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NCAT
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ABSTRACT

Warm Mix Asphalt (WMA) mixtures produced using three different WMA technologies were evaluated in a field project located in Kimbolton, Ohio. The technologies evaluated were Aspha-min® zeolite, 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, dynamic modulus, and emissions testing were conducted to evaluate field performance. Based on the laboratory testing, the different WMA technologies all performed equal to or better than the control mixtures. A decrease in emissions was also determined for the Sasobit® and Aspha-min®, with Evotherm™ showing an increase in emissions, compared to the HMA control. All three WMA technologies, however, greatly reduced the worker exposure at the paver.

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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 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™.

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 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, a number of WMA field trials were constructed, including three that utilized multiple technologies. One of these three multiple technology field projects, located in Ohio, is presented in this report.

PURPOSE AND SCOPE

The main purpose of this study was to evaluate the field performance of three different WMA technologies. The WMA processes were introduced into existing HMA designs. 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 volumetric properties, laboratory performance tests, and field performance data are reported.

In addition, the Ohio Department of Transportation (DOT) and asphalt contractors wanted to assess the potential of WMA to reduce the asphalt fumes emitted at both the plant and paving site, reduce the energy consumption at the plant, extend the paving season, and increase the potential haul distance.

PROJECT DESCRIPTION

The field trial was conducted on State Route 541 (SR 541), a two-lane rural highway with limited traffic running through Guernsey and Coshocton Counties. Three WMA processes were used on this project: Evotherm™ emulsion, Sasobit®, and Aspha-min®. A conventional HMA section was also constructed allowing direct comparisons to be made with regard to field performance. The project consisted of the construction of a two course pavement overlay. The first course was a standard HMA course placed at an average thickness of 0.75 inches, commonly referred to as a leveling course. The wearing surface was placed in four sections, one HMA control section and the three WMA test sections. The wearing course was placed at an average compacted thickness of 1.25 inches, for a total overlay thickness of approximately 2.0 inches. Each test section was approximately three miles in length. Figure 1 presents the project location in relation to several major cities. Figure 2 illustrates the layout of the different test sections along SR 541.

Figure 1. Project Location, in Relation to Nearby Major Cities (*10*)

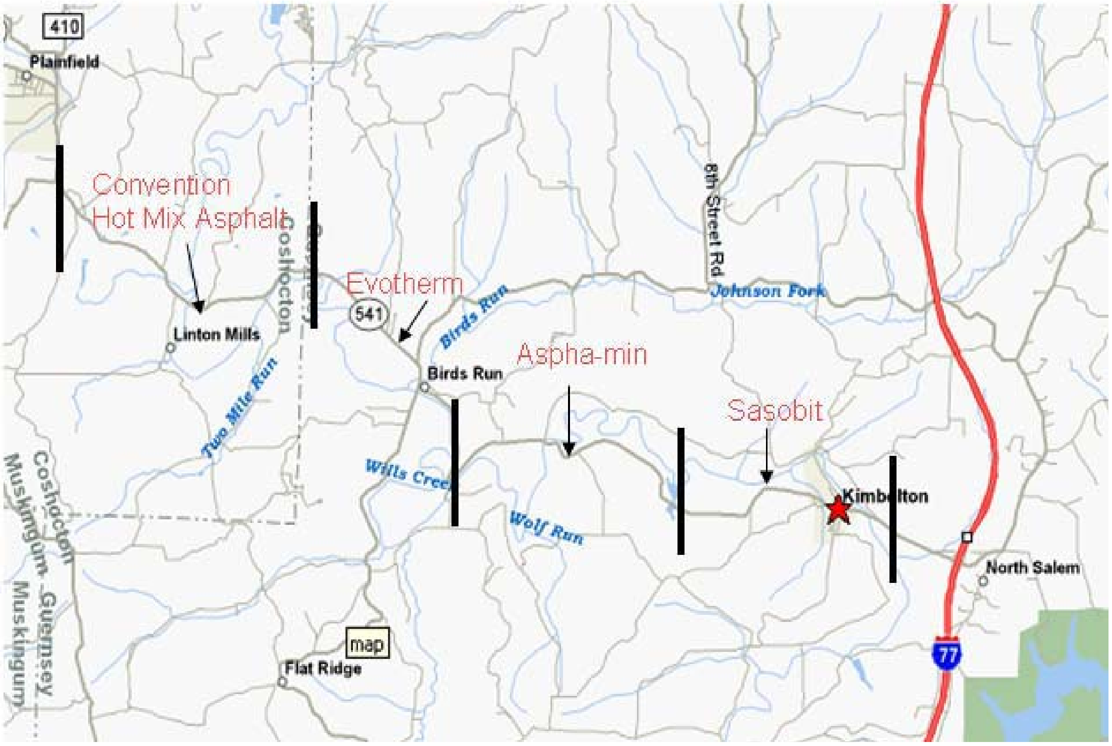

Figure 2. Project Layout Along SR 541, Kimbolton, Ohio (*11*)

