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Laboratory and Field Evaluation of Two Warm-Mix Additives in Connecticut and Validation of an Alternative Moisture Susceptibility Test

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Laboratory and Field Evaluation of Two Warm-Mix Additives in Connecticut and Validation of an Alternative Moisture Susceptibility Test

Alexander Karl Bernier

B.S.C.E., University of Connecticut, 2010

A Thesis
Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science at the University of Connecticut 2012
APPROVAL PAGE

Master of Science Thesis

Laboratory and Field Evaluation of Two Warm-Mix Additives in Connecticut and Validation of an Alternative Moisture Susceptibility Test

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INTRODUCTION

Pavement additives which allow reduction in mixing temperatures for hot-mix asphalt (HMA) have been in use for over two decades in Europe and they have only recently become adapted by State Highway Agencies (SHA) in the United States. While the lower production temperatures have huge energy saving and environmental benefits there is concern as to the effect of the reduced temperatures and interaction of the additive and binder on the performance of asphalt pavements. The lower production temperature may accommodate residual moisture in aggregate and cause weak bonding between the asphalt binder and the aggregate. A tool for simulating accelerate moisture damage can aid researchers and practitioners to design against moisture susceptibilities.

OBJECTIVES

The intent of this thesis is to evaluate two predominant warm-mix asphalt (WMA) technologies in the state of Connecticut. Evaluation will include field performance, low-temperature cracking tests and Hamburg Wheel Tracking. In addition to evaluating these WMA additives this thesis also evaluates the effectiveness of the Moisture Induced Stress Tester (MiST). The MiST is an alternative accelerated lab procedure for detecting moisture susceptibility in asphalt materials, such as HMA and WMA. To validate the MiST for use in Connecticut, material from the WMA trial sections as well as cores from six Long-Term Pavement Performance (LTPP) test sections which had 12 years of traffic and weather loading in Colchester, CT were evaluated.

The specific purpose of this research is to identify differences between the two additives and a control mixture and make recommendations for implementation in the
state of Connecticut. Additionally, the MiST results are presented and conclusions are made on the potential adoption of this procedure for use in Connecticut.

The first chapter of this thesis, “Laboratory and Field Evaluation of Two Warm-Mix Additives in Connecticut,” is an article accepted for publication in the Transportation Research Record: The Journal of the Transportation Research Board. The second chapter of the thesis, “Evaluation of an Alternative Moisture Sensitivity Test,” is an article in preparation for submission to the International Journal of Pavement Engineering. Each chapter is treated as a separate entity in regards to methodology and conclusions.
Laboratory and Field Evaluation of Two Warm-Mix Additives in Connecticut

ABSTRACT

This paper presents the details on the first official state Warm-Mix Asphalt (WMA) pavement project in Connecticut. The construction took place between July 20th and 22nd, 2010 and it involved three experimental sections, i.e. one section with a conventional HMA (control section) and two WMA sections with different technologies, wax and foamed asphalt. All three sections are located on Route 70 in central Connecticut. Each section is approximately 1 km long and includes lanes in both directions. The construction was done as 50-mm overlay with 12.5 mm SuperPave mix. Each mix was sampled over three day construction period for further evaluation in the laboratory. The materials were collected in loose form and reheated and compacted in laboratory conditions (laboratory fabricated specimens). This paper discusses the effect of mix type on the results from several tests conducted in the laboratory, such as Semi-Circular Bending, Hamburg Wheel Tracking, Indirect Tensile, and Disk Compact Tension. The results from the WMA specimens are also compared against conventional HMA specimens. Finally, the paper presents the performance data from all three test sections after the first winter season and correlates these observations with the laboratory results.

INTRODUCTION

Three experimental test sections were constructed on Rt. 70 in Meriden, Connecticut between July 20th to the 22nd of 2010. The selected section of Rt. 70 is a two-lane collector road with low truck traffic. Each test section is approximately 1 km long
and spanned both directions of travel (2 lanes total). The site was 16 miles from the asphalt mix plant, which resulted in an approximately 20 minute haul time. Wisecrax© analysis of the preconstruction conditions indicated all sections were in comparable condition before constructing test sections.

In the first section, Sasobit wax pellets were added to PG 64-22 binder at 1.5% by weight one day before mixing. The second WMA section used a foamed asphalt in which water was sprayed into the drum mixers causing the asphalt binder to foam and reduce the required mixing temperature. The last control section was constructed with a conventional hot-mix and was using the base PG 64-22 binder. Multiple cores were taken during construction and used in conjunction with the nuclear gauge to ensure the proper density was being achieved. Thermal imaging was used to measure the mix arrival temperature at the project site and the mat temperature after being placed by the paver. This information was later used for laboratory reheating temperature.

The project was a 50 mm overlay. Milling was performed in particular sections as prescribed by a Connecticut DOT representative and a leveling course was placed one day prior to paving. A Material Transfer Vehicle (MTV) and the same crew and equipment were used throughout the entire project.

LITERATURE REVIEWS

While many European countries have been utilizing WMA for over two decades (1), it has only been in the last 10 years that states throughout the US have implemented this technology. While most agencies have performed trial projects, several states have already developed specifications or provisional specifications for contractors placing WMA (2). Due to a reduction in heating, less of the asphalt binder is volatilized in the WMA. Gandhi (2008) summarized the reduction of output of noxious gases for particular
WMA: Sasobit has a 34% reduction in NO\textsubscript{x} output versus the HMA and 18% reduction in CO\textsubscript{2}, while foamed asphalt has a 31% reduction in CO\textsubscript{2} and 62% reduction in NO\textsubscript{x} (3). Another benefit of using the WMA is an increase in the haul distances as well as extended paving season, since lower ambient air temperatures will not cool mix as quickly (1).

