath the roller between the two drums. FIGURE 3 shows the data and linear trend lines of the surface temperature at each roller pass for the control HMA and Sasobit WMA mixtures and clearly shows that the Sasobit WMA was compacted at lower temperatures than the control HMA for each roller pass. The temperatures may seem low because water was used to prevent pick-up.

The Bomag IC measurement value is called the vibration modulus, $E_{\text{vib}}$ [MN/m$^2$], and is a measure of stiffness. The modulus values are computed based on compression paths of contact forces versus the roller drum displacement curves, thus the $E_{\text{vib}}$ values increase with more roller passes and as the compaction temperature of the asphalt mixture decreases, the $E_{\text{vib}}$ value also increases (7). FIGURE 4 shows the data and trend lines of $E_{\text{vib}}$ values versus roller passes as calculated by the IC. The trend lines for both mixtures follow a natural logarithmic function. While the trend lines appear to show a difference in the stiffness values of the control HMA versus the Sasobit WMA, the results must be considered in light of a statistical analysis due to the significant amount of scatter in the data. Furthermore, it should be noted that the total number of observations for the Sasobit WMA section was 26 whereas the control HMA section was 60.
FIGURE 3  Surface temperature versus roller pass for control HMA and Sasobit WMA.

FIGURE 4  Stiffness versus roller pass for IC roller, breakdown and intermediate – no finish.
Statistical hypothesis tests were conducted on the variances (F-test) and means (student t-test) of the compaction temperatures and stiffness values for the control HMA and Sasobit WMA (8). While the statistical analysis showed that there was a significant difference between the temperature values for the HMA control and WMA Sasobit for all four roller passes; after the first roller pass, there was no significant difference in $E_{\text{vib}}$ values between the Control HMA and the Sasobit WMA, see TABLE 1.

### TABLE 1 Field Evaluation of WMA Compaction using Intelligent Compaction Results

<table>
<thead>
<tr>
<th>Pass</th>
<th>Mat</th>
<th>Compaction Temperature Variance</th>
<th>IC Roller $E_{\text{vib}}$ Value (Stiffness) Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Control (HMA) = SMA ≠ WMA (Sasobit) SMA</td>
<td>Control (HMA) = SMA ≠ WMA (Sasobit) SMA</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Control (HMA) = SMA ≠ WMA (Sasobit) SMA</td>
<td>Control (HMA) = SMA ≠ WMA (Sasobit) SMA</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Control (HMA) = SMA ≠ WMA (Sasobit) SMA</td>
<td>Control (HMA) = SMA ≠ WMA (Sasobit) SMA</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Control (HMA) = SMA ≠ WMA (Sasobit) SMA</td>
<td>Control (HMA) = SMA ≠ WMA (Sasobit) SMA</td>
<td></td>
</tr>
</tbody>
</table>

Nuclear gauges were used to determine density of the pavement at the end of the IC roller pattern and MD SHA also cut cores in order to compare density measurements of cores to the results from the IC. While the nuclear gauge results did not correlate well with the IC compaction results, the cores results indicated that the HMA control and Sasobit WMA exhibited similar densities when subjected to the same rolling patterns. The open surface texture of SMA may have caused the nuclear gauge readings to be inconsistent and inaccurate.

In conclusion, the Sasobit WMA mixture was produced at cooler temperatures than the control HMA. Based on subjective observations, the Sasobit additive increased workability, and based on IC data, compacted quicker than the control HMA. Based on the stiffness results from the IC and the densities from the cores, the same rolling pattern achieved the same air void content and stiffness for both the Sasobit WMA and the control HMA. Thus, it was concluded that for this demonstration project, even with reduced lay down temperatures, the Sasobit WMA compacted similarly to HMA in the field.

### Binder Grade Study to Evaluate Rutting Potential with Lower Temperatures

WMA technologies allow the use of lower temperatures; as a consequence the asphalt binder used in WMA mixes does not age as much as in mixes produced at typical HMA temperatures. With reduced aging of the binder, there is concern that permanent deformation may occur in WMA mixes early in the pavement design life. In fact, previous laboratory studies (using the Asphalt Pavement Analyzer) have indicated a tendency for increased rutting potential as mixing temperatures decreased for HMA and WMA mixtures (9).