MATERIALS

The wearing surface was designed to meet an Ohio DOT Item 441, Type 1 surface mix designed for medium traffic. The job mix formula for this project was a 9.5 mm nominal maximum aggregate size (NMAS) Marshall mixture, designed with a compactive effort of 50 blows on each face. Table 1 presents the design aggregate gradation (dry, not washed) and optimum asphalt content used for the project. Table 2 presents the mix composition, along with the amount of each WMA technology added to the mixture. The mixture used a styrene-butadiene-styrene (SBS) modified PG 70-22 asphalt binder and contained 15 percent reclaimed asphalt pavement (RAP). As noted previously, three WMA processes were used. Evotherm™ emulsion was produced using a binder with the same grade as the control mixture and was substituted for the liquid asphalt. The Evotherm™ emulsion addition rate was adjusted such that the resulting asphalt residue equaled the design asphalt content. Sasobit® was added at a rate of 1.5 percent by total weight of asphalt binder (including the binder in the RAP). Sasobit® pellets were added directly to the mix. Aspha-min® was added at 0.3 percent by total weight of mix. The Aspha-min® was added to the mix at approximately the same point that the asphalt was injected into the mixing drum.

Table 1. Design Aggregate Gradation and Optimum Asphalt Content

Sieve Size, mm (in.)	Percent Passing, %
12.5 (1/2")	100
9.5 (3/8")	92
4.75 (#4)	51
2.36 (#8)	38
1.18 (#16)	28
0.6 (#30)	18
0.3 (#50)	7
0.15 (#100)	4
0.075 (#200)	2.8
AC, %	6.1

Table 2. Mixture Composition and WMA Technology Addition Rates

Aggregate Type	**Size**	**Aggregate Type**	**Percent of Mixture**
Coarse Aggregate	No. 8	Limestone	53
Fine Aggregate	Sand	Natural	32
RAP	Crushed	Limestone/ Natural	15
Asphalt Binder		PG 70-22 SBS Modified	Virgin: 5.3% Total: 6.1%
WMA Type	Aspha-min®	Evotherm™	Sasobit®
Amount Added	0.3% by weight of total mix	5.3% by weight of total mix	1.5% by weight of total binder

RESULTS AND DISCUSSIONS

Construction

Due to weather delays, the project was conducted over approximately a three week period. As mentioned previously, the project consisted of a two-part overlay. The first layer was conventional HMA, with the surface layer divided into four test sections: one control section and three WMA sections. The control section was placed first over two days; however, the first day of construction was not evaluated due to rain halting production. Once the control section was placed, the Evotherm™ test section was placed next. The Aspha-min® section was the second WMA test section placed, and Sasobit® was the last WMA test section placed. Compaction and plant discharge temperatures for each of the test section are presented in Figure 3, indicating compaction temperatures ranged from approximately 230 to 260°F (110 to 127°C), depending on the WMA technology being evaluated.

The asphalt plant that produced the mixes had a separate dryer and coater (Figure 4). For the WMA, the factor controlling the minimum discharge temperature appeared to be the flow of the mix exiting the coater and entering the plant's vertical bucket elevator (Figure 5). If the discharge temperature was too low, the mix exiting the coater backed up and did not feed properly into the vertical bucket elevator.

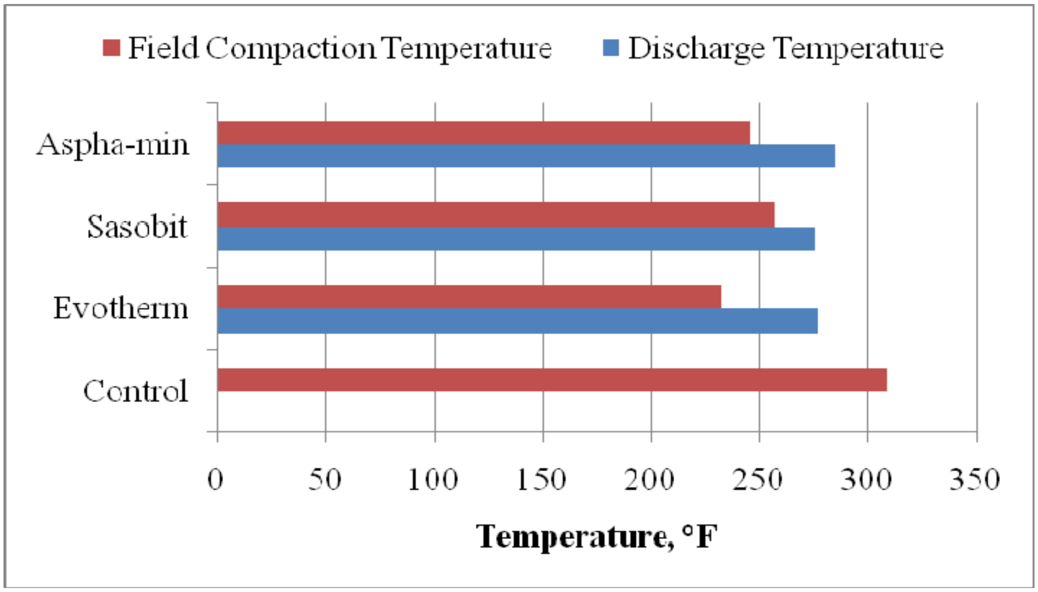

Figure 3. Average Compaction Temperatures

The asphalt mixtures were hauled to the site in tandem-axle, end-dump trucks, with a haul distance of approximately 21 miles (roughly 25 minutes). The test sections were all placed with a Blaw Knox PF 5510 tracked paver with a Carlson EZ III electrically heated screed. Paving took place at approximately 50 feet per minute. Breakdown rolling was accomplished immediately after placement using a Gallion 3-Wheel roller. Intermediate rolling was conducted with a Hamm HD120HV roller, operating in vibratory mode using low amplitude and high frequency in both drums. Finish rolling was conducted in static mode.