Sasobit wax, as a WMA additive, functions by reducing the viscosity of the asphalt at temperatures above the melting point of the wax (120° C) (1,5). A report published by National Center for Asphalt Technology (NCAT) in 2005 on Sasobit as a pavement additive reported a reduction in air voids, reduced rutting susceptibility, and a reduction in tensile strength. The reduction in tensile strength was believed to be caused by the Sasobit acting as a reduction agent for typical oxidative aging that would occur at higher mixing temperatures (4).

Water can be introduced to the asphalt pavement mixing process by spraying water into the mixer using a nozzle. The water vaporizes which causes the expansion of the binder ultimately lowering its viscosity (1). Previous studies have compared the compactiblity, air voids and densification of the WMA to conventional hot mix showing minimal or no differences between the two in the lab (6). However tensile strength measurements and moisture susceptibility has been found to decrease with the foaming of asphalt (7). A study on foamed asphalt at NCAT also found comparable performance in rutting for foamed samples versus the HMA control (7). Many paving companies prefer foaming asphalt over WMA additives because the implementation costs of the foaming apparatus at a plant is more cost-effective.
While many WMA studies have focused on moisture susceptibility, little research has been conducted on the Low-Temperature Cracking (LTC) properties of WMA. Low-temperature thermal cracking is a primary pavement distress in Northern climates (8). This study hopes to provide insight into potential variation of LTC properties of WMA through tests as described by (8, 9, 10, 11).

**OBJECTIVES:**

The purpose of this study was to evaluate the effects of Sasobit wax modifier and mechanical foaming on the field performance, laboratory rutting resistance and fracture energy of asphalt mixes. The experimental effort included in this paper was performed as follows:

1. Evaluate the rutting susceptibility of plant-sampled, laboratory-compacted specimens in the Hamburg Wheel-Tracking device.
2. Evaluate the Indirect Tensile (IDT) creep compliance and tensile strength of plant-sampled, laboratory compacted specimens.
3. Evaluate the fracture energy of plant-sampled laboratory-compacted specimens.
4. Compare pavement performance of the 3 test sections after 1-year of *in-situ* conditions.

**METHODS AND DATA**

*Materials*

During the construction of test sections, loose mixes were sampled from the delivery trucks while they were leaving the asphalt plant. Then, Gyratory Compacted Samples (GCS) were fabricated in the laboratory according to the mix design. Materials were reheated to the temperature measured from haul trucks arriving at the site: 115°C for
WMA, and 140°C for conventional mix. The material was short-term oven aged for 2 hours and then compacted in the Pine gyratory compactor to a height of 150mm with a target of 6.5% air voids. In total, fifty six GCS were produced. All three mixes used the same aggregate blend with a 12.5 mm NMAS as shown in Figure 1. The base asphalt used was a PG 64-22 with a target binder content of 5.4% which was verified on several samples in the ignition oven procedure (ASTM D 6307) (12).

**FIGURE 1: 12.5mm mixture gradation for the three test sections**

After a curing period, the GCSs were cut with a wet saw according to procedure outlined Table 1. Specimens were then tested in the Indirect Tensile (IDT), Disk-Compact (Tension) (DC(T)), Semi-circular Bending test (SCB) and Hamburg Wheel Tracking (HWT).
### TABLE 1 Specimen fabrication summary

<table>
<thead>
<tr>
<th>Mix type</th>
<th>Location in GCS</th>
<th>IDT</th>
<th>DC(T)</th>
<th>SCB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>-12</td>
<td>-24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>-12</td>
<td>-24</td>
</tr>
<tr>
<td></td>
<td>Top</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>HMA</td>
<td>Top</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Top</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Foamed</td>
<td>Top</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Top</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Sasobit</td>
<td>Top</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Each GCS was conceptually divided into 3 parts along its height: top, middle and bottom. Samples coming from these parts were then randomly assigned to the one of three LTC tests and further to the one of three testing temperatures (see Table 1). Although not fully balanced, this design was intended to ensure statistical validity of the results and eliminate any potential bias related to the air voids content. In order to calculate the air voids, bulk specific gravity (BSG) was measured using ASTM D6752 (13) on each sample after cutting, and combined with the maximum theoretical gravity ($G_{mm}$) ASTM D2041 (14). Then the air voids were evaluated as a function of GCS height.

**TESTING PROCEDURES**

All tests were conducted in the Connecticut Advanced Pavement Laboratory (CAP Lab) located at the University of Connecticut. All LTC testing was performed with a servo-hydraulic 100-kN load frame with closed-loop computerized data acquisition.
system, whereas the Hamburg wheel tracking test was done on the Advanced Pavement Analyzer (APA) built by Pavement Technologies.

_Hamburg Wheel Tracking_
Specimens with a height of 75 mm and diameter of 150 mm are submerged in a water bath and undergo repeated loadings by steel wheels at a temperature of 45 °C and 50 °C. The rutting susceptibility was measured by the inflection point on the rut depth curved measured by the machine (rut depth vs. number of passes of the wheels). It is generally accepted that an inflection point below 10,000 cycles occurs for mixes prone to moisture-induced damage (15).

**IDT Creep Compliance and Strength**
The IDT creep compliance was conducted in accordance with AASHTO T 322 (16). This method requires a 38 mm specimen tested in a split cylinder configuration as seen in Figure 2a. Tests were conducted at three temperatures (0˚ C, -12˚ C, and -24˚ C) after a conditioning period of 2 hours at temperature.