In an effort to evaluate if there is greater rutting potential with lower production temperatures, an experiment was conducted using reduced temperatures (in order to simulate WMA production temperatures) in the Rolling Thin Film Oven (RTFO) which simulates early
aging of asphalt binders due to the plant and during early design life. Several binders were
evaluated from field projects, laboratory mixtures, and FHWA’s Accelerated Loading Facility
(ALF) experiment. Each binder was short term aged in the RTFO (AASHTO T 240) at three
different temperatures: 163°C, 130°C, and 110°C. After RTFO aging at various temperatures,
each binder was tested according to AASHTO T 315 for high temperature properties. The
results, given in TABLE 2, show that a reduction in aging temperature from 163°C to 130°C
results in a 3ºC change (i.e. half a grade) in the high temperature continuous grade. Further, a
reduction in aging temperature from 163°C to 110°C results in almost a grade change in the high
temperature continuous grade. However, due to the large coefficient of variation values (greater
than 50 percent); the results indicate that the loss in high temperature continuous grade may be
dependent on the binder and not necessarily the lower production temperatures.

The results of this study were used in NCHRP Project 9-43 “Mix Design Practices for
WMA” to develop preliminary production temperature limitations. Below these limitations,
consideration may be given to increasing the high temperature performance grade of the binder.
In addition, NCHRP 9-43 performed additional long-term aging and low temperature evaluation
to develop recommendations for low temperature binder grade selection based on WMA
production temperatures (10).

### TABLE 2 High Grade Temperature Results at Various Short-term Aging Temperatures

| Binder ID | Source | °C at \(|G'|/sin\delta = 1\) kPA | °C at \(|G'|/sin\delta = 2.2\) kPA | Difference in High Grade Temperatures |
|-----------|--------|-------------------------------|-------------------------------|--------------------------------------|
| B-6354    | Missouri WMA Demo PG70-22 | 74.8 75.9 80.0 | 67.4 68.5 73.2 | -7.4 -6.1 -6.8 |
| B-6348    | Hawaii Project PG70-16   | 72.5 74.4 79.3 | 66.2 68.1 72.9 | -6.3 -6.2 -6.4 |
| B-6328    | Venezuelan PG64-22       | 68.8 70.0 74.8 | 62.2 63.4 68.1 | -6.6 -6.6 -6.7 |
| AAM-1     | SHRP Materials Research Library | 67.1 72.6 75.3 | 65.9 68.8 71.4 | -1.4 -3.1 -5.9 |
| AAM-2     | SHRP Materials Research Library | 60.9 64.0 65.8 | 57.5 59.1 63.2 | -3.4 -4.9 -5.7 |
| AAG-1     | SHRP Materials Research Library | 65.5 67.6 68.2 | 61.9 62.5 63.3 | -3.6 -5.1 -5.4 |
| AAD-1     | SHRP Materials Research Library | 60.5 64.5 67.0 | 57.9 60.2 62.8 | -2.6 -3.7 -4.9 |
| B-672     | FHWA ALF Control, PG70-22 | 73.0 75.5 77.0 | 68.8 70.4 74.9 | -4.2 -5.1 -5.9 |
| B-672 + 1.5% Sasobit | FHWA ALF Control + Sasobit | 78.4 81.3 82.5 | 71.9 74.7 76.2 | -6.5 -6.8 -7.3 |
| B-672 + 3.0% Sasobit | FHWA ALF Control + Sasobit | 84.9 84.7 84.8 | 77.9 78.0 78.4 | -7.0 -6.7 -6.4 |

Impact of Foaming on Moisture Sensitivity

A common WMA technology uses water to foam asphalt binder allowing coating of the
aggregate to occur at lower production temperatures. Foam-based WMA, however, raises
concerns regarding moisture sensitivity of asphalt mixtures. First, there is concern that at
reduced production temperatures, moisture may still be present in the aggregates. Second, the
addition of water to the binder may result in residual moisture in the mixture before compaction.
Typically a very small amount of water (less than 2.0% by weight of binder) is injected to foam
the asphalt and, even at WMA temperatures, the injected water turns to steam which is driven off
the mix.

