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NCAT
at AUBURN UNIVERSITY

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ABSTRACT

Warm-mix asphalt (WMA) mixtures produced using two different WMA technologies were evaluated in a field project located in Milwaukee, Wisconsin. The technologies evaluated were Sasobit® and Evotherm™. A control section was also produced so comparisons could be made between WMA and conventional hot-mix asphalt (HMA). Mixture volumetric properties, rutting susceptibility, moisture resistance, and dynamic modulus measurements were conducted to evaluate material performance. In-place field performance data were also collected. Laboratory tests indicated approximately equal performance between the Sasobit® and control mixtures. Evotherm™ emulsion mixture exhibited higher rut depths, lower tensile strengths, and lower moduli than the HMA, which may be a result of fuel contamination. However, field performances of all three mixtures were comparable after four months of traffic.

INTRODUCTION

Several new processes have been developed in recent years that will reduce the mixing and compaction temperatures of hot-mix asphalt (HMA), improve compaction, or both. Generically, these technologies are referred to as warm-mix asphalt (WMA). Three processes were initially developed in Europe, namely Aspha-min® zeolite, Sasobit®, and WAM Foam® in response to a variety of concerns. Beginning in 2002, interest in these technologies has grown in the United States, based on a study tour sponsored by the National Asphalt Pavement Association. Since that time, a number of new processes have been developed, including U.S.-based processes such as Evotherm™, one of the processes used in this project.

All of these processes work to lower mixing and compaction temperatures. However, the mechanism by which they work varies from process to process. Processes that introduce small amounts of water to hot asphalt, either via a foaming nozzle or a hydrophilic material such as zeolite, or through damp aggregate, rely on the fact that when a given volume of water turns to steam at atmospheric pressure, it expands by a factor of 1,673 (*1*). When the water is dispersed in hot asphalt and turns to steam (from contact with the hot asphalt), it results in an expansion of the binder phase and an increase in workability. The amount of expansion depends on a number of factors, including the amount of water added and the temperature of the binder (*2*).
Wax-like additives, such as Sasobit®, reduce the viscosity of the binder above the melting point of the wax (*3*). Sasobit® has a congealing temperature of about 216°F (102°C) and is completely soluble in asphalt binder at temperatures higher than 248°F (120°C). At temperatures below its melting point, Sasobit® reportedly forms a crystalline network structure in the binder that leads to increased stiffness of the binder (*3–4*).

Emulsions have long been used to produce cold mixes. First-generation Evotherm™ is an emulsion-based technology used to produce WMA. The core of the Evotherm™ technology is a chemistry package that includes additives to improve coating and workability, adhesion promoters, and emulsification agents. Bulk properties of the emulsion, such as viscosity and storage stability, and particle-size distributions, are typical of those found in conventional asphalt emulsions. The total Evotherm™ chemistry package is typically 0.5% by weight of emulsion. Since this field project, several additional methods of introducing Evotherm™ have been developed and evaluated. These include Evotherm™ Dispersed Asphalt Technology (DAT) and Evotherm™ Third Generation (G3).

Beginning in 2003, laboratory studies were conducted to evaluate the effect of WMA processes Aspha-min® zeolite, Sasobit®, and Evotherm™ on mixture performance and evaluate their suitability for U.S. paving practices (*5–7*). The laboratory studies confirmed that the WMA processes improved compaction, even at reduced temperatures. Two concerns were identified with some of the WMA process/aggregate combinations: 1) potential for increased rutting and 2)

potential for increased moisture susceptibility. The former was believed to be related to the decreased aging of the binder at lower production temperatures. The latter was believed to be related to incomplete drying of the aggregates at lower production temperatures (*8*). However, it was believed that these potential concerns could be mitigated, and field trials progressed.

In 2006, several WMA field trials were constructed, including three that utilized multiple technologies. One of these multiple-technology field projects, located in Wisconsin, is presented in this report. The general project description and materials used for the project are discussed first. Then, the test procedures and associated test results are presented. A description of field performance four months after construction follows the test procedures. And, finally, conclusions based on the obtained test results are presented.

PURPOSE AND SCOPE

The main purpose of this study was to evaluate the field performance of two WMA technologies. Two different WMA processes were introduced into existing HMA designs without any other design changes. WMA sections were constructed on in-service roadways along with HMA control sections. Sampling and testing was generally conducted using the data-collection guidelines developed by the WMA Technical Working Group (*9*). Field-mixed, laboratory-compacted samples' volumetric properties, laboratory performance tests, and field-performance data are reported.

PROJECT DESCRIPTION

The field trial consisted of the reconstruction of State Highway 100 (Ryan Road) to a four-lane divided highway. The total pavement thickness was 6.25 inches of Wisconsin Department of Transportation (DOT) type 3 million ESAL mixture over 4 inches of Open-Graded Base Course (OGBC) over 8.5 inches of Dense-Graded (Aggregate) Base Course (DGBC) (*10*). The WMA was used for the top 1.75 inches of the surface course in the westbound passing lane. Two technologies were used on the project: Sasobit® and Evotherm™. The WMA test sections were placed in conjunction with an open house sponsored by Payne and Dolan (the contractor), Wisconsin DOT, and the Wisconsin Asphalt Pavement Association. Figure 1 presents the project location relative to Milwaukee, WI.

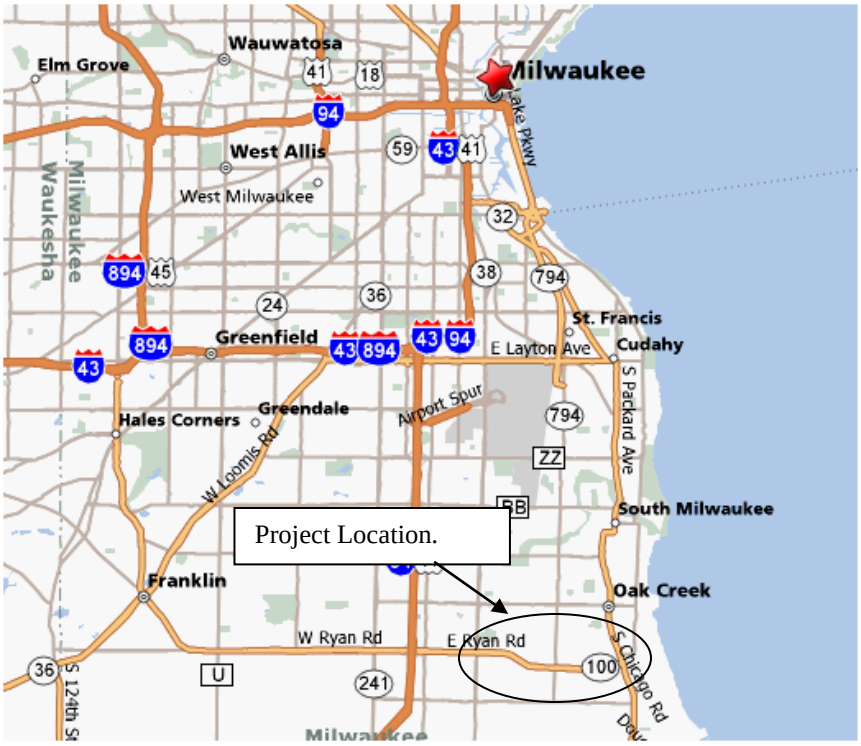

Figure 1 Milwaukee, WI WMA Project Location.

MATERIALS

The job mix formula used was a 12.5 mm nominal maximum aggregate size (NMAS) Superpave mixture designed with a compactive effort of 75 gyrations. A gravel aggregate source was used in this mix design. The mixture used an unmodified PG 64-28 asphalt binder and contained 14% reclaimed asphalt pavement (RAP). As noted previously, two WMA processes were used. Evotherm™ emulsion was produced using the same base binder and replaced the liquid asphalt during production of the Evotherm™ section. The Evotherm™ addition rate was adjusted so that the resulting asphalt residue equaled the design asphalt content. Sasobit® was added at a rate of 1.7% by total weight of virgin asphalt binder. Typically, Sasobit® is added at a rate of 1.5% by total weight of asphalt binder; the extra percentage accounts for the binder included in the RAP. Sasobit® was pre-blended with the binder at the Construction Resource MGT Inc. Washington Street Terminal in Milwaukee, WI. The binder test results for the control binder and Sasobit® modified binders are shown in Table 1. The design aggregate gradation and optimum asphalt content are presented in Table 2.

Binder testing was conducted on material sampled during construction of the test sections according to AASHTO M320. The binder results indicated the addition of Sasobit® increased the stiffness of the binder at high, intermediate, and low test temperatures. The relative change between the original and the RTFO DSR test results is an indication of the aging binder

undergoes during the construction process. The data in Table 1 shows that the Sasobit® modified binder exhibited reduced aging when compared to the control binder. The RTFO DSR test result for the control binder was 111% of the original DSR value, compared to 95% for the Sasobit® modified binder. This indicates that the addition of Sasobit® reduces the aging of the asphalt binder during construction. The addition of Sasobit® resulted in a failing bending beam rheometer *m*-value at -18 °C. This would indicate that the Sasobit® modified binder may reduce the asphalt binder's ability to resist low-temperature cracking. The resulting asphalt binder grade, after blending with Sasobit®, was PG 70-22. Binder testing for the Evotherm™ emulsion was not completed because a sample was not obtained during production.

Table 1 Binder Test Results for Control and Sasobit®

Test Method		Test Temp., °C	Control	Sasobit®	Specification
Original Binder					
Dynamic Shear Rheometer (DSR), AASHTO T315, G*/sin δ, kPa		64	1.327	2.605	1.00 min.
Rolling Thin Film Oven (RTFO) Residue,					
RTFO, AASHTO T240, Mass loss, %		163	-0.217	-0.223	1.00 max.
DSR, AASHTO T315, G*/sin δ, kPa		64	2.804	5.083	2.20 min.
Pressure Aging Vessel Residue at 100 °C					
DSR, AASHTO T315, G*sin δ, kPa		22	2561	4111	5000 max.
Bending Beam Rheometer (BBR), AASHTO T313	Stiffness, MPa	-18	193	256	300 max.
	m-value	-18	0.318	0.278	0.300 min.

