NCAT Report No. 09-10

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April 2009

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Sponsored by
Federal Highway Administration

NCAT Report No. 09-10X

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ABSTRACT

A single Warm Mix Asphalt (WMA) mixture produced using Sasobit® was evaluated against a control Hot Mix Asphalt (HMA) test section in a field project located outside of Iron Mountain, Michigan. Mixture volumetric properties, rutting susceptibility, moisture resistance, Hamburg wheel tracking, and dynamic modulus testing were conducted to evaluate field performance. Plant emissions and in-place field performance data were also collected. Based on the laboratory and field testing, the WMA technology performed equal to or better than the control mixture.

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, based on the findings from a study tour sponsored by the National Asphalt Pavement Association, interest in these technologies has grown in the United States (U.S.). Since that time, a number of new processes have been developed; including U.S. based processes such as Evotherm™ and multiple mechanical foaming devices.

All of these processes work to lower the 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 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 increase in workability. The amount of expansion varies depending 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 percent 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 (3G).

Beginning in 2003, laboratory studies were conducted to evaluate the effect of three 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 achieved 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 alleviated and field trials progressed.

In 2006, a number of WMA field trials were constructed, including three that utilized multiple technologies. This particular field project, located in Michigan, evaluated a single WMA technology, Sasobit®. The results from this evaluation are presented herein.

PURPOSE AND SCOPE

The main purpose of this study was to evaluate the field performance of Sasobit® in a cold weather environment, where the average temperature is below 40°F (4.4°C) for five months out of the year. The Sasobit® was introduced into the existing HMA design with no modifications to the mix design. A test section was constructed on an in-service roadway, along with a HMA control section. Construction of the test sections took place in September 2006. Sampling and testing was generally conducted using the data collection guidelines developed by the WMA Technical Working Group (*9*). Field mixed, laboratory compacted volumetric properties, laboratory performance tests, along with field performance data, are reported.

PROJECT DESCRIPTION

The field trial consisted of the widening of the northbound lane of State Highway 95 (M95). The WMA was used as an overlay for the top 1.5 inches (compacted) of the surface course in the passing lane. The control test section was placed in the newly constructed adjacent travel lane of M95. Figure 1 shows the project location.

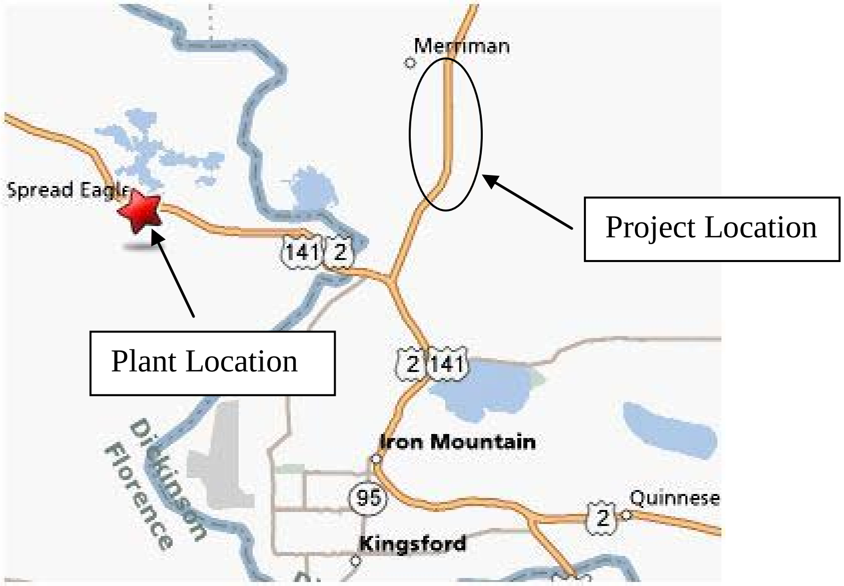

FIGURE 1 Iron Mountain, MI WMA Project and Plant Location.

MATERIALS

The job mix formula used was a 9.5 mm nominal maximum aggregate size (NMAS) Superpave mixture, designed with a compactive effort of 86 gyrations. A basalt aggregate source was used in this mix design. The virgin mixture used an unmodified PG 58-34 asphalt binder. Sasobit® was added at a target rate of 1.5 percent by total weight of asphalt binder. For this project, Sasobit® was pre-blended with the binder. The design aggregate gradation and optimum asphalt content are presented in Table 1. Table 2 lists the target volumetric properties.

TABLE 1 Design Aggregate Gradation and Optimum Asphalt Content

Sieve Size, mm (in.)	Percent Passing, %
19.0 (3/4")	100.0
12.5 (1/2")	100.0
9.5 (3/8")	99.1
4.75 (#4)	75.0
2.36 (#8)	55.9
1.18 (#16)	41.3
0.6 (#30)	27.5
0.3 (#50)	14.5
0.15 (#100)	7.5
0.075 (#200)	5.5
AC, %	5.5

TABLE 2 Volumetric Properties

G_{mm}	G_{sb}	Air Voids	VMA	VFA
2.552	2.450	4.0	16.23	75.40

RESULTS AND DISCUSSIONS

Construction

A total of 1,000 tons of the Sasobit® mixture were produced. Mixing temperatures for the control and WMA were 325 and 260°F (163 and 127°C), respectively. During construction, a control section was placed at a compaction temperature of 300°F (149°C). For the WMA test section, the compaction temperature was approximately 250°F (121°C). The asphalt plant that produced the mixes was located in Spread Eagle, WI. It was a portable, parallel flow plant that incorporated an Adeco drum, Gencor burner, and a Cedar Rapids silo. Figure 2 shows the asphalt plant used for this project. The fuel for the plant was reclaimed oil.

FIGURE 2 Payne and Dolan's Iron Mountain, MI Portable Asphalt Plant.

The asphalt mixtures were hauled to the paving site in both end-dump and live-bottom trucks, with a haul distance of approximately 8 miles (roughly ten minute travel time). The test sections constructed were placed at a width of 12 feet using a Blaw Knox PF 200 paver using a Carlson screed. The screed vibrators were not used. During laydown, the augers were continuously running, ensuring a constant head of material. When placing the Sasobit® mixture, a template was mounted on the paver to produce a notched-wedge longitudinal joint. Compaction was achieved using an Ingersoll Rand DD 110 HF roller as the breakdown roller. The breakdown roller applied three vibratory passes, staying off the joint six inches for the first pass. An Ingersoll Rand DD 130 followed the first roller, applying two vibratory passes across the mat. A Caterpillar 300 B rubber tire roller was used as the third roller, applying four passes across the mat with a tire pressure of 110 psi. A Bomag BW11AS roller was used as the finish roller, applying two static passes.

Laboratory Testing

During construction of the test sections, samples of each asphalt mixture were obtained from loaded trucks at the plant and used to produce test specimens for performance testing. The specimens for both sections were prepared onsite in Payne & Dolan's (doing business as Northeast Asphalt) quality control lab by Payne and Dolan's staff. Laboratory testing included: mixture volumetric properties, Asphalt Pavement Analyzer (APA) testing (AASHTO TP 63), moisture sensitivity testing (AASHTO T 283), Hamburg testing (AASHTO T 324), and dynamic modulus testing (AASHTO TP 62). 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 comparisons could be determined between hot compacted samples and samples that were reheated prior to compaction. Hot compacted were samples compacted immediately without the mix cooling to ambient temperature. The mixture temperature was determined with temperature probes. If the temperature was below the target compaction temperature it was brought back to the target temperature in a forced-air oven. Reheated samples were compacted from mix that cooled to ambient temperature and was reheated at a later date to compact specimens. The mix was reheated at the target compaction temperature. This comparison simulates the difference between the contractor's quality control data and the state DOT's quality assurance data. For dynamic modulus testing, only reheated samples could be made due to gyratory compactor limitations. Hot compacted samples and loose mix for reheating were shipped back to NCAT's main laboratory for testing and analysis.