A laboratory experiment was conducted using Warm Asphalt Mixture Foam (WAM-
Foam). In the WAM-Foam process, the intermediate temperature region between 175°F (79°C)
and 250°F (121°C) is used with conventional mixture production equipment. These lower
temperatures are achieved by using a modified two part asphalt binder system which combines a soft asphalt grade and a foamed hard asphalt grade. The first step adds the soft asphalt to pre-coat the aggregate. The second step adds the foamed hard asphalt into the mixture. The total amounts of hard and soft asphalt depend on the final binder specification requirements of the asphalt mixture but generally fall near a 1:5 ratio of soft to hard asphalt. This two step mixing procedure is utilized to obtain full coating of the aggregate and mixture workability during paving operation at lower temperatures.

A laboratory foaming device was loaned to TFHRC in order to produce WAM-Foam in the laboratory. The control and WMA asphalt mixtures were evaluated for moisture sensitivity using AASHTO T 324 Standard Method of Test for Hamburg Wheel-Track Testing of Compacted HMA and AASHTO T 283 Standard Method of Test for Resistance of Compacted HMA to Moisture-Induced Damage.

The Hamburg Wheel Track Test results showed that foamed asphalt may be more prone to rutting and moisture susceptibility, see FIGURE 5. The tensile strength ratio (TSR) results from AASHTO T 283 indicate that the WMA foam mix may have better performance than the control mix. The WMA foam mix had greater dry and wet strengths and a higher TSR than the control mix, see FIGURE 6. The conflicting results of this study highlight the need for dedicated research on the moisture sensitivity of WMA. The WMA TWG responded to this need and proposed a research need statement on long-term performance of WMA that included a focus on moisture susceptibility of WMA which is now NCHRP Project 9-49 “Performance of WMA Technologies: Stage 1 – Moisture Susceptibility”.

FIGURE 5 Results of Hamburg Wheel Track Test for control and WAM-foam mixtures.
FIGURE 6  Strength and TSR results for WAM-foam and control asphalt mixtures.

Wax Additive Impact on Low Temperature Cracking Performance

Relatively large amounts of naturally occurring waxes in conventional asphalts can be undesirable for low temperature thermal cracking performance. Wax contents can be as low as 0.7% and as high as 6.5% (11). An experiment was conducted to characterize the impact that wax based additives have on low temperature performance characterization of mixtures using Thermal Stress Restrainted Specimen Tests (TSRST, AASHTO TP10). The experimental design and test results are summarized in TABLE 3 which included different binders, modification and aggregates. SHRP binders AAM-1 and AAM-2 with higher-than-average wax content were selected by design to explore a more extreme scenario where added WMA wax might interact with natural wax. Some early lab experiments and field trials with Sasobit used 3% rather than the contemporary 1.5% rate which also adds to the extreme scenario. A generic PG64-22 binder was tested unmodified and modified with Sasobit. Lastly, the generic binder was tested as provided by an unnamed supplier that reportedly modified it with an unspecified wax-type product which has since found no reported use in field trials. Mix made with binder not having any added WMA wax was short term oven aged at 135°C while mix with WMA wax modification was short term oven aged at 115°C and long term oven aging was not conducted.

The binder tests indicate the larger 3% concentration of Sasobit tends to produce 10°C to 6°C loss in low temperature performance grade which is sensible given 3% Sasobit and the relatively large natural wax contents of AAM. The test data are presented graphically FIGURE 7. For each binder type, statistical comparisons of the mixtures’ TSRST fracture temperatures revealed the impact of WMA wax modification is not significant. Nonetheless, there is a quantifiable difference on average where the effect of wax causes a slight loss of low temperature performance. Particularly the amount of average loss is mostly affected by the aggregate type for the SHRP AAM binders. The diabase aggregate mixes tended to show a larger average loss effect than limestone; +1.3°C and +1.6°C for diabase and -0.4°C and +0.7°C. It is of interest to note that the anonymous unspecified wax in the generic binder had the largest average low temperature loss of +2.0°C. Given this occurred with the least sensitive limestone aggregate,
the data illustrates not all wax additives are comparable and binder low temperature rheology should checked for sensitivity to wax modification.