Table 2 Design Aggregate Gradation and Optimum Asphalt Content

Sieve Size, mm (in.)	Percent Passing, %
19.0 (3/4")	100
12.5 (1/2")	97
9.5 (3/8")	89
4.75 (#4)	68
2.36 (#8)	49
1.18 (#16)	34
0.6 (#30)	21
0.3 (#50)	11
0.15 (#100)	7
0.075 (#200)	5.2
AC, %	5.3

RESULTS AND DISCUSSIONS

Construction

A total of 2,270 tons of the Sasobit® and Evotherm™ WMA was produced (1,270 tons of Evotherm™ and 1,000 tons of Sasobit®, respectively). During construction, a control section was placed at a compaction temperature of 300°F (149°C). For the WMA test sections, the compaction temperature was approximately 250°F (121°C). The asphalt plant that produced the mixes was a computer-operated, 400 tons per hour-capacity Gencor drum plant, with 10 cold feed bins and four 200 ton-capacity silos for storage. The plant is shown in Figure 2. The fuel type was reclaimed oil.

Figure 2 Payne and Dolan's Muskego, WI Asphalt Plant.

The asphalt mixtures were hauled 18 miles (about 30 minutes) to the paving site in end dump trucks. The test sections constructed in the mainline were placed using a Blaw Knox PF 3200 paver and a Roadtec® SB-2500C Material Transfer Device to minimize segregation and ensure a uniform texture and pavement temperature across the mat. Mixtures placed in an adjacent turning lane were placed using a Blaw Knox F-218 paver. The paving of the turning lanes was done in echelon with the mainline paving operation. Compaction was achieved using an Ingersoll Rand DD 130 roller as the breakdown roller, while a Hypac C778 roller was used as the finish roller.

Two passes of each roller (vibratory mode during breakdown, static mode during finish) made up the rolling pattern for the project. Mixture sampling took place at the asphalt plant, with material sampled from the truck beds placed in metal five-gallon buckets. Mixture transferred to Payne and Dolan's design lab was placed in paper bags during transportation.

Laboratory Testing

During construction of the test sections, samples of each asphalt mixture were obtained and used to produce test specimens for performance testing. For the Evotherm™ and Sasobit® test sections, specimens for volumetric and Asphalt Pavement Analyzer (APA) testing were prepared onsite in the contractor's quality control laboratory. Samples prepared for Tensile Strength Ratio (TSR) and Hamburg testing were prepared in Payne and Dolan's design laboratory in Waukesha, WI. Laboratory testing included mixture volumetric properties, Asphalt Pavement Analyzer (APA) testing, Tensile Strength Ratio (TSR) testing, Hamburg testing, and Dynamic Modulus testing. These tests represent a portion of those required by the WMA Technical Working Group Material Test Framework for Warm Mix Asphalt Field Trials (*9*). Extra mix was also sampled so hot compacted samples and samples reheated prior to compaction could be compared, simulating the comparison between the contractor's and the state DOT's expected data. For Dynamic Modulus testing, only reheated samples could be produced due to gyratory compactor sample height limitations at Payne and Dolan's design laboratory. These samples were prepared at NCAT's main laboratory in Auburn, AL. Table 3 summarizes the data collected for this field evaluation. Samples for the control test section were prepared in the same manner.

Table 3 Milwaukee, WI Test Samples

Mix	Lab Compaction Temperature, °F	SGC Volumetrics, APA, and TSR		Reheated E*
		Hot at Plant	Reheated at NCAT	
Control	300	X	X	X
Sasobit®	250	X	X	X
Evotherm™	250	X	X	X

Mixture Volumetric Properties

For each field sample, six specimens that were each 115 mm tall and 150 mm in diameter were produced to determine mixture volumetric properties. Subsequently, these samples were tested in the APA. The samples were compacted using 75 gyrations of the Superpave Gyratory compactor (SGC). Samples were compacted at a temperature equal to the anticipated

compaction temperature at the paver. Air void test results are illustrated in Figure 3. Complete test results are presented in Appendix A. The letters in Figure 3 identify sets of specimens with air void contents that are statistically similar. Data in Figure 3 suggests that (1) air void contents were equal to or lower for the WMA test sections than for the control test section, and (2) reheating the mixtures produced higher air voids than when the samples were compacted hot, with no reheating. Reheating samples involved placing loose mix in a forced-draft oven until the desired compaction temperature was reached. A different make and model of SGC was used to compact the reheated samples, so it could not be determined if the reheating process was a primary cause of the difference in the measured air voids.

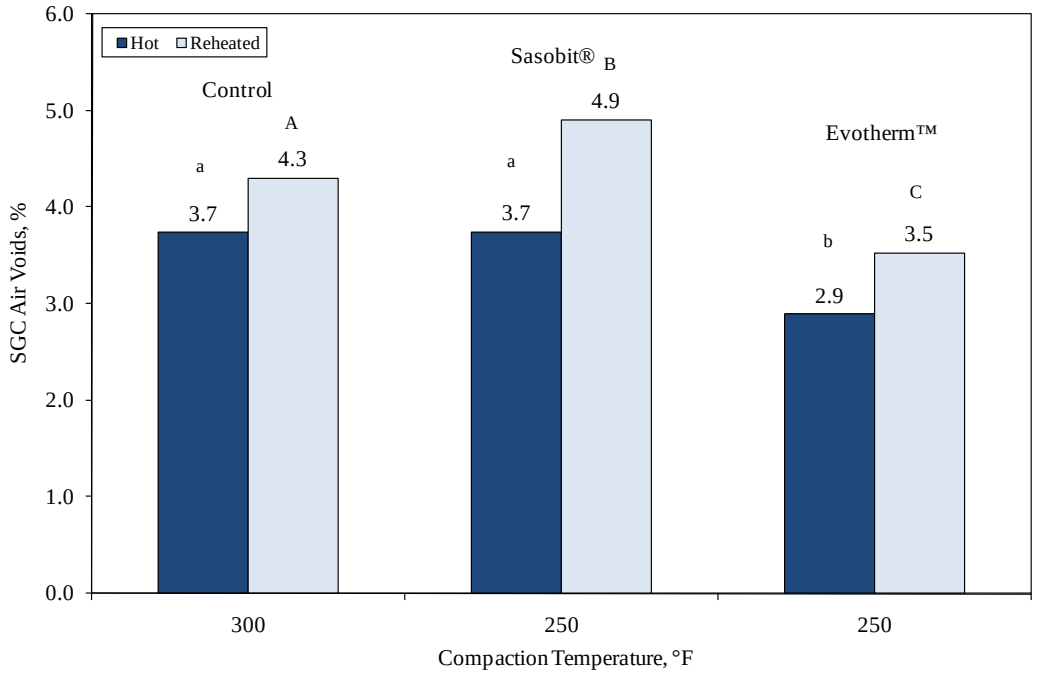

Figure 3 SGC Air Void Contents

An analysis of variance (ANOVA) was conducted on the compaction data to determine if the different WMA technologies had a significant effect on the compaction of samples produced in the laboratory. Results from the analyses concluded that, for the samples compacted prior to reheating, statistically, the Evotherm™ produced lower air voids than the control, while Sasobit® produced air voids that were statistically not different from the control. For the samples compacted after reheating, all three mixes had air voids that were statistically different. This can be seen in Figure 3, where the lowercase letters represent the samples compacted hot, while the uppercase letters represent the samples compacted after reheating. Mixtures having the same letter are statistically similar, while different letters indicate a statistical difference compared to the control mixture.

A review of asphalt content and gradation data (presented in full in Appendix B) indicated a slight increase in asphalt content for the Sasobit® mixture compared to the control and Evotherm™ mixtures. The dust content for the Sasobit®, however, was lower than that for the control and Evotherm™, indicating that the dust content possibly had more influence on the air void content than the measured asphalt content. It was also determined that the reheated samples produced statistically higher air voids than the samples that were compacted with no reheating. However, it cannot be determined if this was solely due to reheating the material or due to the difference in Superpave gyratory compactors (two different manufacturers were used for the hot versus reheating comparison).

Asphalt Pavement Analyzer

Once the volumetric properties were determined, each mixture set was placed in the APA, located at NCAT's main laboratory, to determine the laboratory rut resistance of each asphalt mixture. Testing was conducted in accordance with AASHTO TP 63, with the exception of the load and hose pressure. All testing was conducted at 147°F (64°C). Testing was conducted using a hose pressure of 120 psi and a vertical load of 120 pounds, paralleling the testing parameters of the laboratory evaluations in previous studies (*5–7*). Test results from the APA are shown in Figure 4. The data illustrate that the rut depths for the reheated samples were lower than the rut depths for the samples compacted hot. This is most likely due to the additional aging of the reheated samples. It is also believed that observed fuel contamination caused the high measured rut depths for the Evotherm™ compacted without reheating. The reheating may have vaporized any fuel in the mixture. The fuel contamination can be observed in Figure 5 (not visible in black and white print). Unburned fuel from incomplete combustion apparently caused the fuel contamination, which indicates that the burners may have required tuning for the production of WMA. Reclaimed motor oil was used as fuel. Incomplete combustion was most likely exacerbated by the lower production temperatures used for the WMA. It should be noted that workers noticed a film on safety glasses and the paver when placing the Sasobit®. This film has not been reported at other sites where Sasobit® was placed. If this film was unburned fuel, the slightly higher temperatures used in the Sasobit® production may have minimized its effect on the mix stiffness. Further, as shown in Table 1, Sasobit® stiffens the binder. A distinct fuel smell was reported during the sampling of the Evotherm™ mixture that contained fuel.