Mixture Volumetric Properties

For each field sample, six specimens were compacted hot and six specimens were compacted from reheated mix to determine mixture volumetric properties. The samples were compacted using 86 gyrations (specified N_{design}) of the Superpave gyratory compactor (SGC) according to AASHTO T 312-04. Samples were compacted at a temperature equal to the anticipated compaction temperature at the paver. Air void test results are illustrated in Figure 3. The error bars in Figure 3 indicate ± one standard deviation of the mean. Complete volumetric property test results are presented in Appendix A. From Figure 3, it can be seen that the Sasobit® mixture had lower air voids than the control mixture for the samples compacted hot, while the control mixture had lower air voids for the samples that were reheated prior to compaction. It can also be seen that the reheated samples had higher air voids than the samples compacted hot. It should be noted that the hot samples were compacted on a Troxler model 4141 SGC and the reheated samples were compacted on a Pine model AFG1A SGC. The reheated specimens were compacted in the main NCAT laboratory and not in the mobile laboratory.

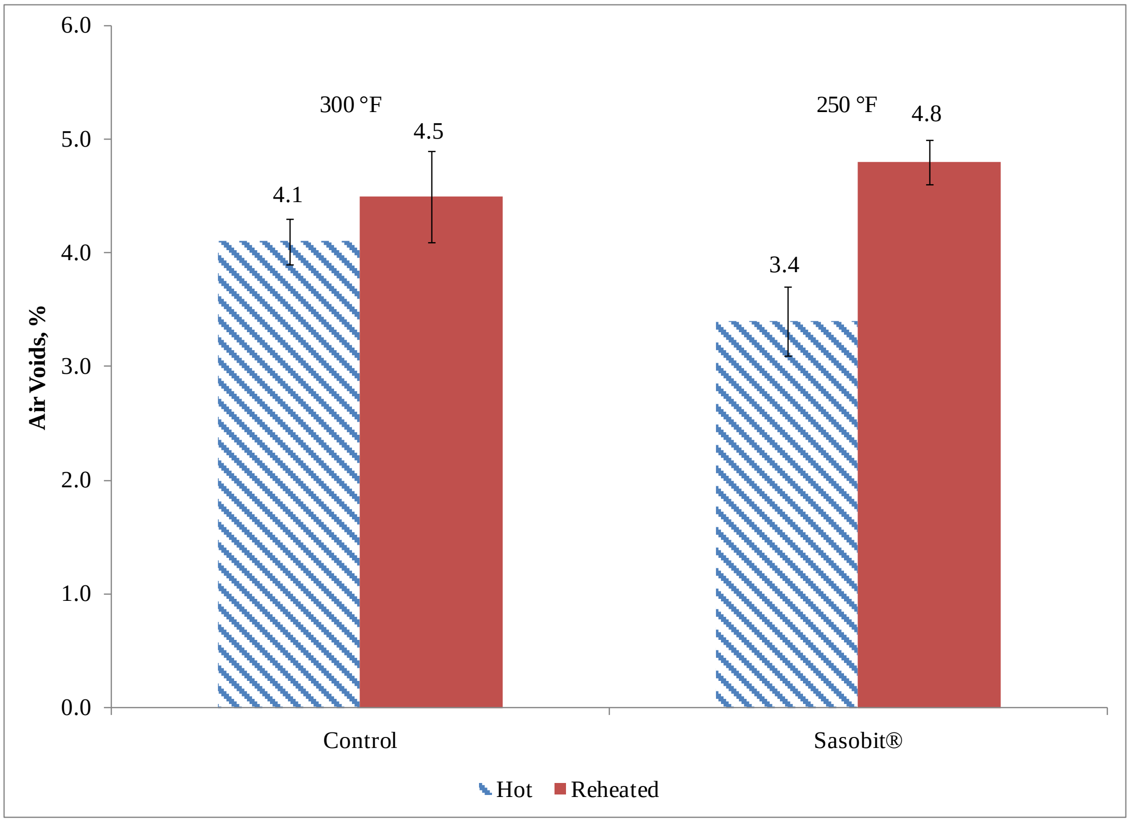

FIGURE 3 SGC Air Voids Content.

An analysis of variance (ANOVA) was conducted on the compaction data to determine which factors significantly affected the air void content. The factors that were considered included mix type (Sasobit® and HMA control), mix preparation method (compacted hot and compacted from reheated mix), and their interaction. A level of significance of $\alpha = 0.05$ was used to identify factors that significantly affected air voids. Mix type was not identified as a significant factor (*p-value* = 0.06). Mix preparation method and the interaction between mix type and mix preparation method were identified as factors that significantly affected the air void content. Therefore, air voids obtained from samples compacted hot were significantly different than those compacted from reheated mix. Since a different brand and model gyratory compactor was used to compact the reheated samples, it cannot be conclusively determined if the difference in sample air voids results from reheating or from differences between the gyratory compactors.

The interaction between mix type and mix preparation method is illustrated in Figure 4. The mean air voids for the Sasobit® samples compacted hot are 0.75 percent less than those of the HMA control. An ANOVA performed on the hot compacted data by itself indicates mix type significantly affected (improved) compaction (*p-value* = 0.003). However, the mean air voids of the reheated Sasobit® samples was 0.27 percent greater than the mean air voids for the HMA control samples. While this type of reversal might be expected for WMA systems which rely on residual moisture, it was not expected with Sasobit® and may result from sampling or testing variability.

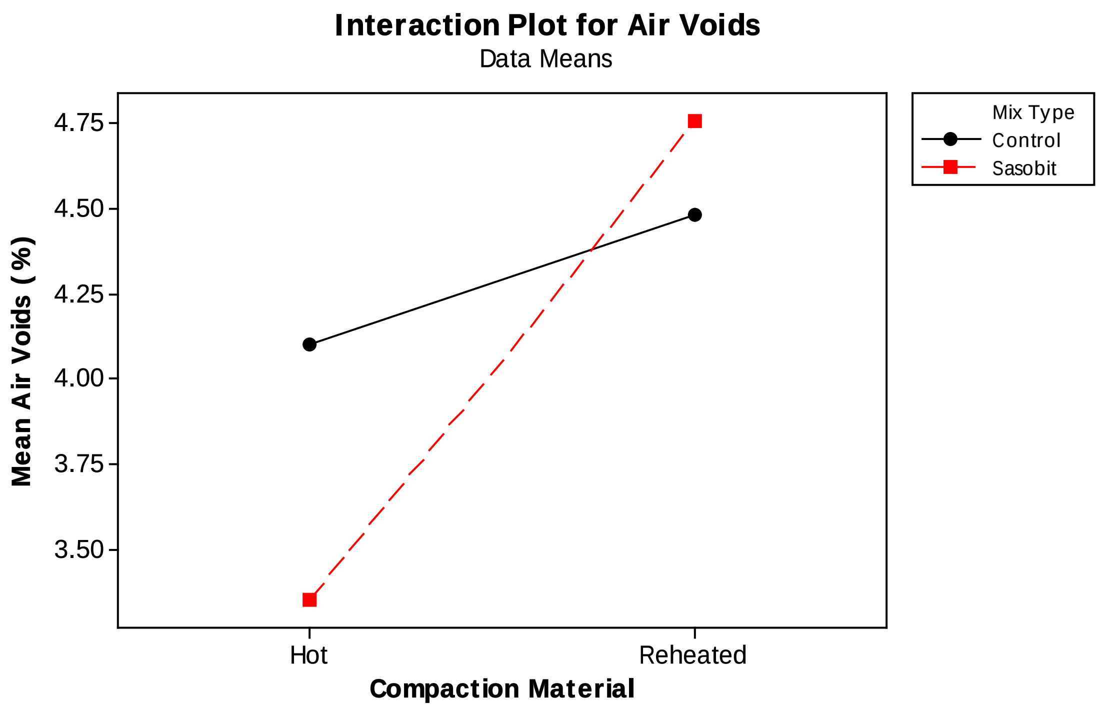

FIGURE 4 Interaction Plot for Densification Data.