A seating load of 0.35 kN was applied to raise the sensors above their noise levels. The specimen was then immediately loaded to 100 µs in the horizontal direction in the center of a specimen. The load required to achieve this strain was then held constant for 1000 s and the creep compliance function was calculated for each specimen using displacement and load readings. Compliance $D(\dot{\epsilon})$ was calculated using the simple average approach, i.e. treating each specimen separately.

After testing for creep compliance was finalized, the specimens were tested for tensile strength at their corresponding temperatures. This was conducted by applying a constant rate of displacement (12.5 mm/min) on the specimen while recording the induced load.
The critical cracking temperature of each mix was calculated according to the TCMODEL procedure implemented in the current version of the Mechanistic-Empirical Pavement Design Guide (M-E PDG) (17). This model uses relaxation modulus interconverted from the IDT creep compliance in order to calculate thermal stresses. A plot of thermal stress versus temperature is then compared to the envelope of the tensile strength. The temperature at which the two curves intersect is reported as the critical cracking temperature ($T_C$).

Semi-Circular Bending Test

The low-temperature fracture energy and toughness was evaluated using the Semi-Circular Bending (SCB) test. The SCB test specimens require 25mm thick slices cut from a 150 mm diameter GCS. The slice is then cut along a diametric line to produce two semi-circular test specimens. A 15mm crack is then introduced at the mid-point of the halved surface to produce a sample whose geometry can be seen in Figure 2b.

After conditioning for one hour at test temperature, a seating load of 0.35 kN was applied after which the load frame switched to strain-control mode. In the strain control mode, the load is adjusted to achieve a desirable strain pattern. In the case of the SCB testing, the crack mouth opening displacement (CMOD) gauge is opened at constant rate of 0.003 mm/min. To compare the results fracture energy ($G_f$) and toughness ($K_q$) were calculated using the following equations adapted from ASTM E399 (18):

$$K_q = \frac{P_o S}{BW^{3/2}} \left[ 1 + \left( 1 - \frac{r_1}{r_2} \right) \times h\left( \frac{a}{W} \right) \right] \times f_i\left( \frac{a}{W} \right)$$

$P_o =$ applied force,
$S =$ span,
$B =$ thickness,
$W =$ specimen width,  
$a =$ initial crack length, and  
$r_1$, $r_2 =$ inner and outer radius respectively

For $h\left(\frac{a}{W}\right)$ and $f_1\left(\frac{a}{W}\right)$ the following equations were used:

$$h\left(\frac{a}{W}\right) = 0.20 - 0.32\left(\frac{a}{W}\right) + 0.12\left(\frac{a}{W}\right)^2 \quad (2)$$

$$f_1\left(\frac{a}{W}\right) = \frac{0.644 + 1.11\left(\frac{a}{W}\right) - 1.49\left(\frac{a}{W}\right)^2 + 0.73\left(\frac{a}{W}\right)^3}{\left(1 - \frac{a}{W}\right)^{3/2}} \quad (3)$$

In order to calculate the total fracture energy, an exponential function was used to extrapolate the softening region of the load-displacement curve. The curve was extrapolated until zero force and the total area under the load-displacement curve was used in the energy calculations. The extrapolation process is a generally accepted practice in fracture mechanics and it is rather necessary due to limited range of the CMOD gauges and the noise level of the load cell.

**Disk Compact (Tension) Test**

The second method to determine the fracture energy and toughness was the Disk Compact Tension test (DC(T)). DC(T) tests are performed on 50 mm thick specimens cut to disk-like geometry as seen in Figure 2c. Two one-inch holes are cored from one side of the specimen where a 5 mm deep chord is trimmed from the edge. The trimmed edge allows for the CMOD transducer to be placed over a 50 mm pre-crack made with a wet saw during sample preparation.
The DC(T) test starts with the application of a seating load of 0.35 kN on the specimen. Once this load is achieved, the testing procedure varies the load applied to the specimen to maintain a constant rate of 1.0mm/min CMOD measured by the transducer. The test ends when the applied load falls below a minimal threshold value or when the limit of the CMOD is reached. Fracture energy and toughness are then calculated in a similar manner to the SCB, with the extrapolation of the load vs. CMOD curve beyond the termination of the test.

The fracture energy $G_f$ is determined using Equation 4 from ASTM D 7313-07a (19):
\[
G_f = \frac{A_c}{B \cdot l}
\]

where:
- \(G_f\) = fracture energy (J/m\(^2\))
- \(A_c\) = area under the load-CMOD curve
- \(B\) = specimen thickness and, \(l\) = initial ligament length (m)

The equation for the fracture toughness \(K_Q\) was adapted from the ASTM E399 and can be shown as follows:

\[
K_Q = \frac{P_Q}{B \sqrt{W} \times f_3 \left( \frac{a}{W} \right)}
\]

where:
- \(P_Q\) = applied force (N)
- \(W\) = specimen width (m)
- \(a\) = initial crack length (m)

and,

\[
f_3 = \left( \frac{2 + \frac{a}{W}}{0.76 + 4.8 \left( \frac{a}{W} \right) - 11.58 \left( \frac{a}{W} \right)^2 + 11.43 \left( \frac{a}{W} \right)^3 - 4.08 \left( \frac{a}{W} \right)^4} \right) \left( 1 - \frac{a}{W} \right)^{3/2}
\]

**Performance Data Collection**

Both WMA sections and control section were surveyed one week before construction in 2010 and approximately one year after construction in spring, 2011. Surveys were conducted using two Automatic Road ANalyzer (ARAN) vans operated by the Connecticut Department of Transportation. Both lane-rutting data and high-resolution imagery were collected with respect to location along the test sections at 5 m intervals.