**TABLE 3** Experimental Design and Results of Low Temperature TSRST Experiment

<table>
<thead>
<tr>
<th>Binder</th>
<th>Natural Wax Content</th>
<th>Mix Design Aggregate</th>
<th>WMA Wax Modifier</th>
<th>Continuous Low Temp. PG (°C)</th>
<th>Temperatures at Fracture (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAM-1 (PG64-16)</td>
<td>4.21%</td>
<td>Diabase</td>
<td>none</td>
<td>-22</td>
<td>-22.9, -23.0, -24.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Limestone</td>
<td>3% Sasobit</td>
<td>-16</td>
<td>-22.4, -23.0, -20.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>none</td>
<td>same as above</td>
<td>-25.1, -24.2, -19.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3% Sasobit</td>
<td>same as above</td>
<td>-22.5, -23.1, -23.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Limestone</td>
<td>3% Sasobit</td>
<td>-15</td>
<td>-24.0, -25.4, -25.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>none</td>
<td>same as above</td>
<td>-28.7, -24.4, -28.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3% Sasobit</td>
<td>same as above</td>
<td>-26.3, -26.5, -26.4</td>
</tr>
<tr>
<td>Generic PG64-22</td>
<td>Not Measured</td>
<td>Limestone</td>
<td>none</td>
<td>-26</td>
<td>-29.0, -26.4, -28.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3% Sasobit</td>
<td>-22</td>
<td>-29.0, -27.7, -29.3</td>
</tr>
</tbody>
</table>

**FIGURE 7** Box plots of low temperature fracture tests on mixes with various WMA wax additives
CONCLUSIONS

The results of these early studies confirmed the ability of WMA asphalt mixtures to be produced and constructed at lower temperatures with improved workability and similar properties to HMA. Based on the experiments conducted in this study, the following conclusions may be drawn:

- The use of WMA (specifically Sasobit) does not appear to increase rutting potential at temperatures typical to early traffic opening or in early design life.
- The Sasobit WMA additive reduced the production and compaction temperatures as compared to control HMA. Based on IC data, the Sasobit WMA compacted quicker than the control HMA and based on IC stiffness and core density results, the same level of compaction was achieved for Sasobit WMA SMA as with the control HMA SMA using the same number of roller passes.
- Results of a binder grade study showed a major effect of reduced short-term aging temperature on high temperature binder grade. For 10 different binders, on average, temperature reductions of about 30°C resulted in a half grade change for the high temperature continuous grade, whereas a temperature reduction of over 50°C resulted in almost a whole grade change for the high temperature continuous grade. Considering the variability of the results among the 10 binders studied, the loss in high temperature performance grade may be dependent on the binder and not necessarily the lower production temperatures.
- An evaluation of moisture sensitivity using AASHTO T 283 and the HWTD revealed that the moisture sensitivity of WAM-foam asphalt is different than an HMA mixture with the same aggregate and binder. The HWTD results indicated that WAM-foam may be sensitive to moisture; however, the HWTD results conflicted with the AASHTO T 283 results.
- For each binder type, statistical comparisons of the mixtures’ TSRST fracture temperatures revealed the impact of WMA wax modification is not significant but may cause a slight loss of low temperature performance grade. The amount of average loss is mostly affected by the aggregate type for the SHRP AAM binders.

These studies provided highway agencies, such as the MD SHA and FHWA’s Western Federal Lands, the confidence to pursue WMA on large projects. In addition, these early studies highlighted the need for additional research to provide guidance on the following:

- The ability to use the same binder grade with WMA that is used with HMA,
- Further developing laboratory methods for correctly replicating WMA mixtures in the lab and procedures for properly conditioning and long-term aging WMA to assess performance,
- Assessing moisture sensitivity of WMA mixtures, and
- Performing binder low temperature rheology to check for sensitivity to wax modification.
ACKNOWLEDGEMENTS

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