The asphalt content of the mix samples was measured according to AASHTO T 164-06 method. Gradation analysis of the extracted aggregate was conducted according to AASHTO T 30-03. A review of asphalt content and gradation data (presented in full in Appendix B) indicated a slight increase in dust content for the Sasobit® mixture and a resulting decrease in voids-in-mineral aggregate (VMA), compared to the control mixture. The asphalt content for the Sasobit®, however, was lower than the control. The decrease in air voids for the Sasobit® samples was greater than the decrease in VMA, even with the lower asphalt content. This indicates Sasobit® affected laboratory compaction, even at the lower compaction temperature for the hot compacted samples.

Asphalt Pavement Analyzer

Once the air void contents of the specimens compacted to N_{design} gyrations were determined, each mixture set was tested in the APA to assess the mixture's resistance to permanent deformation. Testing was conducted in accordance with AASHTO TP 63-06 with the exception of the hose pressure and vertical load. All testing was conducted at 136°F (58°C), the base PG high temperature grade. Testing was conducted using a hose pressure of 120 psi and a vertical load of 120 pounds, paralleling the testing parameters of the previous NCAT WMA laboratory evaluations (*5-7*). Rut depths were recorded manually before and after the test. Test results, obtained from manual measurements, are shown in Figure 5. The error bars in Figure 3 indicate ± one standard deviation of the mean. Complete APA test data is presented in Appendix C. The data illustrates that the rut depths for the Sasobit® were similar to the rut depths for the control mixture, even with a difference in compacted air voids. It can also be seen that the measured rut depths for the reheated samples were higher than the rut depths for the samples compacted hot. Typically, additional aging results from reheating the mixtures and would be expected to decrease the measured rut depths. The higher rut depths may result from the higher sample air voids of the reheated samples, although regression analysis indicated no relationship (R^2 = 0.20) between specimen air voids and measured APA rut depth.

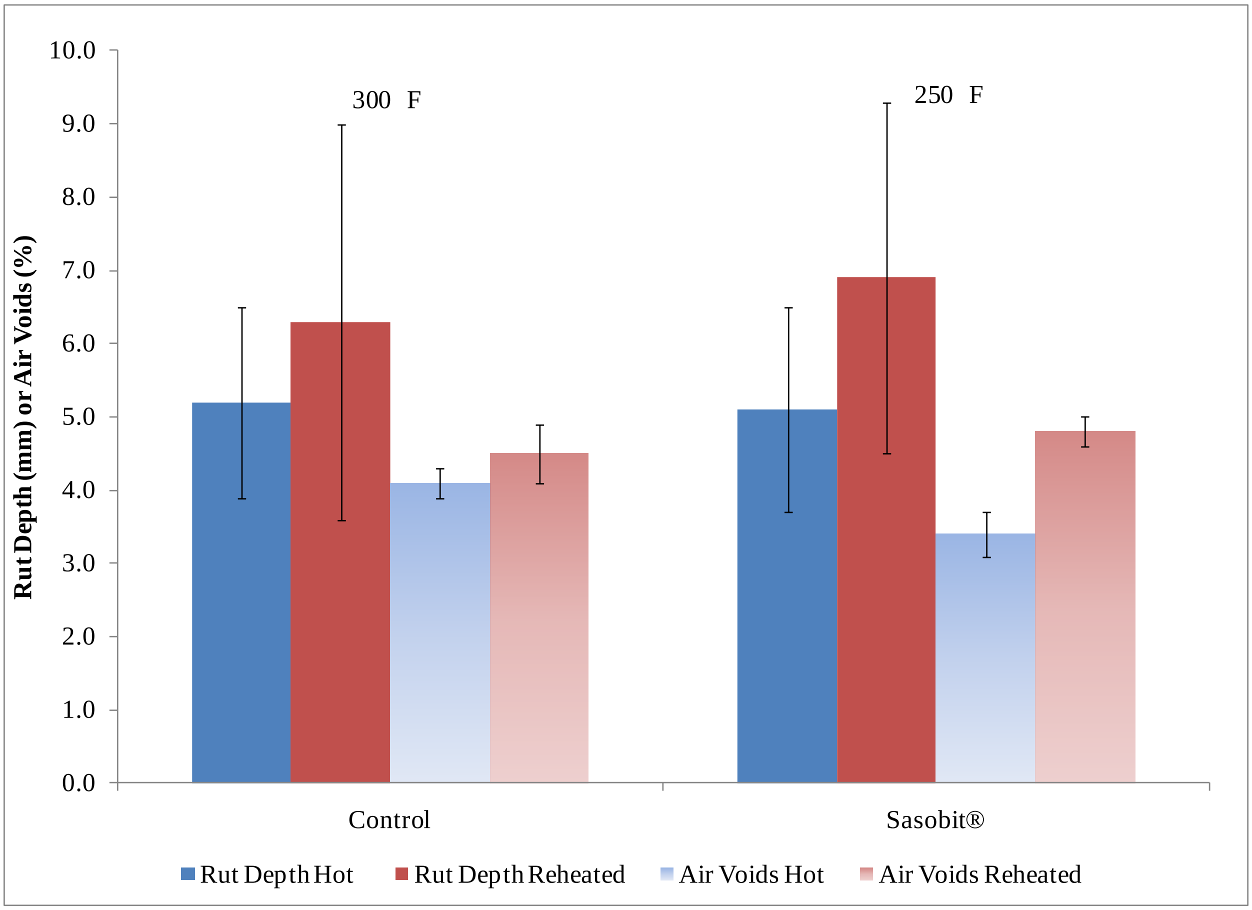

FIGURE 5 Asphalt Pavement Analyzer Rut Depth Results.

An ANOVA was conducted using the General Linear Model (GLM) on the APA rut depth data to determine if the mix type (Sasobit® and Control) or mix preparation method (hot and reheated) significantly affected the resistance to permanent deformation. The analysis indicated that neither the WMA technology nor whether the samples were reheated or compacted hot significantly affected the measured rut depth. However, with a regression coefficient of only 15 percent (determined as part of the GLM), the variability of the test data may have influenced the statistical analysis. Potential outliers for the measured rut depth were identified in the reheated control data. A Grubb's test, applicable to small data sets, was conducted to determine if they were, in fact, outliers, which could be excluded from the analysis. Results indicated that the extreme measurements were not outliers; therefore all data were included in the analysis.

Moisture Resistance

Specimens of each mixture were prepared according to AASHTO T 283-03 to assess moisture damage susceptibility. Testing was also conducted in accordance with AASHTO T 283-03 and one freeze-thaw cycle was included when conditioning specimens. Unfortunately, AASHTO T

283 testing was only conducted on reheated samples, due to limitations producing samples on-site during construction. The tensile strength ratio (TSR) data is presented in Table 3. Complete AASHTO T 283 test results are presented in Appendix D. An acceptable criterion for the test is a TSR value of 0.80 or greater. From the data, it can be seen that both the control and Sasobit® test sections had TSR values that satisfied the minimum required value (see Figure 6). Error bars for the measured tensile strength indicate ± standard deviation of the mean. The relatively low tensile strengths measured is believed to be a result of the softer binder used for the project. The tensile strengths of the mixture containing Sasobit® were higher than the control, most likely resulting from the stiffening effect of Sasobit® on the binder.