Pre-construction survey data was analyzed by the ConnDOT using Wisecrax® software. The output in linear meters of transverse and longitudinal cracking verified that all test sections were in the comparable condition before construction. Wisecrax® was
used because there was a substantial amount of surface distress in the pavement before the test sections were placed. For the post-construction survey, comparable cracking data was obtained by the visual examination of the high-resolution pavement images taken by the ARAN vans. The methodology of visual examination followed ASTM D6433-03 (20). The rutting data in both surveys was collected using a laser distance bar across the front of the van. The results of the rut depths for each section are presented in the results section of this paper.

DISCUSSION OF RESULTS

Results from the density measurements, rutting susceptibility, LTC testing and field performance are reported below. Analysis for each test includes an Analysis of Variance (ANOVA) with the mix type, test temperature and specimen gyratory location to check for significant influence of these parameters. Supportive figures are shown with one standard error bars from the mean value for each treatment.

Densities of specimens

Ninety density measurements were taken on specimens cut from different relative locations from each GCS. The results of bulk specific gravity measurements ($G_{mb}$) and maximum theoretical gravity measurements ($G_{mm}$) were used to calculate the air voids in each specimen and location. Figure 3 shows the comparison of air voids by location and mix type.
It can be seen from the Figure 3 that the densities varied most in the middle of the specimens. This can be attributed to the pressure distribution through the GCS as it is being compacted. The lowest compaction occurs at the ends of the GCS (high air voids content) and it increases towards the center of the GCS where the air voids are typically the lowest and constant over center part (21). Analysis shows that air voids differ insignificantly between mix types. Previous testing supports reduced variation in the compactibility of WMA (8). Statistical comparison did show significance between the locations within the GCS (i.e. top, middle, bottom) when mix type was not considered as a factor.

_Hamburg Wheel Tracking_

The results from the Hamburg test are summarized in Table 2. Several of the trials were considered to be outliers and omitted due to the testing error. Many of the trials reached their stripping inflection point near the conclusion of the test, or demonstrated very mild transitions between the rutting and stripping portions of the deflection curve.
To best identify the inflection point, quadratic functions were fit to each curve and the inflection points were determined using the fitted equations.

**TABLE 2 Stripping inflection point and corresponding rut depth for tested mixes.**

<table>
<thead>
<tr>
<th>Mix</th>
<th>45°C</th>
<th>50°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rut Depth(mm)</td>
<td>Inflection(Passes)</td>
</tr>
<tr>
<td>Conventional</td>
<td>6.04</td>
<td>16666</td>
</tr>
<tr>
<td>Foamed</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Sasobit</td>
<td>7.92</td>
<td>20000</td>
</tr>
</tbody>
</table>

Based on the results from the Hamburg WT test, the foamed asphalt actually reduced the rutting susceptibility at 50°C relative to the conventional mix, and had no adverse effects on the inflection point. The Sasobit wax additive appears to have increased rutting severity, but extended the inflection point. Hurley and Prowell reported an improvement in rutting susceptibility with the addition of Sasobit (4). From these results it could be expected that the Sasobit wax additive can add protection against moisture damage, but decreases the rutting resistance of the mix. Increased rut depth in the Sasobit mix can be attributed to the ‘improved workability’ studies previously described (6). The prolonged inflection point relative to the foamed and conventional mixes is likely to be linked with the higher densification levels, which reduces air voids in the mix.

All of the tests exceed the 10,000 pass requirement for strong-performing pavement (22) as described by the test protocol. In APA testing conducted in Nebraska, the Sasobit wax mixture had the lowest reported rutting (2). This difference between researcher’s results can be attributed to the inter-laboratory variation in wheel tracking...
devices as well as WMA lab mixing procedures (i.e. plant blended additives vs. binder terminal blended).

**IDT Creep Compliance and Strength**

Figure 4 shows the critical cracking temperatures, $T_{cr}$ calculated from the TCMODEL. The values indicate that both WMA have higher critical temperatures than the control mix. This may suggest that thermal cracking could be a potential issue in the WMA sections; however, the differences between $T_{cr}$ values are relatively small and can be caused by the approximations and accuracy of the model algorithm. While few published studies have reported $T_{cr}$ values for WMA, similar results reported by Cooper (2009) suggest Sasobit can adversely affect the low-temperature properties. Their rheological testing showed an increase in the low PG grade of a binder after the addition of Sasobit (23).

![FIGURE 4 IDT Critical Cracking temperatures ($T_{cr}$), °C](image)

The IDT tensile strength results are presented in Figure 5. Visual observation of this figure shows the expected overall increase in the tensile strength as the temperature...
decreases. The comparison of strength values between different mixes suggests that both foamed asphalt and Sasobit wax have little effect on the tensile strength. An Analysis of Variance (ANOVA) was run to determine the contribution of temperature and mix on the variation in the results. It was concluded that temperature is highly significant, but mix type was insignificant for tensile strength results. The tensile strength results suggest there are minimal low-temperature effects of either foaming or Sasobit wax additives. The differences of mixtures have been more distinct in the high-temperature range of many Tensile Strength Ratio studies (2).

FIGURE 5 IDT Tensile Strength results

*Semi-Circular Bending*

SCB test produces fracture energy and toughness as a function of temperature. As seen in Figures 6(a) and 6(b), respectively, there was only slight variation between mixes and no consistent trends were observed that would distinct any particular mix. ANOVA was performed with different response variables, such as total fracture energy, pre-peak energy, post-peak energy and fracture toughness to determine if the factors, such as test
temperature, mix type and location, had any effect on the results. The ANOVA indicated that only temperature is a significant factor for all of the response variables tested. It can be concluded from the SCB results that the three mixtures have statistically the same fracture properties.