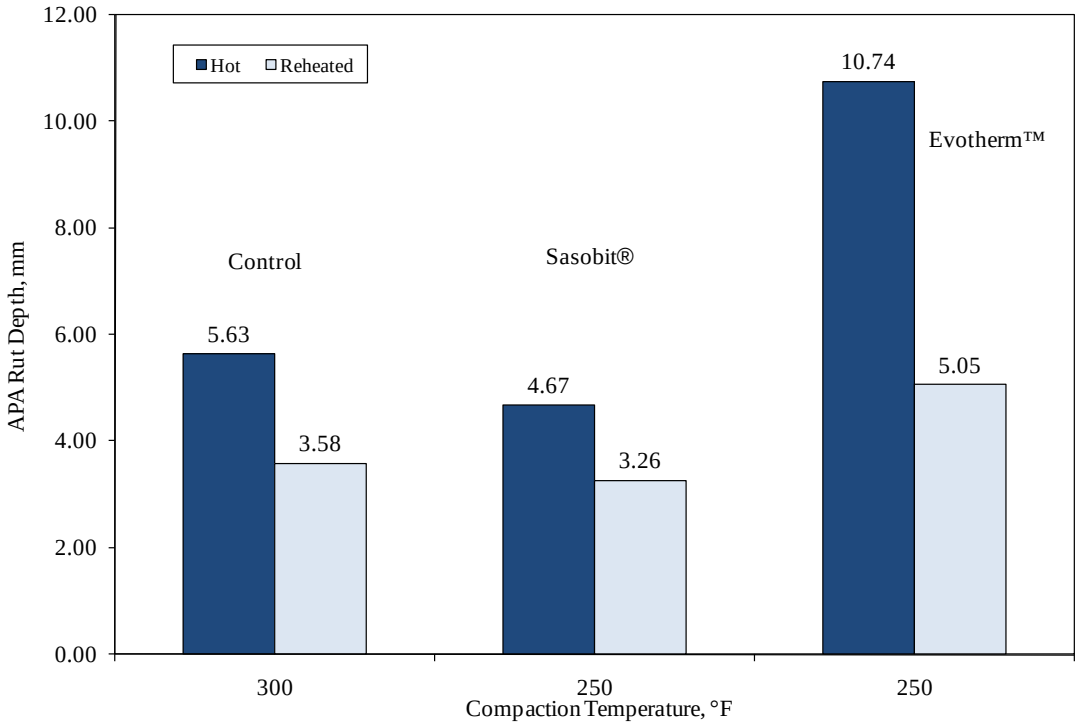

Figure 4 Asphalt Pavement Analyzer Rut Depth Results

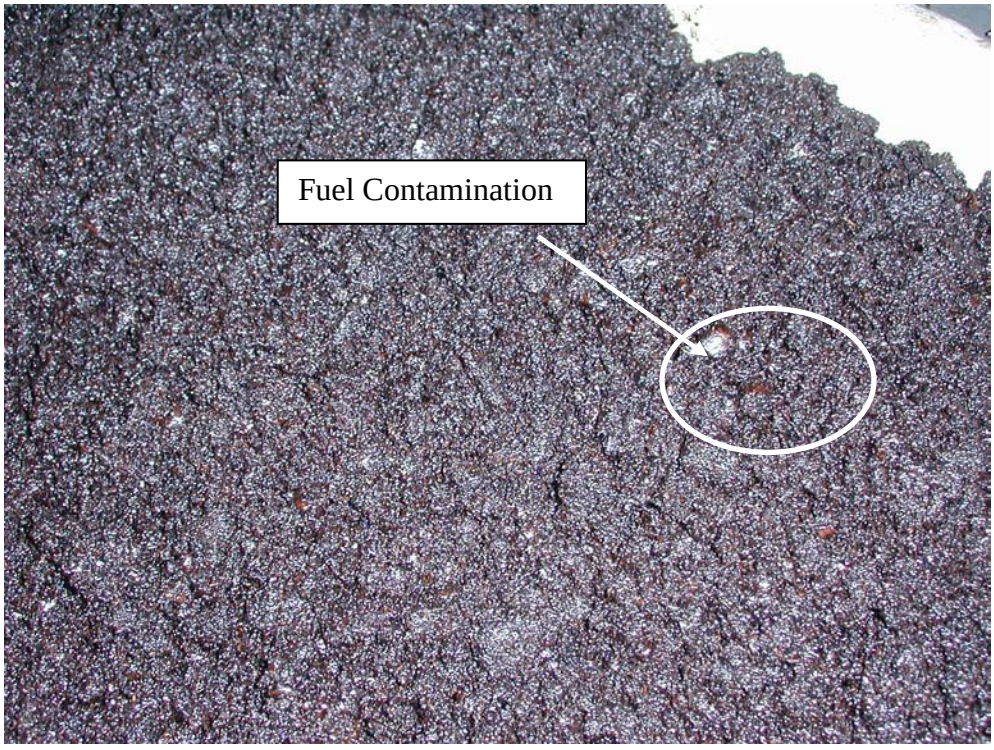

Figure 5 Fuel Contamination of Evotherm™

An analysis of variance (ANOVA) was conducted on the measured rut data to determine if the different WMA technologies had a significant effect on the resistance to permanent deformation of samples produced in the laboratory. Based on a significance level of 0.05, results from the analyses concluded that both the WMA technology and whether the samples were compacted hot or reheated were statistically significant factors. For the WMA technologies, the Sasobit® produced statistically lower rut depths than the control mixture, while the Evotherm™ produced rut depths that were significantly higher than the control mixture. It is believed that fuel contamination had an effect on the measured rut depths for the Evotherm™. The data also show that the reheated samples produced statistically lower rut depths than the samples prepared hot.

Moisture Resistance

Specimens of each mixture were prepared according to AASHTO T 283 to assess moisture damage susceptibility of the asphalt mixtures. TSR testing was conducted on both the sample compacted hot and the reheated sample. This determined if moisture dissipation had an effect on the moisture resistance of the WMA mixtures, especially the Evotherm™ emulsion, which uses water to deliver the technology. The data for each test section have been divided into samples compacted hot and samples reheated. These data are presented in Tables 4 and 5. Complete TSR test results are presented in Appendix C. Figure 6 graphically presents the TSR data obtained. The data show that all but the reheated Evotherm™ samples had a TSR value that satisfied the Wisconsin Department of Transportation minimum-required TSR value of 80% (including the control mixture). The lower indirect tensile strengths observed for the Evotherm™ samples compacted hot may be a result of softer binder, residue moisture from the emulsion, or fuel contamination. Research has shown that softer binders are less resistant to moisture damage (*10*). Reheating increased the unsaturated tensile strengths of all the mixes. The Sasobit® mixture had the smallest increase. These increases correspond to the RTFO test data presented previously.

Table 4 Tensile Strength Ratio Results, Samples Compacted Hot

Mix Type	Compaction Temperature, °F	Indirect Tensile Strength		TSR, %
		Unsaturated, psi	Saturated, psi	
Control	300	109.6	103.2	94
Sasobit®	250	118.7	109.6	92
Evotherm™	250	47.9	46.0	96

Table 5 Tensile Strength Ratio Results, Samples Compacted After Reheating

Mix Type	Compaction Temperature, °F	Indirect Tensile Strength		TSR, %
		Unsaturated, psi	Saturated, psi	
Control	300	140.2	126.8	90
Sasobit®	250	120.2	98.4	82
Evotherm™	250	72.1	45.7	63

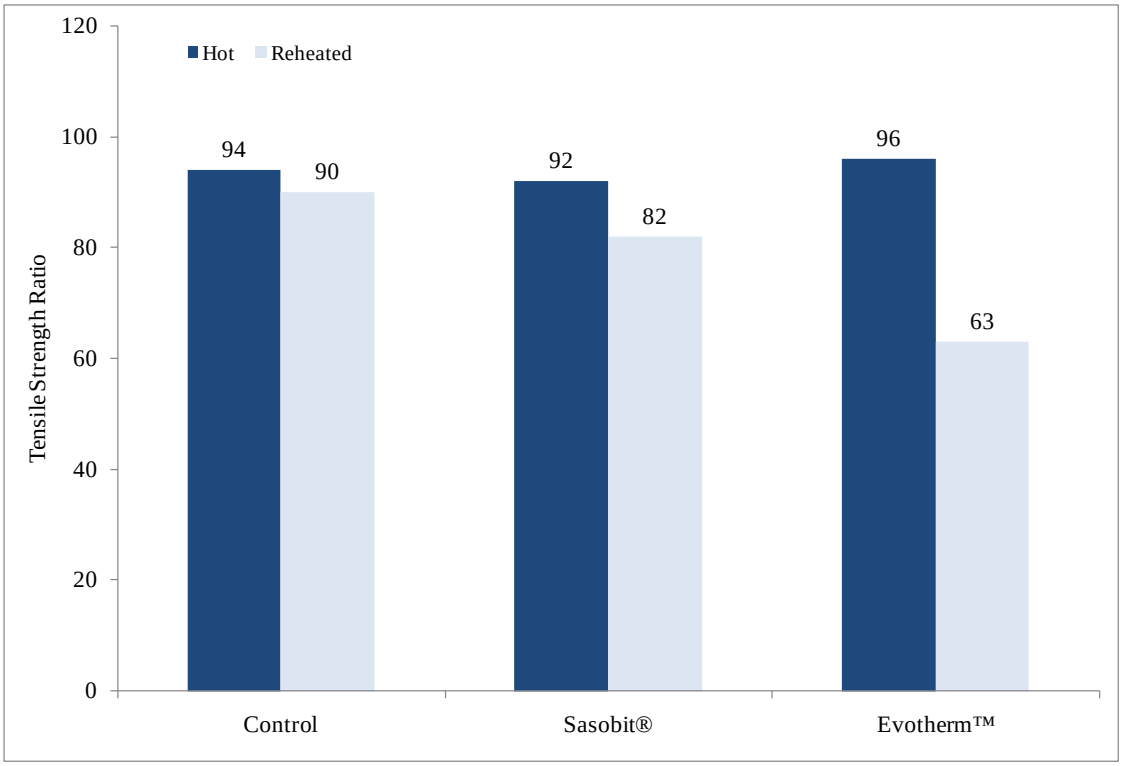

Figure 6 Tensile Strength Ratio Results

Hamburg Wheel Tracking

To further evaluate moisture damage susceptibility, samples were prepared and tested using the Hamburg wheel-tracking device according to AASHTO T324. Hamburg tests were conducted on samples compacted hot and after reheating. This test is typically used to predict moisture damage of HMA but has been found to be sensitive to other factors, including binder stiffness, short-term aging, compaction temperature, and anti-stripping treatments (*12*). All these factors have been identified as potential problems in the evaluation of WMA, so the results from the Hamburg wheel-tracking device may provide a method of identifying a WMA mixture that performs well.