TABLE 3 Tensile Strength Ratio Results, Samples Compacted After Reheating

Mix Type	Sample #	Compaction Temperature, °F	Indirect Tensile Strength		TSR
			Unsaturated, psi	Saturated, psi	
Control	1	300	53.9	54.8	1.02
Sasobit®	1	250	73.6	70.6	0.96

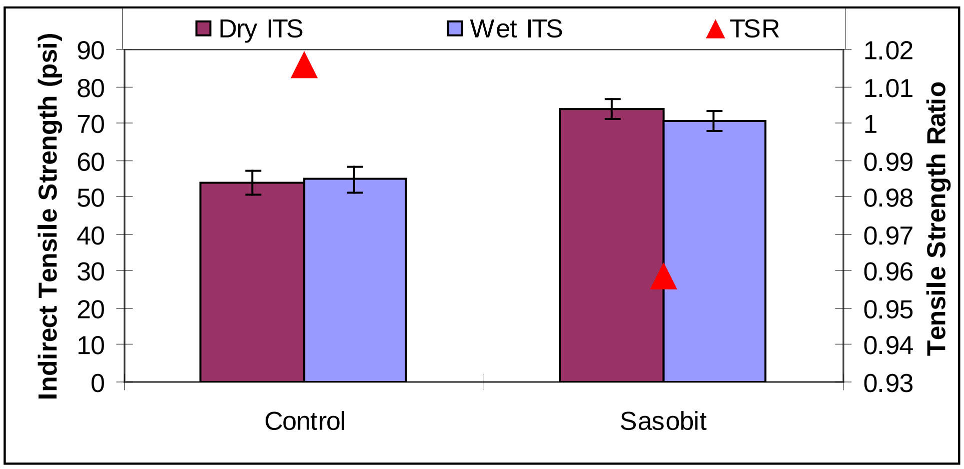

FIGURE 6 AASHTO T 283 Results

Hamburg Wheel Tracking

To further evaluate moisture damage susceptibility, samples were prepared and tested using the Hamburg wheel tracking device. Hamburg tests were conducted on reheated mix samples according to AASHTO T 324-06, using a test temperature of 122°F (50°C). This test is typically used to predict moisture damage and rutting resistance of HMA, but has been found to be sensitive to other factors, including binder stiffness, short-term aging, compaction temperature, and anti-stripping treatments (*10*). All of these factors have been identified as potential problem areas in the evaluation of WMA, so the results from the Hamburg wheel tracking device may provide a method of accurately establishing a good performing WMA mixture.

Test results for the reheated samples from the Hamburg wheel tracking device are presented in Table 4. In most cases, the stripping inflection point indicates whether the mixture will be prone to moisture damage or not. The higher the stripping inflection point and lower the rutting rate and total rutting, the better the asphalt mixture is expected to perform. From these data, it can be seen that, based on the stripping inflection point, the Sasobit® performed better than the control section in the Hamburg test. However, both sections did very poorly, in terms of total rutting at 10,000 cycles.

TABLE 4 Hamburg Wheel Tracking Results, Samples Compacted After Reheating

Mix Type	Stripping Inflection Point, cycles	Rutting Rate, mm/hr	Total Rutting @ 5,000 cycles, mm	Total Rutting @ 10,000 cycles, mm
Control	3,500	5.18	10.26	20.53
Sasobit®	5,200	4.82	9.57	19.13

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 under confined conditions at seven frequencies at each of three temperatures. Testing frequencies were in accordance with AASHTO TP62-03, with the test temperatures in accordance to AMPT testing capabilities. Complete dynamic modulus data are presented in Appendix E. Dynamic modulus master curves generated for the Sasobit® and Control are presented in Figure 6. Figure 6 displays the master curves for the samples that were reheated prior to compaction. The reference temperature for the master curves is 70°F (21.1°C).

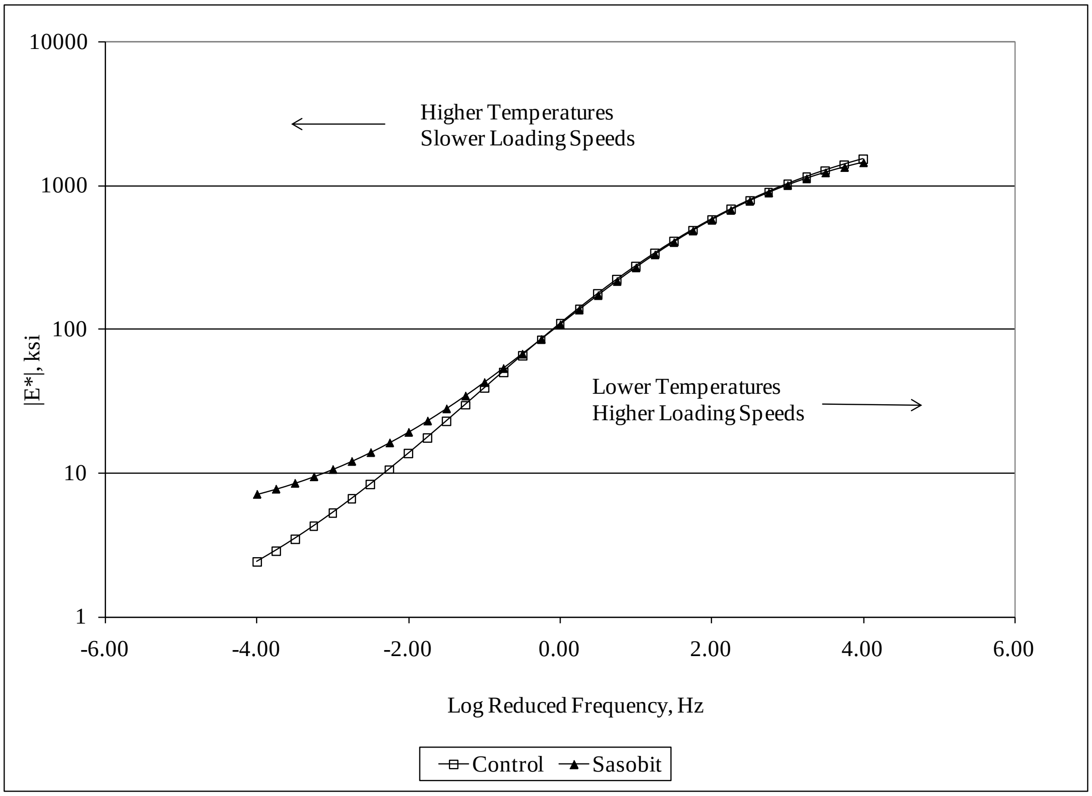

FIGURE 6 Dynamic Modulus Master Curves, Samples Compacted After Reheating.

The master curve indicates that the Sasobit® increased the mixture stiffness in the region represented by higher temperatures and slower traffic speeds. Little difference is evident in the regions representing intermediate and low temperatures. Tukey's Mean comparisons by test temperature and frequency were conducted to determined if there were statistical differences between the mean dynamic modulus data for the control and Sasobit® mixes. None of the comparisons indicated that there was a significant difference between the mean dynamic modulus values.

Emissions Testing

Stack emissions testing was conducted for both the Sasobit® and Control sections to determine how much, if any, the use of Sasobit® reduced the emissions produced during construction. The emission testing was collected by the contractor. The results from the emissions testing are presented in Table 4 below (*12*). Data shows an overall decrease in emissions when WMA is produced, with 18 percent lower carbon dioxide (CO_2) and 34 percent lower nitrous oxides (NO_x). Also, ten percent less fuel was used during the production of Sasobit®. Table 5 also shows that there was an eight percent increase in the production of volatile organic compounds (VOCs). Due to the results from the stack emissions test results for the Wisconsin WMA field trial (*11*), the burner and drum flighting were adjusted in an attempt to prevent unburned fuel from occurring in the asphalt drum and improve heat penetration in the drum. However, the increase in measured VOCs, as well as a reported increase in carbon monoxide (CO), indicated that additional fine tuning was needed (*12*). Both measures are indicators of incomplete fuel combustion. By fine tuning the burner, unburned fuel should not be released into the drum, decreasing the amount of VOC's and CO produced.

TABLE 5 Stack Emissions Results (*12*)

Emission	Reduction, %	Increase, %
NO_x	34.0	
VOC		8.0
CO_2	18.0	
Fuel Usage	10.0	

FIELD PERFORMANCE

The site was revisited two years after construction to compare the field performance of the WMA to that of the HMA. Field performance evaluation of the Sasobit® and control sections was conducted through visual observations, field rut depth measurements, and through core analysis. The visual inspections were conducted to identify and classify any distresses in accordance with the LTPP guidelines. Rut depth measurements were taken in both the WMA and HMA sections using a string line. Field cores were obtained to evaluate the densification that had occurred and the indirect tensile strength. The field cores were obtained adjacent to where the original construction field cores were extracted. The layout of the cores for each section is shown in Figure 7. As can be seen, three cores were taken in the wheel path, and a fourth core taken between the wheel paths. This was done for both test sections.