![Graph showing fracture energy and toughness results](image)

**FIGURE 6 (a) Fracture energy and (b) Fracture toughness calculated from SCB results**

*Disk Compact Tension*

The DC(T) data were used to calculate the fracture energy and toughness similar to the SCB test. The average fracture energy results are shown in Figure 7(a) and no strong difference can be observed between the three mixes. Overall it should be mentioned that the Sasobit-wax mixes had consistently higher variability as compared to the foamed asphalt and conventional mix. ANOVA showed, similar to the SCB and tensile strength results, that temperature has a highly significant effect, but the mix type and air voids have insignificant effect on the fracture energy and toughness. Figure 7(b) shows the results from fracture toughness calculations. Again, temperature was the only factor to have significant influence on $K_I$. 
Field Performance

Field performance data was collected approximately one year after the construction. During that time sections went through severe winter conditions including 25 days with a high temperature below 32°F and an absolute low temperature of -1°F. Cracking field performance is presented for each section in Figure 8, whereas Figure 9 shows the rutting data. A comparison can be made between the sections because they were all exposed to identical weather conditions and traffic volumes. Figure 8 shows the linear meters of cracking per 150 m section.
FIGURE 8 Cracking by section in linear meters (both directions) for 150m sections

It can be seen from Figure 8 that the Sasobit section had the greatest amount of linear cracking and the conventional section had the least linear cracking. The majority of the cracking was transverse, which indicates the low temperature as the primary cause. The TCMODEL (Figure 4) supports the trends in cracking performance from Figure 8. It should be noted however that the test sections are only one year old and all observed cracking was very low. The potential relative differences will develop over the years which will lead to more firm conclusions about the performance of these sections. Just for the comparison, cracking observed after the first winter was less than 2% of the cracking measured in 2010 before the construction of test sections.

Rut depths measured by the ARAN were averaged per section per direction and they are displayed in Figure 9. Similar to the laboratory results, the data was also processed using ANOVA. The results showed significant differences between all 3 mixes, with foamed asphalt having the lowest average rutting and Sasobit wax having the highest amount of rutting.
Without being able to normalize this data to the initial rutting level immediately after construction, it is difficult to conclude if the rutting that has occurred over one year was a function of mix type or it was related to the pre-construction activities. Also, the observed rutting is fairly minor and can be partially attributed to the mix densification due to traffic loading as well as other factors. Future surveys will help distinguish between the sections.

**CONCLUSION**

This study compared laboratory and field performance of two WMAs and one conventional HMA. The test sections were placed consecutively on state Route 70 in Meriden, CT. Laboratory evaluation on the laboratory-compacted samples included Hamburg WT, IDT, SCB and DC(T) tests. The field surveys were conducted before construction and one year after the construction using Automatic Road Analyzer vans.
While the overall performance of the mixes appears to be quite similar after one year, there are several distinct differences identified in this study:

- Sasobit wax had the longest time until the stripping inflection point, but had the greatest amount of rutting. This observation could be linked to improved workability and larger reductions in air voids with densification.

- TCMODEL results support the in-place transverse cracking performance of each section; however it should be mentioned that sections went only through one severe winter cycle.

- Tensile strength did not vary significantly between any of the mixes when temperature was fixed.

- Fracture energy and toughness measured in the SCB and DC(T) show no significant differences by mix when temperature was fixed.

- Sasobit wax showed higher rutting trends in the field and had the largest amount of linear feet of cracking overall. This performance could be attributed to the variance in subsurface conditions although sections were in fairly uniform condition prior to construction.

  In summary, the differences quantified between mixes in the lab, and the measurable differences from the field test sections showed similar trends. The most susceptible critical cracking temperature quantified in the lab was for the Sasobit wax additive. This mix type had the greatest amount of cracking observed after 1-year in the field. Statistical analysis of the tensile strength and fracture energy of the mixes showed insignificant variation between them, which is similar to previous studies exploring WMA additives that showed very little variation in dynamic modulus values with various additives (2, 4).
Although this study is still ongoing, the majority of the findings in this paper align with previous research. The pavement condition in all three test sections will continue to be evaluated in the following years.

AKNOWLEDGMENTS

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Evaluation of an Alternative Moisture Sensitivity Test

ABSTRACT

This study examined the Moisture Induced Stress Tester (MiST) as a means of identifying stripping potential in asphalt materials. Material tested in the MiST included field samples from six Long-Term Pavement Performance (LTPP) test sections as well as field and laboratory compacted warm-mix asphalt samples produced in a drum plant. Wearing surface cores from the LTPP test sections were run through the MiST and water samples before and after the test were analyzed using Infrared (IR) spectrometry. The warm-mix specimens were MiST conditioned and compared to traditional Tensile Strength Ratio tests (AASHTO T283) as well as pre- and post-treatment bulk specific gravities. The results showed comparable results between MiST conditioning and the T283 for HMA but similar comparison was not true for the tested WMA specimens. Furthermore, the IR analysis showed potential differences between the mixes, however the low concentrations and ambiguous peaks made it difficult to draw any firm patterns.

LITERATURE REVIEW

Moisture sensitivity of asphalt pavements is a complex phenomenon caused by many different factors. From aggregate-binder incompatibilities to bad plant and paving practices, there is abundant opportunity to place moisture-susceptible pavement (24). New technologies such as Warm-Mix Asphalt (WMA) and Low-Energy Asphalt (LEA) further increase the potential for moisture in aggregate during production with lower required temperatures. As states continue to implement these new technologies, the need for a rapid and sensitive method for detecting moisture susceptibility is required. Current practices for many State Highway Agencies, (SHA) including Connecticut, require over
32 hours of conditioning for accelerated moisture susceptibility identification. The concept of pore pressure applied by water at elevated temperatures was integrated into an alternative accelerated moisture conditioning system known as the Moisture Induced Stress Tester (MiST). Alternative technologies such as the MiST can greatly improve the efficiency and accuracy for quality assurance by providing faster results, or a greater volume of results.