Test results from the Hamburg wheel-tracking device are presented in Tables 6 and 7 (compacted hot and after reheating, respectively). In most cases, both the stripping inflection point and the rutting rate indicate whether the mixture will be prone to moisture damage. Based on the stripping inflection point, the reheated Sasobit® performed very well in the Hamburg. The total rutting at 10,000 cycles was less than 50% of the control. This corresponds to the stiffening effect of Sasobit® on the binder. Sasobit® samples compacted hot were not available for Hamburg testing. For the Evotherm™, poor performance in the Hamburg is further indication of fuel contamination that apparently occurred during construction. The Hamburg test results for the reheated Evotherm™ mixture are improved compared to the samples compacted without reheating. Some of the volatiles from the fuel contamination may have dissipated during reheating.

Table 6 Hamburg Wheel-Tracking Device Results, Samples Compacted Without Reheating

Mix Type	Avg. VTM, %	Stripping Inflection Point, cycles	Rutting Rate, mm/hr	Total Rutting @ 10,000 cycles, mm	Unsaturated Tensile Strength, psi	Saturated Tensile Strength, psi	TSR
Control	7.7	7200	1.295	5.139	109.6	103.2	94
Sasobit®	No Samples Available						
Evotherm™	7.5	1950	8.083	32.073	47.9	46.0	96

Table 7 Hamburg Wheel-Tracking Device Results, Samples Compacted After Reheating

Mix Type	Avg. VTM, %	Stripping Inflection Point, cycles	Rutting Rate, mm/hr	Total Rutting @ 10,000 cycles, mm	Unsaturated Tensile Strength, psi	Saturated Tensile Strength, psi	TSR
Control	7.1	> 10,000	1.311	5.202	140.2	126.8	90
Sasobit®	7.0	9050*	0.605	2.401	120.2	98.4	82
Evotherm™	7.3	3450	5.574	22.118	72.1	45.7	63

Note: * represents the average of two samples, one with a determined stripping inflection point, and the other with a stripping inflection point greater than 10,000 cycles. 10,000 was used to determine average stripping inflection point.

Dynamic Modulus

Dynamic modulus tests were conducted on field-mixed, reheated, laboratory-compacted samples using an IPC Global AMPT (Asphalt Mixture Performance Tester). Testing was conducted at seven frequencies at three temperatures. Complete dynamic modulus data are presented in Appendix D. Testing frequencies were in accordance with AASHTO TP62. Test temperatures were in accordance with AMPT testing capabilities. Dynamic modulus master curves generated

for each test section are presented in Figure 7. The reference temperature for the master curves is 70°F (21.1°C).

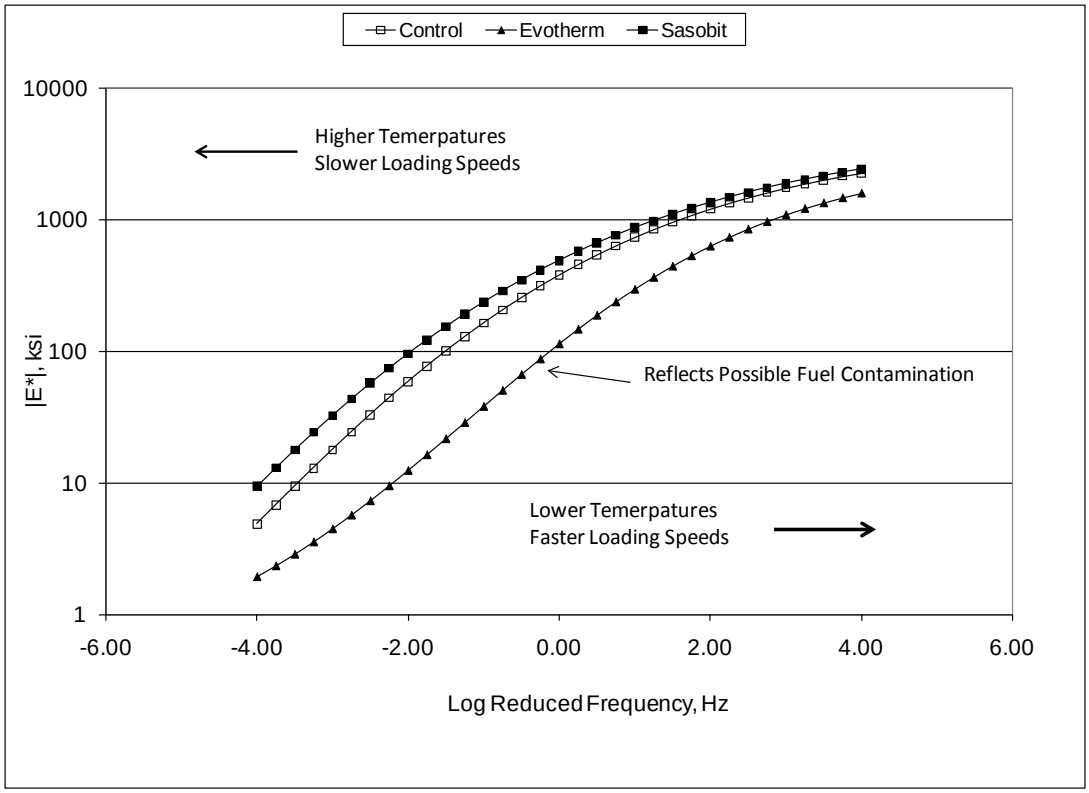

Figure 7 Dynamic Modulus Master Curves, Samples Compacted After Reheating

An ANOVA was performed on the dynamic modulus data to determine if the addition of WMA technologies affected the stiffness of the different test sections. Mixture, temperature, frequency, and their interactions were used as factors. All the factors, including mixture (Control, Sasobit®, and Evotherm™) and the two-way interactions, were significant. Tukey's test at a 95% confidence interval was performed at each temperature and frequency to determine where the significant differences between mixtures occurred. The results showed that the Sasobit® was statistically the same as the control mixture. For the Evotherm™, a significant difference was found at the lower temperatures, which could indicate an increased resistance to thermal cracking due to less oxidation of the asphalt binder. At the higher testing temperatures, there was no significant difference between the Evotherm™ and the control mixture. The lack of a statistical difference at higher test temperatures most likely results from increased testing variability at these temperatures, which is common to dynamic modulus tests.

Emissions Testing

At the asphalt contractor's request, an industrial hygiene survey was conducted during construction of the WMA test sections and the control section. Among the items evaluated during the survey was asphalt fume collection, both at the paver and from personnel monitors. A stack-emissions test was also conducted at the asphalt plant to determine the reduction, if any, in emissions produced from the WMA mixtures. Figure 8 shows a few asphalt fume-collection pumps placed on the asphalt paver during construction of the test sections.

Figure 8 Example Locations of Asphalt Fume-Collection Pumps

NIOSH Method 5042 was used to analyze the asphalt fume samples collected. The asphalt fume concentration-collection devices were located in areas where maximum fume exposure was assumed. This allowed for a better comparison of fume reduction between the control and WMA mixtures following the recommendations of the WMA Technical Working Group's guidelines for documenting emissions and energy reductions (*13*). Asphalt fume results for the Sasobit® mixture at the paver were 43% to 91% lower than for the control test section. For the Evotherm™ mixture, the asphalt fumes were 22% to 82% lower than for the control mixture. The large range of asphalt fume reduction is believed to be a result of the location of the fume-collection devices.

Personal sampling data were collected according to OSHA Method 58 (*14*). Based on the personnel sampling results, seven of the eight samples taken over the two-day testing period

were non-detectable. The one detectable sample had a test result of 0.42 mg/m3 (inhalable fraction). This sample was from the screed operator during the paving of the control section and was 84% of the American Conference of Governmental Industrial Hygienists Threshold Limit Value (ACGIH TLV) of 0.5 mg/m3 (inhalable fraction).

Table 8 presents the results from the stack emissions testing at the asphalt plant. Data show an overall decrease in emissions when WMA is produced, from 5% lower CO_2 to 14% lower NOx. Also, 9% less fuel was used during the production of Evotherm™. Table 8 also shows a 313% increase in the production of volatile organic compounds (VOCs) during production of WMA when compared to the control. This may indicate that unburned fuel was released into the asphalt drum, increasing the amount of VOCs emitted. By fine-tuning the burner, unburned fuel should not be released into the drum, decreasing the amount of VOCs produced.

Further, approximately 45 lbs of water per ton of WMA were introduced into the drum as part of the Evotherm™ emulsion. A significant amount of fuel is required to heat aggregate to convert this water into steam. This would increase the amount of fuel used, offsetting savings from lower production temperatures.