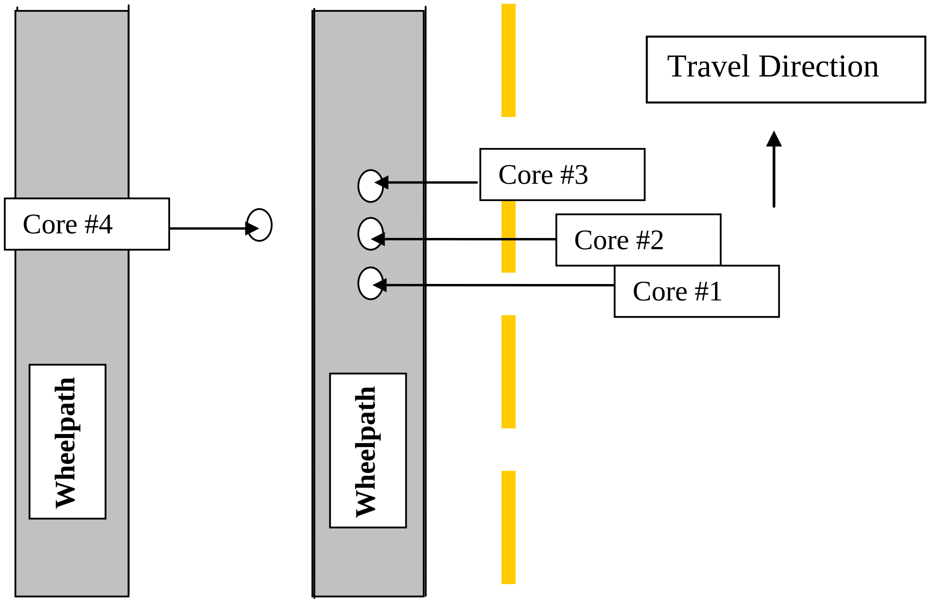

FIGURE 7 Core Layout for Control and Sasobit® WMA Test Sections, 2 Year Evaluation.

As cores were being taken, a visual inspection of each test section was conducted. Field rut measurements were also taken for each section. For the Sasobit®, no measureable rutting was observed. Although the addition of Sasobit® has been shown to increase the low temperature cracking failure temperature, no low temperature cracking was observed. Only minor pop-outs of coarse aggregate particles were observed for the Sasobit® section (Figure 8). For the control section, rut depths of 1/16 inch were recorded in the right wheel path and 1/8 inch measured in the left wheel path. Cores for the control section were taken approximately 50 yards from the location of the Sasobit® cores. No cracking was observed for the control test section.

FIGURE 8 Coarse Aggregate Pop-out from Sasobit® Test Section.

Figures 9 and 10 show the performance of the Sasobit® test section compared to the control section, after two years of traffic. The error bars in both figures indicate ± one standard deviation of the mean. Figure 9 is the in-place air voids of the two test sections, while Figure 10 shows the indirect tensile strengths measured from the cores taken from the two test sections. Following construction, in-place density results for the Sasobit® section were similar to the control section, even though the compaction temperature was approximately 50°F lower for the Sasobit section. After two years, the in-pace density of the control section has increased while the Sasobit® has stayed the same. This is most likely due to the Sasobit® being in the passing lane, and thus not receiving the same amount of traffic as the control section. The indirect tensile strengths of both the Sasobit® WMA and Control mixtures increased as expected after two-years of in-place aging. No visual stripping was observed in the field cores from either section (Figure 11). Figure 12 shows the physical appearance of the Sasobit® and control test sections after two years of traffic.

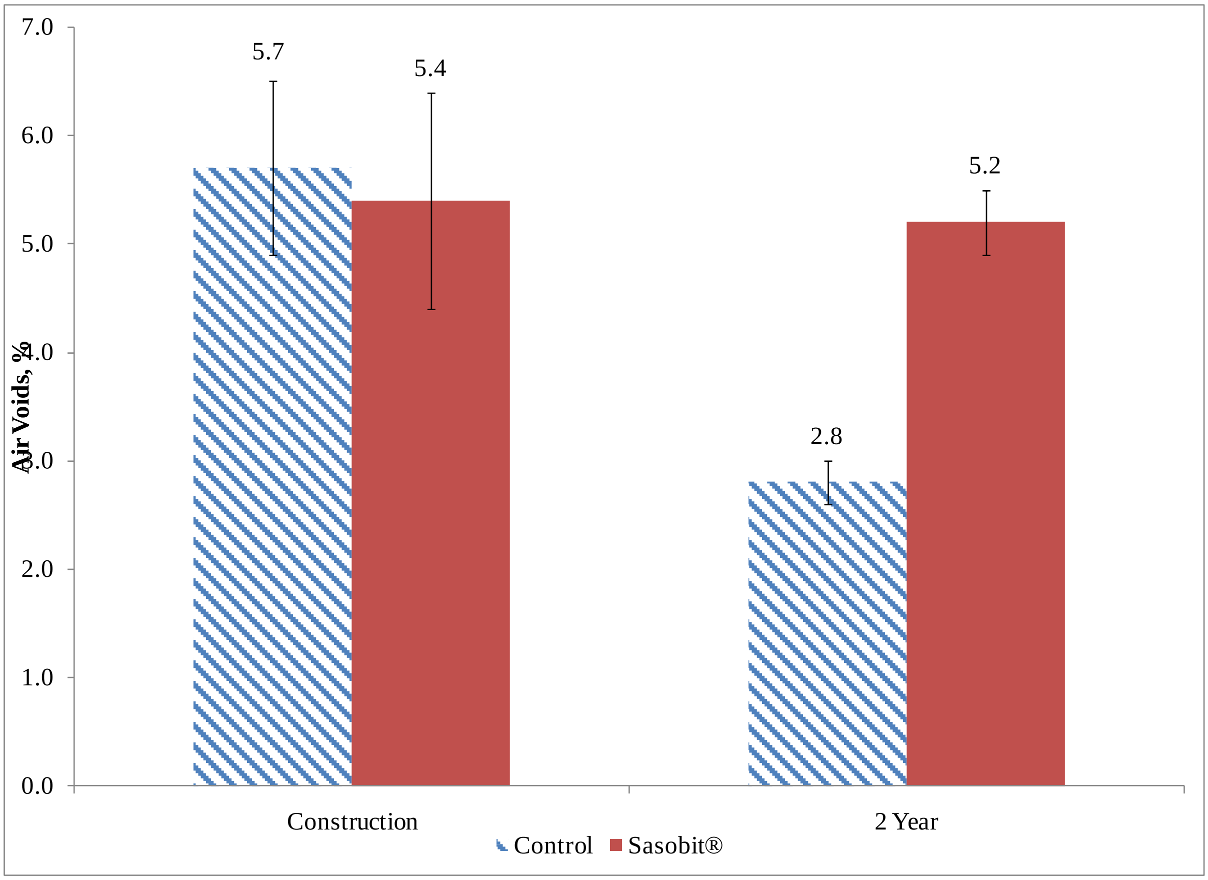

FIGURE 9 In-place Air Voids Through Two Years of Traffic.