Moisture at the aggregate-binder interface is common cause for stripping (24). Many tests from Hamburg-Wheel Tracking to the Texas Boiling Test utilize high-moisture as an environment for accelerate testing of moisture susceptibility. There are several common types of stripping failures in pavement and they are summarized in Tarrer and Wagh, (1991). Detachment is the separation of asphalt from the aggregate surface by loss of adhesion. Displacement is the separation of aggregate and binder by a previous break in the binder film. Spontaneous emulsification is a process in which the water particles become suspended in asphalt. Two physical stripping phenomena are pore pressure and hydraulic scouring (24). While all these failures are grouped under the common term, “stripping,” the test procedures summarized below often can only detect one or several phenomena, and cannot identify all stripping susceptibilities.

Previous work conducted by Plancher et al. (1977) provided insight to the chemical processes in asphalt stripping phenomena. Their research performed several solvent baths after varying levels of aging to determine which functional groups within asphalt binder had the strongest adsorption to several different aggregates. It was found that in general, ketones had the strongest adsorption to aggregate, while anhydrides demonstrated the weakest bond (25). Further work has continued in this vein of research (26) and with
more modern measuring devices Song et al. in 2011 quantified the soluble components of asphalt binder after first dissolving the binder in toluene. Based on this work, the researchers identified aldehydes, alcohols and phenols as water-soluble components of the binder (27).

**Moisture Induced Stress Tester**

The first model of the MiST was built in 2002. A study performed at Mississippi Transportation Research Center (2005) emphasized the benefits and disadvantages of this preliminary design. Initially, the MiST monitored turbidity of the water over time, as well as slow cycle times (28). The MiST version 9, used in this study no longer evaluates turbidity, but can condition more specimens at once than the initial models and cycles pore pressure at a significantly faster rate. The MiST 1 cycled loads at 5.55 cycles/min (Buchanan and Vernon, 2005), and the MiST 9 runs a much improved 18.5 cycles/min.

Early work with the MiST compared several HMA treatments and determined the MiST did not correlate with AASHTO T283 results (28). Further research has since been conducted and found to better correlate (29-31). Other testing devices have also been developed which combine elevated temperatures and pressure to accelerate moisture damage in the laboratory (32).

**OBJECTIVES**

The objective of this study was to evaluate the Moisture Induced Stress Tester (MiST) as a means of accelerated moisture susceptibility testing for asphalt materials. Using Long-Term Pavement Performance cores from 6 test Specific Pavement Studies in Connecticut as well as laboratory compacted and field cores from two WMA and a control HMA produced and placed in Connecticut, the following tests were undertaken:

- Fourier Transform Infrared Spectroscopy (FT-IR)
• Bulk Specific Gravity
• Indirect Tensile Strength Testing

It was hypothesized that similar Tensile-Strength Ratio values would be measured using a modified Lottman procedure (AASHTO T283) and the MiST conditioning procedure. Additionally, it was speculated that as stripping occurs, FT-IR would be able to quantify different levels of leached asphalt in the water sampled from the MiST device.

The Moisture Induced Stress Test Apparatus

The MiST machine uses a cyclic pore pressure loading and high water temperatures to simulate a harsh moisture condition for asphalt pavement. Previous studies were performed to determine the optimal temperature and cycles for a wide range of material (28-31). It was decided to use the recommended test procedures based on the outcome of these studies to determine whether or not custom test procedures would be required for adaptation of the MiST for Connecticut conditions. The machine is presented in Figure 1.
FIGURE 1 the Moisture Induced Stress Tester by Instrotek

EXPERIMENTAL PLAN

In total 54 field samples and laboratory specimens were evaluated using three different treatments. From the field, nine cores from the WMA test sections and control as well as eighteen samples from the LTPP test sections were MiST conditioned. The remaining laboratory compacted specimens were either controls, MiST conditioned or conditioned according to AASHTO T283 as described in the subsequent paragraph. The differences between each treatment were quantified using a combination of bulk specific gravity as well as the indirect tensile strength test.

LTPP Test Sections
The six LTPP sections which are evaluated in this study were part of the SPS-9A experiment sponsored by the Federal Highway Administration. These particular sections were placed in Connecticut in 1997 and the differences between the sections are outlined in Table 1. It should be noted that the first 3 sections contain 20% of Recycled Asphalt Pavement (RAP) whereas the other 3 sections did not contain any RAP in their mix design.

### Table 1 Summary of LTPP SPS 9-A sections placed in Colchester, CT

<table>
<thead>
<tr>
<th>Section ID</th>
<th>090901</th>
<th>090902</th>
<th>090903</th>
<th>090960</th>
<th>090961</th>
<th>090962</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction</td>
<td>EB</td>
<td>EB</td>
<td>EB</td>
<td>WB</td>
<td>WB</td>
<td>WB</td>
</tr>
<tr>
<td>ConnDOT Log Mileage</td>
<td>25.48-27.48</td>
<td>27.48-29.70</td>
<td>29.70-31.72</td>
<td>31.72-29.64</td>
<td>29.64-27.56</td>
<td>27.56-25.48</td>
</tr>
<tr>
<td>Top layer thickness, in</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Mix Type</td>
<td>Class 1</td>
<td>Superpave</td>
<td>Superpave Alternative</td>
<td>Class 1</td>
<td>Superpave</td>
<td>Superpave Alternative</td>
</tr>
<tr>
<td>Virgin Binder Grade</td>
<td>AC-20</td>
<td>PG 64-28</td>
<td>PG 64-22</td>
<td>AC-10</td>
<td>PG 58-34</td>
<td>PG 58-28</td>
</tr>
<tr>
<td>Percent Binder</td>
<td>5.4</td>
<td>5.3</td>
<td>5.3</td>
<td>5.0</td>
<td>4.8</td>
<td>5</td>
</tr>
<tr>
<td>AV</td>
<td>4.4</td>
<td>3.6</td>
<td>3.3</td>
<td>2.8</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>VMA</td>
<td>16.8</td>
<td>14.4</td>
<td>13.7</td>
<td>13.9</td>
<td>14.9</td>
<td>15.5</td>
</tr>
<tr>
<td>RAP content</td>
<td>0</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Anti-strip agent content by weight of binder</td>
<td>0</td>
<td>0.25%</td>
<td>0.25%</td>
<td>0</td>
<td>0.375%</td>
<td>0.375%</td>
</tr>
</tbody>
</table>