Table 8 Stack Emissions Test and Fuel-Usage Results, Milwaukee, WI (*15*)

Emission	Avg. WMA	Avg. HMA	Reduction, %	Increase, %
NOx, lb/ton	0.058	0.068	14.0	
VOC, lb/ton	0.097	0.024		313.0
CO2, lb/ton	50.4	53.0	5.0	
Fuel Usage, gal/ton	1.79	1.98	9.0	

PRODUCTION OBSERVATIONS

During the production and placement of the WMA test sections, surveys were distributed to the employees that participated in the project (*14*). Questions ranged from "How did the WMA technologies react during laboratory testing, compared to the control?" to "How did the WMA technologies react during the laydown operations, compared to the control?". Based on the responses, the WMA technologies evaluated behaved virtually the same as the control mixture during the mix design stage, but during the quality-control testing during construction, the Evotherm™ was more difficult to handle at the cooler temperatures, compared to the Sasobit®, which was reported as surprisingly easy to handle at the lower temperatures. For the Sasobit®, it was also reported that no odor or fumes were noticed during handling, while the Evotherm™ had a distinct fuel smell. This was further confirmation of fuel contamination during the production of the Evotherm™ test section.

For the laydown and coring operations, Sasobit® and Evotherm™ were both reported to have less roll-down under the roller as compared to the control mixture. It was also reported that, as cores were obtained, the Evotherm™ stuck to the drill bit more than the control mixture or the Sasobit®, and residue was left on the drill core after removing the core. Hand work was reported to be more difficult for both WMA technologies.

FIELD PERFORMANCE

Figures 9 and 10 show the field performance of the WMA test sections through the first four months after construction. Unfortunately, the test sections were located in the passing lane, so additional field data will likely not be obtained. Also, cores were not obtained from the control section after four months due to traffic-control constraints. As the data shows in Figure 9, the in-place density increased for the WMA test sections over the first four-month period of traffic. The initial in-place densities for the two WMA test sections are almost identical to the control sections, even though there was up to an 85°F reduction in compaction temperature (Figure 11).

Figure 10 shows that the indirect tensile strength of the WMA test sections increased due to aging and increased in in-place density. The tensile strengths of the field cores at the time of construction are comparable, if somewhat lower than, the dry tensile strengths from laboratory TSR tests conducted on the samples that were not reheated.

The average rut depth for both sections was less than 1 mm, indicating that the WMA was rut resistant in the field, even with the fuel contamination of the Evotherm™ mixture. Remember that the WMA test sections were placed in the passing lane, which may have minimized the field rutting.

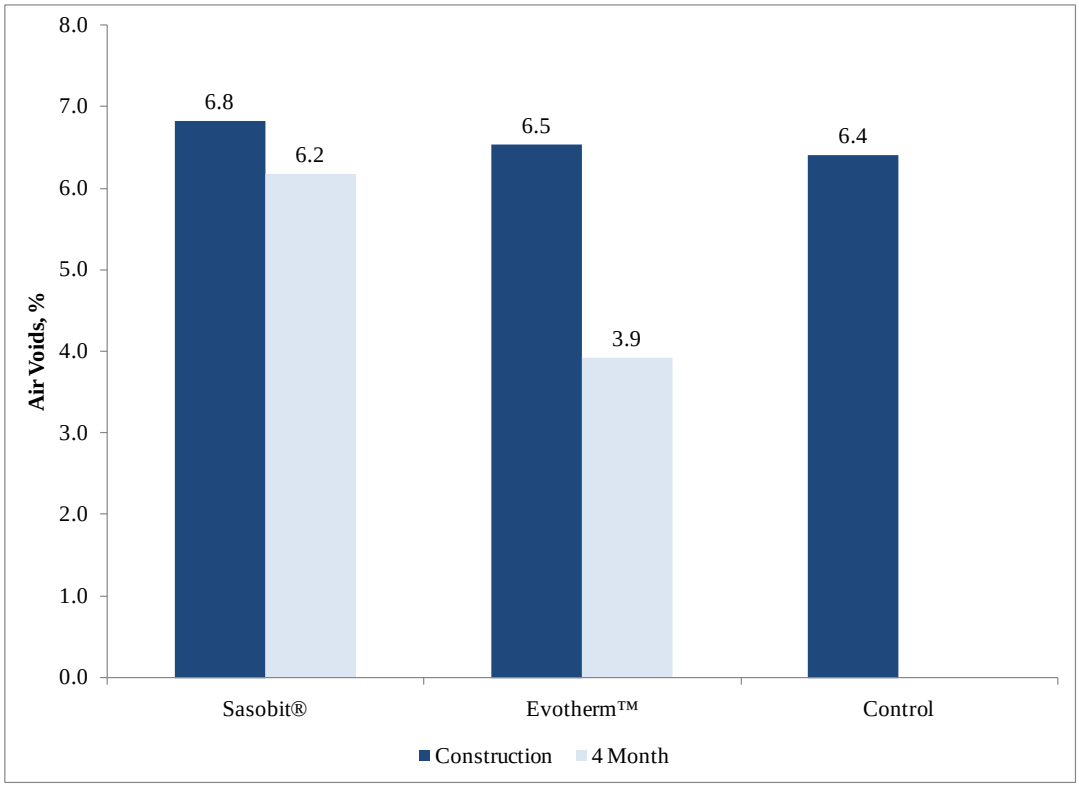

Figure 9 In-place Air Voids, Through Four Months of Traffic

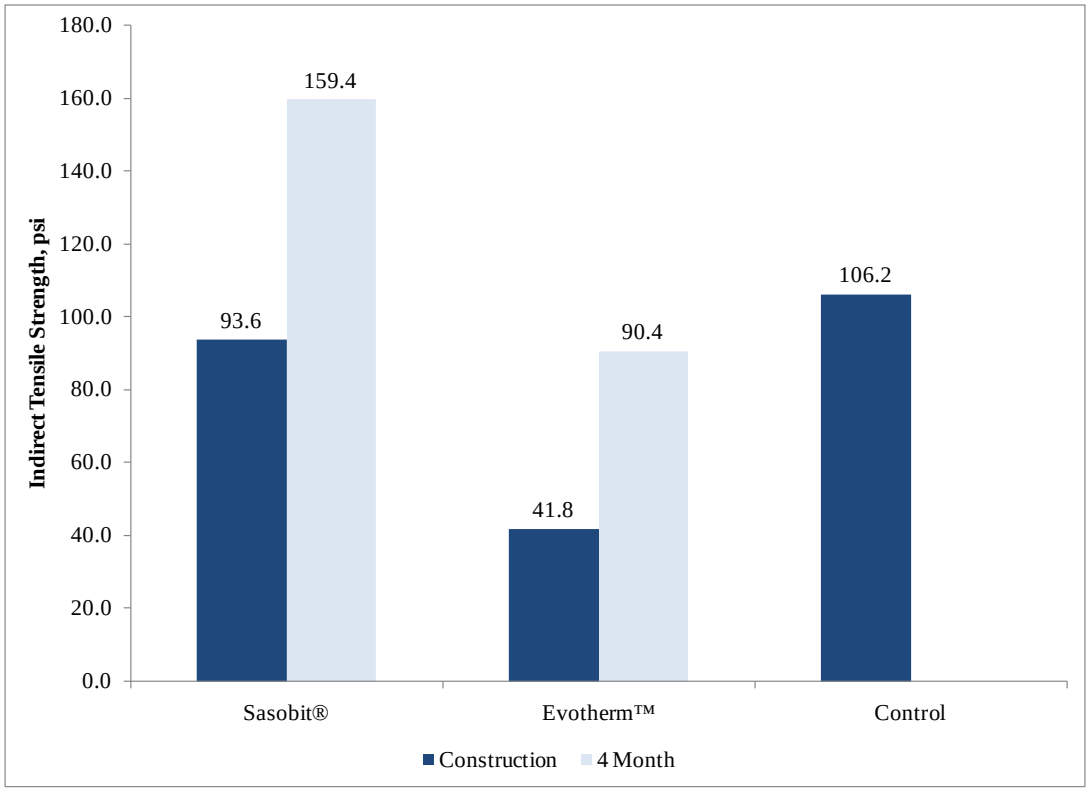

Figure 10 Indirect Tensile Strength Results, Through Four Months of Traffic

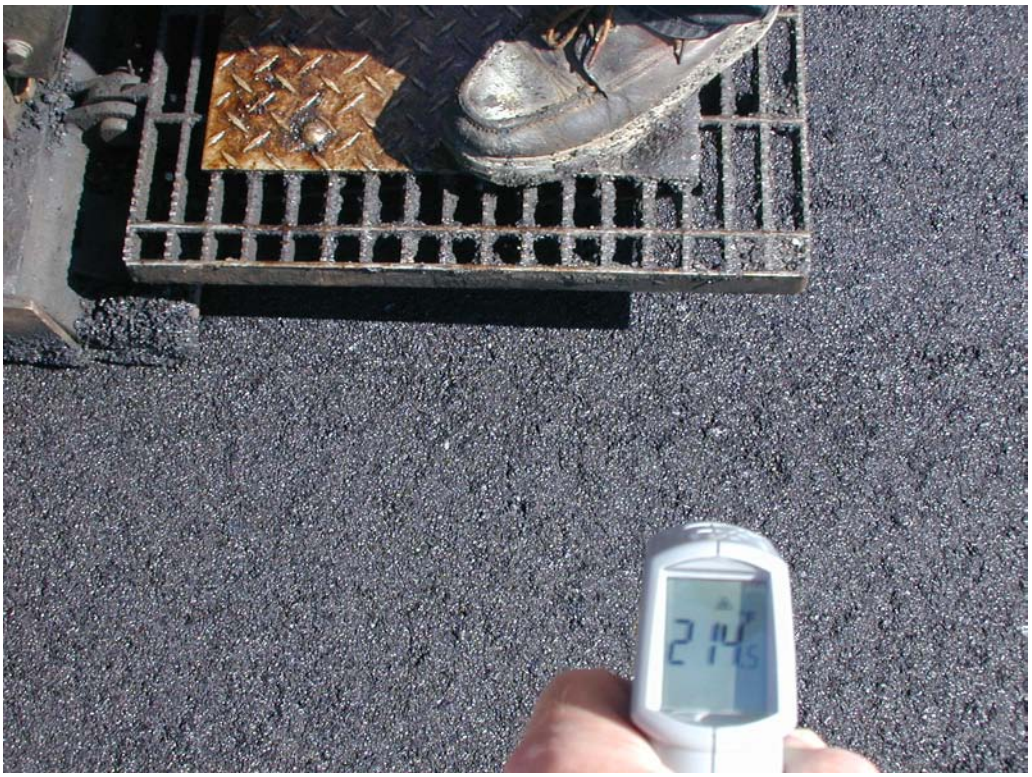

Figure 11 Laydown Temperature, Evotherm™

CONCLUSIONS

In June 2006, WMA field evaluations were constructed on Ryan Road, in Milwaukee, WI. These test sections were used to evaluate the field performance of two WMA technologies, Evotherm™ and Sasobit®. Specific conclusions generated from this evaluation include the following:

- WMA test sections were placed at compaction temperatures ranging from 50 to 85°F lower than the control test section.
- Compared to the control mixture compacted at 300°F (149°C), laboratory air voids for the WMA sections were statistically lower for the Evotherm™ and statistically the same for the Sasobit® at a compaction temperature of 250°F (121 °C).
- Laboratory rutting-susceptibility tests conducted in the APA indicated that the Evotherm™ resulted in statistically higher measured rut depths, and Sasobit® resulted in statistically lower measured rut depths compared to the control. It is believed that the fuel contamination of the Evotherm™ contributed to the higher measured rut depths. The field rut measurements indicated that the WMA was not more susceptible to rutting than the HMA.
- Laboratory TSR tests indicate similar performance between the two WMA technologies and the control at the lower compaction temperatures, except for the reheated Evotherm™ samples. Hamburg wheel-tracking tests confirmed the results obtained from the TSR

testing. The softer binder in the Evotherm™ mixture, resulting from the fuel contamination, most likely caused the lower tensile strengths and poor performance in the Hamburg wheel-tracking test.

- The dynamic modulus determined for the two WMA technologies resulted in values that were statistically the same for the Sasobit® and the control, and statistically the same at the higher testing temperatures for the control mixture and the Evotherm™. The Evotherm™ was found to have significantly lower stiffness at the lower test temperatures. Numerically, however, the Evotherm™ had lower stiffness at higher test temperatures, most likely resulting from fuel contamination,
- Based on stack-emissions testing and an industrial hygiene survey, a decrease in asphalt fumes, emissions, and fuel usage was observed during the production of WMA. An increased amount of VOCs was determined for the stack emissions during the production of the Evotherm™ mixture, but that could be attributed to unburned fuel in the asphalt drum during production. Plant stack-emissions tests were not performed on the production of the Sasobit® section.

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APPENDIX A

VOLUMETRIC DATA

TABLE A1 Volumetric Properties, Control Mixture - Hot

Mix Type:	Control	Asphalt Specific Gravity (Gb):	1.028
Ndesign:	75	Apparent Specific Gravity (Gsa):	
Ninitial:		Effective Specific Gravity (Gse):	2.743
		Bulk Specific Gravity (Gsb):	2.684

Sample Number	Asphalt Content, %	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %
1	5.2	300	4857.0	2858.9	4859.7	2.428	2.525	3.9	14.3	72.9
2	5.2	300	4863.4	2868.0	4865.9	2.434	2.525	3.6	14.0	74.4
3	5.2	300	4877.5	2875.1	4880.2	2.433	2.525	3.7	14.1	74.0
4	5.2	300	4857.0	2862.2	4859.3	2.432	2.525	3.7	14.1	73.9
5	5.2	300	4861.4	2860.6	4863.3	2.427	2.525	3.9	14.3	72.9
6	5.2	300	4857.6	2861.0	4859.7	2.430	2.525	3.7	14.2	73.5
Avg.						2.429	2.525	3.7	14.1	73.6

TABLE A2 Volumetric Properties, Control Mixture - Reheated

Mix Type:	Control	Asphalt Specific Gravity (Gb):	1.028
Ndesign:	75	Apparent Specific Gravity (Gsa):	
Ninitial:		Effective Specific Gravity (Gse):	2.743
		Bulk Specific Gravity (Gsb):	2.684

Sample Number	Asphalt Content, %	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %
1	5.2	300	4843.6	2854.5	4849.8	2.428	2.525	3.9	14.3	72.9
2	5.2	300	4849.0	2844.8	4856.6	2.410	2.525	4.5	14.9	69.4
3	5.2	300	4842.9	2838.9	4850.9	2.407	2.525	4.7	15.0	68.8
4	5.2	300	4847.0	2847.4	4853.7	2.416	2.525	4.3	14.7	70.5
5	5.2	300	4843.0	2848.7	4851.6	2.418	2.525	4.2	14.6	71.0
6	5.2	300	4844.1	2850.8	4853.1	2.419	2.525	4.2	14.6	71.2
Avg.						2.419	2.525	4.3	14.7	70.7

TABLE A3 Volumetric Properties, Sasobit Mixture - Hot

Mix Type:	Sasobit	Asphalt Specific Gravity (Gb):	1.028
Ndesign:	75	Apparent Specific Gravity (Gsa):	
Ninitial:		Effective Specific Gravity (Gse):	2.740
		Bulk Specific Gravity (Gsb):	2.684

Sample Number	Asphalt Content, %	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %
1	5.2	250	4870.7	2867.1	4873.9	2.427	2.522	3.8	14.3	73.6
2	5.2	250	4866.3	2860.5	4867.9	2.424	2.522	3.9	14.4	73.0
3	5.2	250	4869.5	2869.5	4870.6	2.433	2.522	3.5	14.1	75.0
4	5.2	250	4870.5	2861.2	4872.6	2.421	2.522	4.0	14.5	72.5
5	5.2	250	4863.8	2863.5	4865.9	2.429	2.522	3.7	14.2	74.0
6	5.2	250	4867.4	2866.3	4868.9	2.431	2.522	3.6	14.2	74.4
Avg.						2.430	2.522	3.7	14.3	73.8

TABLE A4 Volumetric Properties, Sasobit Mixture - Reheated

Mix Type:	Sasobit	Asphalt Specific Gravity (Gb):	1.028
Ndesign:	75	Apparent Specific Gravity (Gsa):	
Ninitial:		Effective Specific Gravity (Gse):	2.740
		Bulk Specific Gravity (Gsb):	2.684

Sample Number	Asphalt Content, %	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %
1	5.2	250	4837.0	2831.8	4845.0	2.403	2.522	4.7	15.1	68.7
2	5.2	250	4828.8	2822.7	4837.6	2.397	2.522	5.0	15.4	67.6
3	5.2	250	4831.3	2826.3	4839.4	2.400	2.522	4.8	15.2	68.2
4	5.2	250	4827.3	2824.7	4839.4	2.396	2.522	5.0	15.4	67.5
5	5.2	250	4833.1	2826.8	4841.1	2.399	2.522	4.9	15.3	68.1
6	5.2	250	4837.2	2828.4	4848.4	2.395	2.522	5.0	15.4	67.3
Avg.						2.397	2.522	4.9	15.3	67.9

TABLE A5 Volumetric Properties, Evotherm Mixture - Hot

Mix Type:	Evotherm	Asphalt Specific Gravity (Gb):	1.028
Ndesign:	75	Apparent Specific Gravity (Gsa):	
Ninitial:		Effective Specific Gravity (Gse):	2.733
		Bulk Specific Gravity (Gsb):	2.684

Sample Number	Asphalt Content, %	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %
1	5.2	250	4855.7	2871.1	4857.1	2.445	2.517	2.9	13.6	79.0
2	5.2	250	4854.9	2869.6	4856.1	2.444	2.517	2.9	13.7	78.8
3	5.2	250	4860.5	2874.8	4861.6	2.446	2.517	2.8	13.6	79.4
4	5.2	250	4868.0	2879.1	4869.7	2.445	2.517	2.8	13.6	79.1
5	5.2	250	4864.4	2876.3	4865.8	2.445	2.517	2.9	13.6	79.0
6	5.2	250	4879.8	2882.1	4881.8	2.440	2.517	3.0	13.8	77.9
Avg.						2.443	2.517	2.9	13.7	78.9

TABLE A6 Volumetric Properties, Evotherm Mixture - Reheated

Mix Type:	Evotherm	Asphalt Specific Gravity (Gb):	1.028
Ndesign:	75	Apparent Specific Gravity (Gsa):	
Ninitial:		Effective Specific Gravity (Gse):	2.733
		Bulk Specific Gravity (Gsb):	2.684

Sample Number	Asphalt Content, %	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %
1	5.2	250	4818.5	2846.0	4823.6	2.437	2.517	3.2	13.9	77.1
2	5.2	250	4825.5	2846.2	4830.3	2.432	2.517	3.4	14.1	76.1
3	5.2	250	4817.6	2838.1	4822.8	2.427	2.517	3.6	14.3	75.0
4	5.2	250	4811.9	2836.9	4818.6	2.428	2.517	3.5	14.2	75.2
5	5.2	250	4821.8	2837.9	4829.1	2.422	2.517	3.8	14.5	73.8
6	5.2	250	4815.1	2835.4	4821.3	2.425	2.517	3.7	14.4	74.4
Avg.						2.423	2.517	3.5	14.2	75.3