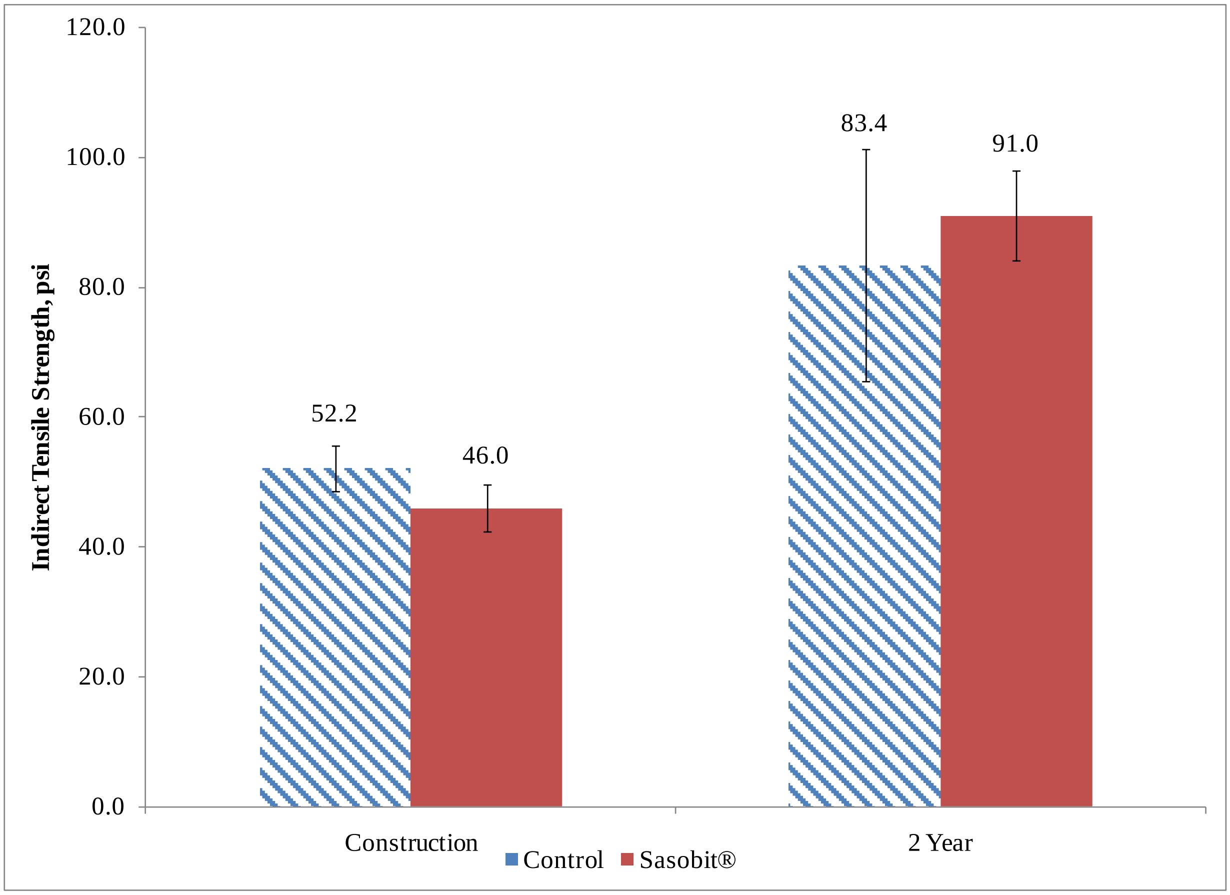

FIGURE 10 Indirect Tensile Strength Results, Through Two Years of Traffic.

FIGURE 11 2 Year Cores, Control (Top) and Sasobit® (Bottom)

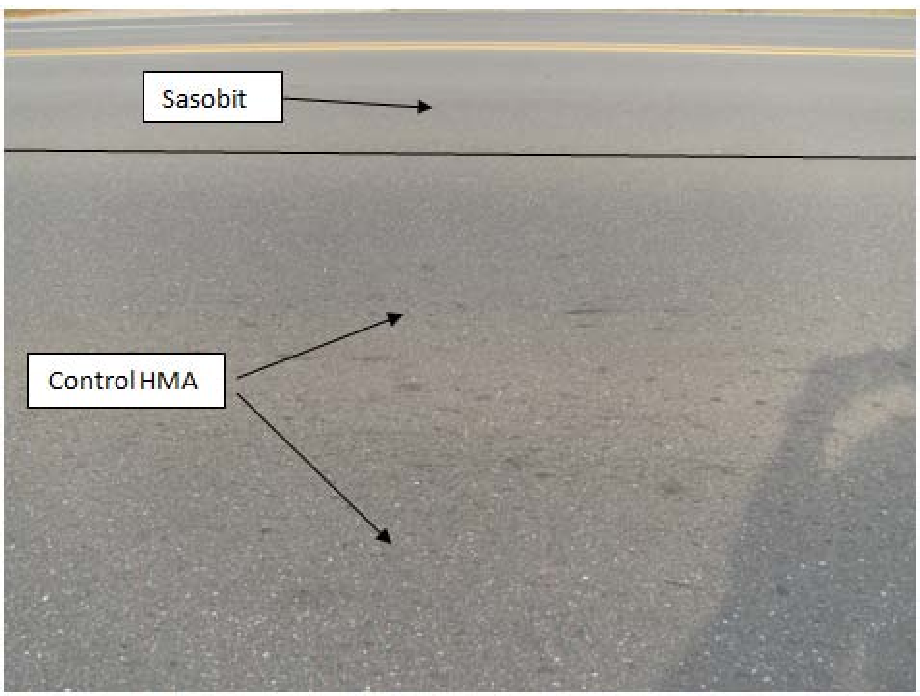

FIGURE 12 Sasobit® and Control Test Sections after Two Years of Traffic.

CONCLUSIONS

In September 2006, a WMA field evaluation was constructed on M95, in Iron Mountain, MI. This test section was used to evaluate the field performance of the Sasobit® WMA technology. Specific conclusions from this evaluation include:

- The WMA test section was successfully placed at a compaction temperature 50°F lower than the control test section,
- Laboratory air voids for the WMA section were found to be statistically different than the control section for the samples compacted hot, but not for the reheated samples. However, the use of different gyratory compactors may have affected the analysis,
- Laboratory rutting susceptibility tests conducted in the APA indicated that the Sasobit® resulted in measured rut depths which were not statistically different from the control,
- Laboratory moisture susceptibility tests indicate similar performance to the control. The measured tensile strengths were higher for the Sasobit® mixture. Hamburg wheel tracking tests, however, suggest that both the control and Sasobit® test sections have the potential for both permanent deformation and moisture damage. However, it should be noted that after two years neither permanent deformation nor moisture damage appear to be an issue for either mix,
- The dynamic modulus determined for the Sasobit® resulted in values that were statistically the same as the control. The addition of Sasobit® increased the mixture stiffness at high temperatures and slow loading rates,
- Based on emission stack testing, a decrease in asphalt stack emissions and fuel usage was determined during the production of WMA. An increase in CO and VOCs for the WMA indicates the need for additional burner tuning to fully combust the burner fuel, and
- Early performance indicates that Sasobit® WMA can be successfully used in cold weather climates.

ACKNOWLEDGEMENTS

This work was sponsored by the FHWA under a cooperative agreement with NCAT. Mr. Hurley and Dr. Prowell were employed by NCAT when this testing was completed. The authors would like to thank the asphalt contractor, Payne & Dolan, particularly Lincoln Noel, John Bartoszek, Jack Weigel, and Brett Stanton for supporting this research. The author's also thank the Michigan Department of Transportation for their assistance in collecting relevant project data. The authors also thank the laboratory staff at NCAT for completing the testing in a timely manner.

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APPENDIX A - VOLUMETRIC DATA

APPENDIX A1: Volumetric Properties, Control Mix - Hot

Mix Type:	Control	Asphalt Specific Gravity (Gb):	1.028
Ndesign:	86	Apparent Specific Gravity (Gsa):	
Test Date:		Effective Specific Gravity (Gse):	2.817
		Bulk Specific Gravity (Gsb):	2.755

Sample Number	Asphalt Content, %	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %
1	5.5	300	4907.7	2923.1	4909.1	2.471	2.572	3.9	15.2	74.3
2	5.5	300	4922.9	2927.0	4924.8	2.464	2.572	4.2	15.5	72.9
3	5.5	300	4920.8	2927.8	4922.9	2.466	2.572	4.1	15.4	73.3
4	5.5	300	4916.8	2929.4	4917.9	2.473	2.572	3.9	15.2	74.6
5	5.5	300	4921.2	2923.1	4923.0	2.461	2.572	4.3	15.6	72.3
6	5.5	300	4916.2	2922.7	4917.9	2.464	2.572	4.2	15.5	72.9
Avg.						2.467	2.572	4.1	15.4	73.4

APPENDIX A2: Volumetric Properties, Control Mix - Reheated

Mix Type:	Control	Asphalt Specific Gravity (Gb):	1.028
Ndesign:	86	Apparent Specific Gravity (Gsa):	
Test Date:		Effective Specific Gravity (Gse):	2.817
		Bulk Specific Gravity (Gsb):	2.755