While several of the sections exhibited polishing of the wearing surface aggregate over the 12 years in-service, section 090961 and 090962 demonstrated severe stripping problems, as shown by the core displayed in Figure 2.
FIGURE 2 LTPP field core from section 090962, stripping, i.e. moisture distress within test section

The WMA test sections were placed on Rt. 70 in Connecticut in July, 2010. The three 1-km sections were paved as a 50mm overlay on a two-lane collector road in both traffic directions. One section was a conventional HMA while the two WMA trial sections contained (a) Sasobit wax additive, (b) water injection for foaming asphalt. Mix was sampled for lab compaction at the plant and field cores were taken during construction. The site was a 20 minute haul distance from the plant.

Three gyratory compacted specimens from each WMA treatment and the HMA control group were compacted in a Superpave gyratory compactor to a height of 95 mm. After a curing period, the specimens were conditioned to a temperature of 25° C for 2 hours and tested in the indirect tensile strength test. A second set of 3 cores from each treatment was saturated in a vacuum pump for 7 minutes after which the specimens were placed in a freezer at – 18° C for 16 hours. After the freezing cycle, the cores were
conditioned at 60° C for 24 hours. Finally, these cores were submerged in a 25 ° C water bath for 2 hours. After the conditioning period the indirect tensile strength test is performed at 50 mm/min (33). This is the standard procedure for AASHTO T283.

The final set of laboratory specimens were conditioned in the MiST. The procedure recommended by previous research submerges the specimens in water, maintained at 60° C and applying 275.8 kPa pore pressure at 0.5Hz for 3,500 cycles. After the machine completes all 3,500 cycles, the cylinders are then submerged in a 25° C water bath for 2 hours before performing the indirect strength test at 50 mm/min displacement rate (33). Figure 3 presents the experimental test effort in a flow chart.

FIGURE 3 Experimental flow chart
Laboratory specimens were fabricated from mixture collected at the plant and reheated to the temperatures measured by thermal imaging of the mix arriving at the paver during construction. The target air voids for the samples was 7 +/- 0.5%.

Bulk specific gravity measurements were conducted using the automatic vacuum sealing method (34) for the field specimens and the Saturated Surface-Dry method (35) was used for the laboratory compacted specimens both before and after conditioning.

It was hypothesized that adsorption-water displacement would occur during MiST conditioning. In order to test this hypothesis, water samples were collected before and after each LTPP test specimen was MiST treated and an Attenuated Total-Reflectance Fourier Transform Infrared-Spectrometer (ATR FT-IR) was used to analyze the samples. The water samples were measured in the ATR FT-IR in order to identify any absorbance peaks in the solution’s spectra relating to asphalt. Previous studies used FT-IR in a controlled experiment to determine the diffusion rate of water through a thin film of asphalt (36).

For comparison in FT-IR analysis, a control sample was produced by boiling 10 g of asphalt in 400 mL of water for 3 hours. Spectra were measured from this control specimen to compare the results with the MiST –tested water.

DISCUSSION OF RESULTS

LTPP Sections

Using the Core-Lok method (34) the bulk specific gravity of 3 specimens each were compared before and after MiST conditioning. The results from the comparison are illustrated in Figure 4. It can be seen that section 61 had the largest percent difference in its density after MiST conditioning.
FIGURE 4 Bulk Specific Gravity (B_{sg}) percent difference pre-MiST/post-MiST. Thicker line weight borders indicate presence of RAP.

It is noteworthy that the results from the LTPP test sections containing RAP had a greater percent difference. It is critical to note that these LTPP sections containing RAP have factors beyond the 20% RAP addition that contribute to their larger deviation (37). Larsen and Rodrigues report several instances of roller operational issues which may have affected the uniformity and density in these sections.

Spectroscopic analysis of the water samples from each conditioning cycle were processed using the procedure developed by Yut (2012), where a baseline correction normalization of the spectra was conducted in MATLAB before any comparisons were made (38). Figure 5 shows a sample of the post-processed spectra measured at the completion of the MiST tests compared to a baseline tap water sample. It can be seen that section LTPP-03 and LTPP-62 reflect several unique peaks as well as proportional peaks.
FIGURE 5 Typical Pre-MiST/Post-MiST Spectra from an LTPP field core

To better understand the difference between the LTPP sections, a baseline correction and normalized band-area approach was used (38, 39). Comparative analysis was performed across all sections to identify the trends and unique peaks. Figures 6a and 6b show the relative band areas identified as relating to asphaltic materials (40) and how they changed for each section.
FIGURES 6 a-d – Post-MiST water samples normalized band areas at (a) Wavelength 635 cm\(^{-1}\) by section; (b) Wavelength 1060 cm\(^{-1}\) by section; (c) Wavelength 1340 cm\(^{-1}\) by section; (d) Wavelength 1865 cm\(^{-1}\) by section