APPENDIX B

ASPHALT CONTENTS AND GRADATIONS

Table B1 Measured Asphalt Content and Gradation - Control Mixture

Gradation		Sample 1				
Sieve Size (mm)	**Sieve^0.45**	**Rep1**	**Rep2**	**Avg.**	**Std Dev**	**JMF**
37.5	5.11	100.0	100.0	100.0	0.0	100.0
25.0	4.26	100.0	100.0	100.0	0.0	100.0
19.0	3.76	100.0	100.0	100.0	0.0	100.0
12.5	3.12	97.7	99.1	98.4	1.0	96.5
9.5	2.75	90.6	93.1	91.9	1.8	88.5
4.75	2.02	69.1	70.3	69.7	0.8	68.2
2.36	1.47	51.2	52.1	51.7	0.6	49.3
1.18	1.08	36.2	36.7	36.5	0.4	33.9
0.6	0.8	24.1	24.4	24.3	0.2	21.3
0.3	0.58	13.2	13.3	13.3	0.1	11.3
0.15	0.43	7.5	7.4	7.5	0.1	6.6
0.075	0.31	5.7	5.5	5.6	0.1	5.2

Asphalt Content	Sample 1				
	Rep1	**Rep2**	**Avg.**	**Std Dev**	**Opt. AC**
	5.07	5.06	5.07	0.01	5.3

Table B2 Measured Asphalt Content and Gradation - Evotherm™ Mixture

Gradation		Sample 1				
Sieve Size (mm)	**Sieve^0.45**	**Rep1**	**Rep2**	**Avg.**	**Std Dev**	**JMF**
37.5	5.11		100.0	100.0		100.0
25.0	4.26		100.0	100.0		100.0
19.0	3.76		100.0	100.0		100.0
12.5	3.12		96.9	96.9		96.5
9.5	2.75		89.0	89.0		88.5
4.75	2.02		67.6	67.6		68.2
2.36	1.47		50.1	50.1		49.3
1.18	1.08		35.4	35.4		33.9
0.6	0.8		23.8	23.8		21.3
0.3	0.58		13.3	13.3		11.3
0.15	0.43		7.8	7.8		6.6
0.075	0.31		6.0	6.0		5.2

Asphalt Content	Sample 1				
	Rep1	**Rep2**	**Avg.**	**Std Dev**	**Opt. AC**
	4.96	4.99	4.98	0.02	5.3

Table B3 Measured Asphalt Content and Gradation - Sasobit® Mixture

Gradation		Sample 1				
Sieve Size (mm)	**Sieve^0.45**	**Rep1**	**Rep2**	**Avg.**	**Std Dev**	**JMF**
37.5	5.11	100.0		100.0		100.0
25.0	4.26	100.0		100.0		100.0
19.0	3.76	100.0		100.0		100.0
12.5	3.12	97.7		97.7		96.5
9.5	2.75	92.4		92.4		88.5
4.75	2.02	71.5		71.5		68.2
2.36	1.47	53.1		53.1		49.3
1.18	1.08	36.6		36.6		33.9
0.6	0.8	23.9		23.9		21.3
0.3	0.58	12.5		12.5		11.3
0.15	0.43	6.9		6.9		6.6
0.075	0.31	5.2		5.2		5.2
Asphalt Content		**Sample 1**				
		Rep1	**Rep2**	**Avg.**	**Std Dev**	**Opt. AC**
		5.34		5.34		5.3

APPENDIX C

TENSILE STRENGTH RATIO RESULTS

Project: WMA: Milwaukee Date: 7/10/2006

Tested By: D. Ford Calculated By: D. Ford

Sample Identification: Control Mixture

	Conditioned Samples			Unconditioned Samples		
Sample Number	5	7	8	1	2	4
(A) Diameter, in	5.914	5.906	5.908	5.908	5.915	5.907
(B) Height, in	3.762	3.754	3.760	3.750	3.757	3.750
(C) Weight in Air, gm	3872.6	3870.8	3871.5	3871.0	3871.0	3868.5
(D) SSD Weight, gm	3890.9	3887.0	3890.4	3888.0	3894.6	3884.9
(E) Submerged Weight, gm	2235.7	2233.3	2243.0	2239.7	2238.1	2231.3
(F) Bulk Specific Gravity [A/(D - E)]	2.340	2.341	2.350	2.348	2.337	2.339
(G) Theoretical Maximum Gravity	2.525	2.525	2.525	2.525	2.525	2.525
(H) % Air Voids [100*(1-F/G)]	7.3	7.3	6.9	7.0	7.5	7.3
(I) Volume of Air Voids [H*(D - E)/100]	121.497	120.710	114.133	115.231	123.431	121.521
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3964.5	3959.8	3951.6	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	91.90	89.00	80.10			
(L) % Saturation [100*(K/I)]	75.6	73.7	70.2			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	3650	3550	3600	3800	3750	3900
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	109.2	107.4	112.1
(R) Conditioned S_T, psi [2P/(A*B*π)]	104.4	101.9	103.2	N/A	N/A	N/A
(S) Average S_T, psi	103.2			109.6		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:	0.94					

Project: WMA: Milwaukee Date: 10/27/2006

Tested By: D. Ford Calculated By: D. Ford

Sample Identification: Control Mixture - Reheated

	Conditioned Samples			Unconditioned Samples		
Sample Number	1	2	8	3	4	5
(A) Diameter, in	5.916	5.906	5.922	5.924	5.930	5.914
(B) Height, in	3.741	3.735	3.731	3.729	3.738	3.729
(C) Weight in Air, gm	3871.5	3867.2	3874.7	3870.7	3874.2	3873.7
(D) SSD Weight, gm	3885.3	3883.6	3893.1	3889.1	3896.1	3887.8
(E) Submerged Weight, gm	2234.6	2234.4	2238.1	2235.8	2240.3	2239.3
(F) Bulk Specific Gravity [A/(D - E)]	2.345	2.345	2.341	2.341	2.340	2.350
(G) Theoretical Maximum Gravity	2.525	2.525	2.525	2.525	2.525	2.525
(H) % Air Voids [100*(1-F/G)]	7.1	7.1	7.3	7.3	7.3	6.9
(I) Volume of Air Voids [H*(D - E)/100]	117.433	117.636	120.465	120.350	121.463	114.361
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3959.7	3952.2	3966.0	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	88.20	85.00	91.30			
(L) % Saturation [100*(K/I)]	75.1	72.3	75.8			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	4400	4250	4550	4800	4800	5000
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	138.3	137.9	144.3
(R) Conditioned S_T, psi [2P/(A*B*π)]	126.6	122.7	131.1	N/A	N/A	N/A
(S) Average S_T, psi	126.8			140.2		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:	0.90					

Project: WMA: Milwaukee Date: 7/10/2006

Tested By: D. Ford Calculated By: D. Ford

Sample Identification: Evotherm Mixture

	Conditioned Samples			Unconditioned Samples		
Sample Number	6	7	8	2	3	4
(A) Diameter, in	5.898	5.916	5.900	5.901	5.908	5.915
(B) Height, in	3.742	3.743	3.757	3.748	3.746	3.758
(C) Weight in Air, gm	3868.8	3867.6	3865.8	3869.7	3871.1	3864.5
(D) SSD Weight, gm	3882.3	3881.8	3880.5	3881.6	3881.5	3878.5
(E) Submerged Weight, gm	2231.9	2226.6	2229.9	2230.5	2230.5	2225.5
(F) Bulk Specific Gravity [A/(D - E)]	2.344	2.337	2.342	2.344	2.345	2.338
(G) Theoretical Maximum Gravity	2.517	2.517	2.517	2.517	2.517	2.517
(H) % Air Voids [100*(1-F/G)]	6.9	7.2	7.0	6.9	6.8	7.1
(I) Volume of Air Voids [H*(D - E)/100]	113.332	118.609	114.724	113.674	113.018	117.640
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3950.5	3951.9	3948.2	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	81.70	84.30	82.40			
(L) % Saturation [100*(K/I)]	72.1	71.1	71.8			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	1400	1625	1775	1800	1650	1550
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	51.8	47.5	44.4
(R) Conditioned S_T, psi [2P/(A*B*π)]	40.4	46.7	51.0	N/A	N/A	N/A
(S) Average S_T, psi	46.0			47.9		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:	0.96					

Project: WMA: Milwaukee Date: 10/19/2006

Tested By: J. Mingus Calculated By: J. Mingus

Sample Identification: Evotherm Mixture - Reheated

	Conditioned Samples			Unconditioned Samples		
Sample Number	1	2	4	3	6	8
(A) Diameter, in	5.910	5.910	5.910	5.920	5.920	5.910
(B) Height, in	3.730	3.730	3.730	3.730	3.730	3.730
(C) Weight in Air, gm	3856.6	3856.7	3851.0	3854.5	3859.1	3853.2
(D) SSD Weight, gm	3870.8	3871.7	3871.1	3869.8	3873.6	3873.3
(E) Submerged Weight, gm	2222.0	2227.4	2223.6	2221.1	2225.0	2231.2
(F) Bulk Specific Gravity [A/(D - E)]	2.339	2.345	2.337	2.338	2.341	2.347
(G) Theoretical Maximum Gravity	2.517	2.517	2.517	2.517	2.517	2.517
(H) % Air Voids [100*(1-F/G)]	7.1	6.8	7.1	7.1	7.0	6.8
(I) Volume of Air Voids [H*(D - E)/100]	116.579	112.039	117.504	117.313	115.386	111.230
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3939.9	3937.3	3937.5	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	83.30	80.60	86.50			
(L) % Saturation [100*(K/I)]	71.5	71.9	73.6			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	1550	1650	1550	2500	2500	2500
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	72.1	72.1	72.2
(R) Conditioned S_T, psi [2P/(A*B*π)]	44.8	47.7	44.8	N/A	N/A	N/A
(S) Average S_T, psi	45.7			72.1		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:	0.63					