Sample Number	Asphalt Content, %	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %
1	5.5	300	4594.2	2734.0	4596.6	2.467	2.572	4.1	15.4	73.4
2	5.5	300	4598.3	2731.2	4600.6	2.460	2.572	4.4	15.6	72.1
3	5.5	300	4593.4	2726.9	4596.4	2.457	2.572	4.5	15.7	71.6
4	5.5	300	4597.9	2729.6	4599.5	2.459	2.572	4.4	15.7	71.9
5	5.5	300	4596.9	2724.0	4598.9	2.452	2.572	4.7	15.9	70.6
6	5.5	300	4588.5	2714.8	4590.3	2.447	2.572	4.9	16.1	69.7
Avg.						2.457	2.572	4.5	15.7	71.5

APPENDIX A3: Volumetric Properties, Sasobit Mix - Hot

	Mix Type:	Sasobit					Asphalt Specific Gravity (Gb):		1.028	
	Ndesign:	86					Apparent Specific Gravity (Gsa):			
	Test Date:						Effective Specific Gravity (Gse):		2.805	
							Bulk Specific Gravity (Gsb):		2.755	
Sample Number	Asphalt Content, %	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %
1	5.5	250	4919.8	2927.2	4920.8	2.468	2.562	3.7	15.4	76.0
2	5.5	250	4921.0	2927.9	4922.4	2.467	2.562	3.7	15.4	75.9
3	5.5	250	4914.9	2923.8	4916.9	2.466	2.562	3.7	15.4	75.7
4	5.5	250	4909.7	2929.5	4910.9	2.478	2.562	3.3	15.0	78.1
5	5.5	250	4914.2	2939.0	4916.1	2.486	2.562	3.0	14.7	79.8
6	5.5	250	4912.8	2943.0	4914.1	2.492	2.562	2.7	14.5	81.3
Avg.						2.476	2.562	3.4	15.1	77.8

APPENDIX A4: Volumetric Properties, Sasobit Mix - Reheated

	Mix Type:	Sasobit					Asphalt Specific Gravity (Gb):		1.028	
	Ndesign:	86					Apparent Specific Gravity (Gsa):			
	Test Date:						Effective Specific Gravity (Gse):		2.805	
							Bulk Specific Gravity (Gsb):		2.755	
Sample Number	Asphalt Content, %	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %
1	5.5	250	4693.9	2775.7	4695.4	2.445	2.562	4.6	16.1	71.7
2	5.5	250	4691.9	2777.1	4694.5	2.447	2.562	4.5	16.1	72.1
3	5.5	250	4692.1	2770.3	4695.6	2.437	2.562	4.9	16.4	70.3
4	5.5	250	4690.4	2774.8	4693.9	2.444	2.562	4.6	16.2	71.5
5	5.5	250	4695.6	2771.0	4698.7	2.436	2.562	4.9	16.4	70.1
6	5.5	250	4698.5	2770.3	4702.2	2.432	2.562	5.1	16.6	69.4
Avg.						2.440	2.562	4.8	16.3	70.8

APPENDIX B - ASPHALT CONTENTS AND GRADATIONS

TABLE B1: Asphalt Content and Gradation - Control

Gradation	Sample 1				
Sieve Size (mm)	**Rep1**	**Rep2**	**Avg.**	**Std Dev**	**JMF**
12.5	100.0	100.0	100.0	0.0	100.0
9.5	99.3	98.3	98.8	0.7	99.1
4.75	76.5	75.0	75.8	1.1	75.0
2.36	57.9	57.0	57.5	0.6	55.9
1.18	43.4	42.6	43.0	0.6	41.3
0.6	30.1	29.5	29.8	0.4	27.5
0.3	16.0	15.6	15.8	0.3	14.5
0.15	8.6	8.5	8.6	0.1	7.5
0.075	6.1	6.1	6.1	0.0	5.5
Asphalt Content	5.51	5.33	5.42	0.13	5.52

TABLE B2: Asphalt Content and Gradation - Sasobit®

Gradation	Sample 1				
Sieve Size (mm)	**Rep1**	**Rep2**	**Avg.**	**Std Dev**	**JMF**
12.5	100.0	100.0	100.0	0.0	100.0
9.5	99.3	99.0	99.2	0.2	99.1
4.75	78.5	79.7	79.1	0.8	75.0
2.36	61.8	62.3	62.1	0.4	55.9
1.18	47.7	47.8	47.8	0.1	41.3
0.6	34.2	34.0	34.1	0.1	27.5
0.3	18.5	17.8	18.2	0.5	14.5
0.15	9.6	8.8	9.2	0.6	7.5
0.075	6.8	5.9	6.4	0.6	5.5
Asphalt Content	4.86	5.42	5.14	0.40	5.52

APPENDIX C – ASPHALT PAVEMENT ANALYZER RESULTS

TABLE C1: Asphalt Pavement Analyzer Results - Control Compacted Hot

Mix Type:	Control							Applied Wheel Load (lbs):	120
Test Temperature:	58° C (136° F)							Hose Presure (psi):	120
Sample Number	Sample	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	Rut Depth, (mm)
1	1	300	4907.7	2923.1	4909.1	2.471	2.572	3.9	6.47
2	1	300	4922.9	2927.0	4924.8	2.464	2.572	4.2	6.05
3	1	300	4920.8	2927.8	4922.9	2.466	2.572	4.1	3.59
4	1	300	4916.8	2929.4	4917.9	2.473	2.572	3.9	3.95
5	1	300	4921.2	2923.1	4923.0	2.461	2.572	4.3	6.31
6	1	300	4916.2	2922.7	4917.9	2.464	2.572	4.2	4.57
						Average:		4.1	5.16
						Standard Deviation:		0.2	1.3

TABLE C2: Asphalt Pavement Analyzer Results - Control Compacted After Reheating

Mix Type:	Control							Applied Wheel Load (lbs):	120
Test Temperature:	58° F (136° C)							Hose Presure (psi):	120
Sample Number	Sample	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	Rut Depth, (mm)
1	1	300	4594.2	2734.0	4596.6	2.467	2.572	4.1	4.77
2	1	300	4598.3	2731.2	4600.6	2.460	2.572	4.4	3.58
3	1	300	4593.4	2726.9	4596.4	2.457	2.572	4.5	11.21
4	1	300	4597.9	2729.6	4599.5	2.459	2.572	4.4	7.57
5	1	300	4596.9	2724.0	4598.9	2.452	2.572	4.7	5.90
6	1	300	4588.5	2714.8	4590.3	2.447	2.572	4.9	4.84
						Average:		4.5	6.31
						Standard Deviation:		0.3	2.7

TABLE C3: Asphalt Pavement Analyzer Results - Sasobit Compacted Hot

Mix Type:	Sasobit						Applied Wheel Load (lbs):		120
Test Temperature:	58° C (136° F)						Hose Presure (psi):		120
Sample Number	Sample	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	Rut Depth, (mm)
1	1	250	4919.8	2927.2	4920.8	2.468	2.562	3.7	5.74
2	1	250	4921.0	2927.9	4922.4	2.467	2.562	3.7	4.11
3	1	250	4914.9	2923.8	4916.9	2.466	2.562	3.7	6.88
4	1	250	4909.7	2929.5	4910.9	2.478	2.562	3.3	5.51
5	1	250	4914.2	2939.0	4916.1	2.486	2.562	3.0	5.12
6	1	250	4912.8	2943.0	4914.1	2.492	2.562	2.7	2.96
						Average:		3.4	5.05
						Standard Deviation:		0.4	1.4

TABLE C4: Asphalt Pavement Analyzer Results - Sasobit Compacted After Reheating

Mix Type:	Sasobit						Applied Wheel Load (lbs):		120
Test Temperature:	58° F (136° C)						Hose Presure (psi):		120
Sample Number	Sample	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	Rut Depth, (mm)
1	1	250	4693.9	2775.7	4695.4	2.445	2.562	4.6	5.22
2	1	250	4691.9	2777.1	4694.5	2.447	2.562	4.5	6.91
3	1	250	4692.1	2770.3	4695.6	2.437	2.562	4.9	4.09
4	1	250	4690.4	2774.8	4693.9	2.444	2.562	4.6	5.93
5	1	250	4695.6	2771.0	4698.7	2.436	2.562	4.9	9.64
6	1	250	4698.5	2770.3	4702.2	2.432	2.562	5.1	9.90
						Average:		4.8	6.95
						Standard Deviation:		0.2	2.4