Besides the peaks noted in Figure 6, section 02 had measurable absorbance at 721 cm\(^{-1}\) and section 61 had absorbance at 1456 cm\(^{-1}\) which were both indicative of asphalt binder. The peaks shown in Figure 6(c) are attributed to anti-stripping agent; this was predicted because the functional group associated with this peak (NH\(_2\)) is typically found in anti-stripping agents and is less likely to be found in pure binder. Additionally the peak in Figure 6(a) was attributed to aggregate, the wavelength is commonly associated with Silica, which is a large portion of the chemical composition of all aggregate in Connecticut. Based on this visual analysis alone, it can be concluded that FT-IR spectroscopy can be used to identify asphalt presence.
Not only should asphalt be identifiable, however, but trends of leaching rates should be quantifiable from different mixes. To best identify the performance rates, the most prevalent spectroscopic peak was compared to the physical changes illustrated in Figure 4. The results shown in Figure 7 illustrate the correlation between structural deficiency and relative FT-IR index of wavelength 1060 cm\(^{-1}\).

![Graph showing correlation between percent difference in bulk specific gravity and FT-IR index of 1060 cm\(^{-1}\).](image)

**FIGURE 7 Percent difference in bulk specific gravity versus relative spectra concentration at 1060 cm\(^{-1}\)**

The linear regression shown in Figure 7 has a significant slope, but an R-squared value of 0.42, while this is identified as poor correlation, it is believed that the trend would grow to a stronger correlation with a larger data set. With this relationship identified, further work must be conducted to determine the underlying chemical reactions but it is suggested that physical changes to the specimen inversely correlated to a higher relative absorbance of asphalt-related spectroscopic peaks in the water upon completion of MiST treatment. It is speculated that the weaker specimens (cores which
had higher volumetric change) had already succumbed to stripping and thus previously leached a portion of their asphalt material leaving less behind available for detection in the MiST test.

**WMA Sections**

The percent difference in bulk specific gravity for both field cores and laboratory produced specimens is shown in Figure 8. It can be seen that the field specimens showed a drastically smaller change relative to their laboratory counterparts after MiST conditioning. It is important to note that none of these mixtures was suspected to have moisture susceptibility. The laboratory compacted specimens for both WMA additives changed 1.0% and the Sasobit WMA had the greatest change in density for any field specimens.

![FIGURE 8 Percent difference in G_mb for WMA field and laboratory specimens](image)

In order to effectively determine the differences between standard AASHTO T283 and MiST conditioning, the individual strength test measurements were used to calculate the Tensile Strength Ratio (TSR) – a ratio of conditioned specimen strength to
unconditioned specimen strength. By using individual instead of averaged values the variance is preserved from both strength tests when calculating average results. Triplicate strength measurements for each condition and treatment yielded 9 TSR measurements. The TSR values are shown in Figure 9 while Figure 10 contains the measured tensile strength.

FIGURE 9 TSR Results for from MiST and AASHTO T283
It can be seen in Figure 9, the Sasobit test section did not match conventional AASHTO T283 conditioning and the MiST conditioning due to the lower strength values after T283 method. It suggests that a new criterion for the acceptance should be developed specifically for the MiST testing. The conventional HMA and foamed WMA section had statistically identical results for both accelerated conditioning procedures at a 95% confidence interval. The measured tensile strength results (Figure 10) indicate higher average strengths for the HMA, and while the error bars show high variability an Analysis of Variance shows mix type being highly significant (p-value < 0.001) and treatment is very-nearly significant (p-value = 0.081). With a larger data set, the significance of treatment type could be better determined. The results reported by Shu et al. (2011) showed an increase in the TSR values for foamed WMA that was MiST conditioned; the results from this study showed similar behavior for Sasobit, but not for the foamed mix (31).
CONCLUSIONS

This study evaluated the Moisture Induced Stress Test as a rapid moisture susceptibility conditioning apparatus. Using two warm-mix technologies, a control HMA and six LTPP test sections the MiST was validated and compared to the AASHTO T283 laboratory procedure used in Connecticut. Additionally, spectroscopic analysis using Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy was implemented to identify the potential presence of asphalt in the water from MiST Testing. The following findings were noted:

- The $G_{mb}$ for LTPP mixes containing RAP was greater than that of their counterpart sections
- FT-IR Spectroscopic Analysis identified significant peaks relating to the presence of asphalt in the post-conditioned water for LTPP field cores at the 1060 cm$^{-1}$ wavelength
- Negative correlation was identified between percent-difference in $G_{mb}$ and the 1060 cm$^{-1}$ absorbance-area index. This leads to speculation on the availability of asphalt material previously leached from the cores caused by moisture distresses.
- The presence of aggregate (635 cm$^{-1}$) and anti-stripping agent (1865 cm$^{-1}$) were identified in several water samples from various sections
- The change in $G_{mb}$ from the WMA field cores was much lower than the laboratory compacted specimens
- Tensile Strength Ratio correlated well for the HMA and WMA foamed but varied significantly for Sasobit wax
It can be concluded that the Moisture Induced Stress Test is a viable alternative test method for identifying moisture susceptibility. The use of spectroscopy as a means of quantifying moisture susceptibility should be further investigated but the evidence in this study demonstrated the benefits of chemical analysis for explanation of physical behavior in the on-going effort to mitigate moisture susceptibility.

It is suggested that further sensitivity analysis be conducted on the MiST for use in Connecticut using a wider variety of aggregates, gradations and binders. Furthermore a longer residence time in the MiST may provide for stronger differences in FT-IR spectra when collecting water samples from the MiST.

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