Project: WMA: Milwaukee Date: 7/10/2006

Tested By: D. Ford Calculated By: D. Ford

Sample Identification: Sasobit Mixture

	Conditioned Samples			Unconditioned Samples		
Sample Number	6	7	8	3	4	5
(A) Diameter, in	5.904	5.899	5.910	5.905	5.898	5.902
(B) Height, in	3.762	3.752	3.752	3.753	3.761	3.753
(C) Weight in Air, gm	3872.3	3875.8	3871.7	3867.9	3869.6	3873.9
(D) SSD Weight, gm	3887.9	3888.7	3894.0	3888.0	3885.2	3892.3
(E) Submerged Weight, gm	2236.9	2238.8	2242.8	2236.2	2233.8	2242.9
(F) Bulk Specific Gravity [A/(D - E)]	2.345	2.349	2.345	2.342	2.343	2.349
(G) Theoretical Maximum Gravity	2.522	2.522	2.522	2.522	2.522	2.522
(H) % Air Voids [100*(1-F/G)]	7.0	6.9	7.0	7.2	7.1	6.9
(I) Volume of Air Voids [H*(D - E)/100]	115.592	113.104	116.030	118.136	117.062	113.357
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3956.3	3957.7	3960.9	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	84.00	81.90	89.20			
(L) % Saturation [100*(K/I)]	72.7	72.4	76.9			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	3825	3750	3875	4150	4000	4250
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	119.2	114.8	122.1
(R) Conditioned S_T, psi [2P/(A*B*π)]	109.6	107.9	111.3	N/A	N/A	N/A
(S) Average S_T, psi	109.6			118.7		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:	0.92					

Project: WMA: Milwaukee Date: 10/19/2006

Tested By: J. Mingus Calculated By: J. Mingus

Sample Identification: Sasobit Mixture - Reheated

	Conditioned Samples			Unconditioned Samples		
Sample Number	3	4	7	5	6	8
(A) Diameter, in	5.910	5.920	5.920	5.910	5.920	5.920
(B) Height, in	3.740	3.740	3.730	3.730	3.740	3.740
(C) Weight in Air, gm	3874.3	3869.9	3865.5	3872.5	3867.7	3869.0
(D) SSD Weight, gm	3885.7	3886.1	3874.4	3884.6	3885.3	3885.6
(E) Submerged Weight, gm	2238.3	2230.6	2230.0	2238.9	2231.0	2232.8
(F) Bulk Specific Gravity [A/(D - E)]	2.352	2.338	2.351	2.353	2.338	2.341
(G) Theoretical Maximum Gravity	2.522	2.522	2.522	2.522	2.522	2.522
(H) % Air Voids [100*(1-F/G)]	6.7	7.3	6.8	6.7	7.3	7.2
(I) Volume of Air Voids [H*(D - E)/100]	111.199	121.043	111.688	110.212	120.716	118.700
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3952.5	3956.4	3947.2	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	78.20	86.50	81.70			
(L) % Saturation [100*(K/I)]	70.3	71.5	73.2			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	3500	3300	3450	3950	4125	4450
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	114.1	118.6	128.0
(R) Conditioned S_T, psi [2P/(A*B*π)]	100.8	94.9	99.5	N/A	N/A	N/A
(S) Average S_T, psi	98.4			120.2		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:	0.82					

APPENDIX D

DYNAMIC MODULUS RESULTS

TABLE D1 Dynamic Modulus Data, Control After Reheating

Conditions			Specimen 1		Specimen 2		Specimen 3		Average	Average	Average
Test Temp. °C	Test Temp. °K	Frequency Hz	Modulus MPa	Phase Angle Degrees	Modulus MPa	Phase Angle Degrees	Modulus MPa	Phase Angle Degrees	Modulus MPa	Modulus psi	Modulus ksi
4.4	277.4	0.5	7070	18.89	8254	18.24	7745	17.52	7690	1115309	1115
		1	8063	17.42	9313	16.86	8755	16.23	8710	1263347	1263
		2	9109	16.01	10413	15.59	9790	14.95	9771	1417137	1417
		5	10570	14.15	11948	14	11220	13.45	11246	1631120	1631
		10	11698	12.88	13130	12.91	12323	12.36	12384	1796127	1796
		20	12891	11.42	14497	11.94	13442	11.32	13610	1973994	1974
		25	13349	10.84	14678	11.71	13784	11.01	13937	2021422	2021
21.1	294.1	0.5	1765	31.29	2286	30.1	2239	29.23	2097	304101	304
		1	2236	30.46	2823	29.26	2757	28.13	2605	377878	378
		2	2817	29.18	3468	28.09	3365	27.07	3217	466545	467
		5	3760	26.71	4448	26.37	4300	25.29	4169	604720	605
		10	4558	25.11	5286	24.94	5094	23.81	4979	722203	722
		20	5417	23.45	6238	23.34	5959	22.26	5871	851578	852
		25	5639	23.23	6587	23.07	6198	21.92	6141	890739	891
37.8	310.8	0.5	348.2	34.05	437.9	32.84	455	32.3	414	60003	60
		1	459.1	35.29	573.5	34.16	592.3	33.31	542	78558	79
		2	647.3	35.16	806.2	33.79	810.9	33.16	755	109476	109
		5	982	34.97	1198	33.6	1184	32.92	1121	162638	163
		10	1315	34.76	1581	33.32	1552	32.63	1483	215046	215
		20	1734	34.18	2063	32.63	2007	31.99	1935	280604	281
		25	1870	34.06	2220	32.55	2152	31.97	2081	301780	302

TABLE D2 Dynamic Modulus Data, Evotherm After Reheating

Conditions			Specimen 1		Specimen 2		Specimen 3		Average	Average	Average
Test Temp. °C	Test Temp. °K	Frequency Hz	Modulus MPa	Phase Angle Degrees	Modulus MPa	Phase Angle Degrees	Modulus MPa	Phase Angle Degrees	Modulus MPa	Modulus psi	Modulus ksi
4.4	277.4	0.5	3173	28.41	3209	28.07	3347	28.26	3243	470365	470
		1	3872	27.14	3914	26.62	4082	26.76	3956	573778	574
		2	4676	25.65	4723	25.16	4912	25.08	4770	691889	692
		5	5897	23.44	5928	22.8	6143	22.7	5989	868693	869
		10	6961	21.75	6962	21.08	7158	20.97	7027	1019196	1019
		20	8105	19.96	8092	19.27	8243	19.14	8147	1181593	1182
		25	8496	19.54	8475	18.77	8627	18.66	8533	1237578	1238
21.1	294.1	0.5	593.5	33.06	581.1	33.75	582.1	34.35	586	84931	85
		1	791	34.06	769.8	34.5	771	35.08	777	112735	113
		2	1081	33.94	1048	34.3	1044	35.03	1058	153404	153
		5	1572	33.63	1524	33.86	1520	34.57	1539	223168	223
		10	2043	33.13	1984	33.27	1978	33.95	2002	290322	290
		20	2627	32.3	2543	32.31	2543	32.92	2571	372898	373
		25	2806	32.37	2721	32.3	2709	32.94	2745	398183	398
37.8	310.8	0.5	122	32.31	112.4	33.14	107.1	33.6	114	16510	17
		1	152.8	34.2	142.1	35.03	136	35.57	144	20833	21
		2	211.5	35.44	195	36.37	188.3	36.9	198	28757	29
		5	351.9	35.44	325.8	36.37	316.8	36.77	332	48081	48
		10	496.4	36.16	461.8	37.08	450.4	37.48	470	68101	68
		20	695.9	36.95	648.1	37.83	635.2	38.24	660	95688	96
		25	807.9	35.7	748.2	36.36	732.7	36.84	763	110656	111

TABLE D3 Dynamic Modulus Data, Sasobit After Reheating

Conditions			Specimen 1		Specimen 2		Specimen 3		Average	Average	Average
Test Temp. °C	Test Temp. °K	Frequency Hz	Modulus MPa	Phase Angle Degrees	Modulus MPa	Phase Angle Degrees	Modulus MPa	Phase Angle Degrees	Modulus MPa	Modulus psi	Modulus ksi
4.4	277.4	0.5	8854	17.06	9154	16.81	7493	15.63	8500	1232888	1233
		1	9970	15.83	10310	15.53	8350	14.48	9543	1384165	1384
		2	11139	14.69	11510	14.38	9221	13.43	10623	1540808	1541
		5	12750	13.24	13135	12.95	10413	12.25	12099	1754887	1755
		10	14018	12.22	14423	11.99	11332	11.38	13258	1922892	1923
		20	15308	11.24	15734	11.08	12273	10.55	14438	2094136	2094
		25	15757	10.93	16239	10.72	12597	10.22	14864	2155923	2156
21.1	294.1	0.5	3104	26.88	2910	27.47	2343	28.03	2786	404033	404
		1	3743	25.89	3524	26.51	2837	26.76	3368	488495	488
		2	4477	24.72	4217	25.33	3402	25.36	4032	584801	585
		5	5569	23.02	5284	23.64	4247	23.45	5033	730035	730
		10	6488	21.75	6238	22.27	4954	21.96	5893	854769	855
		20	7549	20.31	7294	20.84	5726	20.42	6856	994443	994
		25	7890	20	7686	20.55	5926	19.93	7167	1039550	1040
37.8	310.8	0.5	619.7	31.96	696.1	30.43	501.9	33.49	606	87880	88
		1	793.4	32.81	878.6	31.4	645.1	34.45	772	112024	112
		2	1065	32.59	1171	31.16	893.1	33.63	1043	151282	151
		5	1520	32.17	1638	30.9	1290	32.83	1483	215046	215
		10	1956	31.65	2083	30.46	1664	32.08	1901	275721	276
		20	2496	30.79	2628	29.7	2114	30.97	2413	349933	350
		25	2663	30.76	2810	29.71	2255	30.72	2576	373623	374