APPENDIX D - TENSILE STRENGTH RATIO RESULTS

Project: WMA: Iron Mountain

Date: 11/9/2006

Tested By: J. Mingus

Calculated By: J. Mingus

Sample Identification: Control Mixture

	Conditioned Samples			Unconditioned Samples		
Sample Number	5	6	8	2	3	4
(A) Diameter, in	5.920	5.905	5.910	5.910	5.920	5.920
(B) Height, in	3.740	3.740	3.730	3.740	3.740	3.740
(C) Weight in Air, gm	3995.9	3993.6	3990.9	4001.9	3994.1	3997.9
(D) SSD Weight, gm	3999.2	3997.9	3996.8	4006.1	3997.3	4001.7
(E) Submerged Weight, gm	2336.9	2341.0	2340.7	2349.6	2334.7	2346.5
(F) Bulk Specific Gravity [A/(D - E)]	2.404	2.410	2.410	2.416	2.402	2.415
(G) Theoretical Maximum Gravity	2.572	2.572	2.572	2.572	2.572	2.572
(H) % Air Voids [100*(1-F/G)]	6.5	6.3	6.3	6.1	6.6	6.1
(I) Volume of Air Voids [H*(D - E)/100]	108.684	104.178	104.428	100.551	109.684	100.807
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	4074.2	4066.0	4064.2	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	78.30	72.40	73.30			
(L) % Saturation [100*(K/I)]	72.0	69.5	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	1775	1925	2000	1850	2000	1775
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	53.3	57.5	51.0
(R) Conditioned S_T, psi [2P/(A*B*π)]	51.0	55.5	57.8	N/A	N/A	N/A
(S) Average S_T, psi	54.8			53.9		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:				1.02		

Project: WMA: Iron Mountain Date: 11/15/2006

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

Sample Identification: Sasobit Mixture

	Conditioned Samples			Unconditioned Samples		
Sample Number	2	3	4	1	5	6
(A) Diameter, in	5.917	5.927	5.925	5.918	5.927	5.916
(B) Height, in	3.726	3.734	3.735	3.720	3.729	3.732
(C) Weight in Air, gm	3932.5	3937.6	3930.8	3928.7	3932.5	3934.9
(D) SSD Weight, gm	3939.2	3943.3	3938.1	3935.7	3940.1	3941.6
(E) Submerged Weight, gm	2282.4	2279.8	2274.3	2279.6	2276.0	2282.6
(F) Bulk Specific Gravity [A/(D - E)]	2.374	2.367	2.363	2.372	2.363	2.372
(G) Theoretical Maximum Gravity	2.562	2.562	2.562	2.562	2.562	2.562
(H) % Air Voids [100*(1-F/G)]	7.4	7.6	7.8	7.4	7.8	7.4
(I) Volume of Air Voids [H*(D - E)/100]	121.866	126.576	129.530	122.650	129.166	123.130
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	4023.6	4030.6	4025.6	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	91.10	93.00	94.80			
(L) % Saturation [100*(K/I)]	74.8	73.5	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	2400	2550	2400	2575	2450	2625
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	74.5	70.6	75.7
(R) Conditioned S_T, psi [2P/(A*B*π)]	69.3	73.4	69.0	N/A	N/A	N/A
(S) Average S_T, psi	70.6			73.6		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:				0.96		

APPENDIX E - DYNAMIC MODULUS RESULTS

APPENDIX E1: Dynamic Modulus Results - Control Reheated

Conditions			Specimen 1		Specimen 2		Specimen 3		Average	Average	Average
Test Temp.	Test Temp.	Frequency	Modulus	Phase Angle	Modulus	Phase Angle	Modulus	Phase Angle	Modulus	Modulus	Modulus
°C	°K	Hz	MPa	Degrees	MPa	Degrees	MPa	Degrees	MPa	psi	ksi
4.4	277.4	0.5	3404	25.85	2986	29.96	3185	28.4	3192	462919	463
		1	4074	24.68	3689	28.55	3897	26.92	3887	563722	564
		2	4841	23.35	4512	26.93	4703	25.33	4685	679561	680
		5	6022	21.45	5757	24.61	5884	23.03	5888	853947	854
		10	6997	20	6841	22.74	6864	21.33	6901	1000873	1001
		20	8071	18.48	8022	20.89	7935	19.58	8009	1161674	1162
		25	8457	18.01	8420	20.25	8269	19.06	8382	1215725	1216
21.1	294.1	0.5	685.5	32.92	489.3	35.62	547.3	34.72	574	83258	83
		1	879.9	33.41	644.4	36.77	720.5	35.25	748	108529	109
		2	1156	33.12	894.7	36.43	975.9	35.52	1009	146326	146
		5	1613	32.54	1325	36.1	1424	35.04	1454	210888	211
		10	2048	31.79	1756	35.59	1867	34.38	1890	274174	274
		20	2583	30.71	2300	34.63	2412	33.26	2432	352689	353
		25	2764	30.42	2486	34.38	2590	33.07	2613	379038	379
37.8	310.8	0.5	148.8	31.77	100.4	30.9	8.5	31.45	86	12459	12
		1	179.7	33.54	115.6	34.36	9.9	33.72	102	14755	15
		2	243.7	34.55	172.1	34.29	14.3	33.92	143	20794	21
		5	373.8	34.91	271.7	35.14	21.2	35.84	222	32233	32
		10	505.4	35.8	378.7	36.43	28.6	37.37	304	44126	44
		20	683.9	36.4	521.8	37.84	38.8	38.4	415	60167	60
		25	783	35.12	622.6	35.79	78.7	22.81	495	71761	72

APPENDIX E2: Dynamic Modulus Results - Sasobit® Reheated											
Conditions			Specimen 1		Specimen 2		Specimen 3		Average	Average	Average
Test Temp.	Test Temp.	Frequency	Modulus	Phase Angle	Modulus	Phase Angle	Modulus	Phase Angle	Modulus	Modulus	Modulus
°C	°K	Hz	MPa	Degrees	MPa	Degrees	MPa	Degrees	MPa	psi	ksi
4.4	277.4	0.5	3008	27.08	3258	27.6	2871	28.34	3046	441743	442
		1	3650	25.69	3965	26.18	3512	27.03	3709	537953	538
		2	4389	24.18	4760	24.63	4254	25.53	4468	647990	648
		5	5542	22.1	5948	22.46	5370	23.4	5620	815125	815
		10	6498	20.44	6933	20.76	6312	21.72	6581	954508	955
		20	7537	18.79	8020	19.07	7344	20	7634	1107187	1107
		25	7881	18.23	8382	18.47	7689	19.48	7984	1157999	1158
21.1	294.1	0.5	568.9	35.15	584.1	34.39	555.3	33.58	569	82591	83
		1	734	35.69	760.9	35.15	716.6	34.52	737	106919	107
		2	985.6	35.2	1014	35.08	949.8	34.82	983	142594	143
		5	1415	34.51	1460	34.67	1368	34.51	1414	205135	205
		10	1832	33.64	1900	33.95	1779	34.02	1837	266438	266
		20	2348	32.36	2446	32.79	2296	33.07	2363	342778	343
		25	2505	31.95	2624	32.51	2460	32.7	2530	366903	367
37.8	310.8	0.5	130.5	32.67	205.4	24.38	129.9	30.08	155	22520	23
		1	155.7	34.47	237.2	26.49	157.6	32.11	184	26615	27
		2	209.6	36.09	276.4	29.08	199.9	34.25	229	33161	33
		5	322.4	36.91	386.4	31.17	308.1	35.04	339	49164	49
		10	436.2	38.01	502.5	32.99	418.8	36.32	453	65631	66
		20	592.3	38.98	665.1	34.52	568	37.57	608	88252	88
		25	685.7	37.29	743	33.82	661.3	35.87	697	101045	101