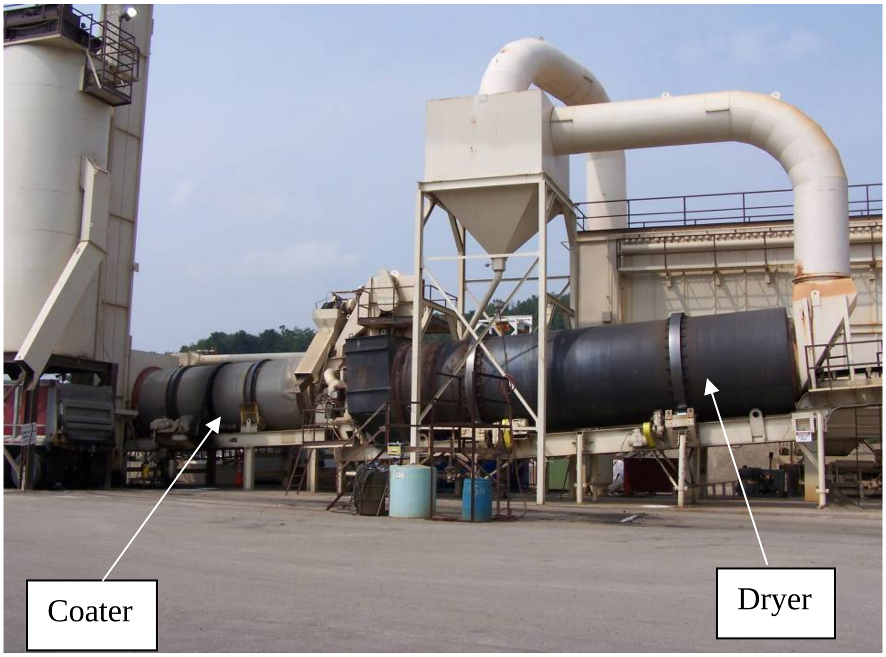

Figure 4. Dryer/Coater Plant (Courtesy of Larry L. Michael)

Figure 5. Mar-Zane Plant 13, Note Vertical Bucket Elevator

Placement of the HMA Control was not observed by NCAT personnel. Placement of the WMA sections was observed by NCAT personnel. At times while paving all of the WMA test sections, there appeared to be difficulties getting all of the mix out of the trucks and into the paver hopper. Mix was frequently dropped on the ground in front of the paver. The mix was shoveled out from under the paver tracks. The WMA containing polymer modified binder and RAP was difficult to shovel. The paver hopper wings were dumped, in some cases the paver slats were exposed, and the paver typically stopped during the truck transfer. Instances were observed where the mix drug out under the screed following the truck transfers. These areas were filled in by hand.

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™ test section, samples were prepared on both days that Evotherm™ was placed; for The Aspha-min® and Sasobit® sections, samples were prepared on a single day's production. Specimens were prepared in the NCAT mobile laboratory trailer (Figure 6). Laboratory testing included: mixture volumetric properties, Asphalt Pavement Analyzer (APA) rut testing, AASHTO T 283 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 comparisons could be determined between hot compacted samples and samples that were reheated prior to being compacted. No testing was conducted to evaluate the effects of WMA additives on asphalt binder properties.

Figure 6. NCAT Mobile Laboratory Trailer

Mixture Volumetric Properties

For each field sample, six specimens were compacted from mix on site and six specimens were compacted from reheated mix to determine mixture volumetric properties. Both hot and reheated mix were used to evaluate the volumetric properties to simulate the difference between contractor and agency volumetric specimens. Typically, samples were taken twice per day, once in the morning and once in the afternoon. The samples were compacted using 75 gyrations of the Superpave Gyratory compactor (SGC). Samples were compacted at a temperature of 250°F. Approximately 30 minutes in an oven was needed to heat the samples to the compaction temperature. As noted previously, Ohio DOT Type I surface mixes for medium traffic are designed using a 50-blow Marshall compactive effort. Marshall samples could not be used for the planned performance tests. However, after the site visit the researchers were informed that Ohio DOT specifications for Item 442, Superpave Asphalt Concrete specifies an N_{design} = 65 gyrations (*13*) which would have been a more appropriate number of gyrations for the mix. Test results are illustrated in Figure 7. The air void contents determined are well below the design void content of four percent for both the hot and reheated samples. This is believed to have been caused by compacting the specimens to 75 gyrations in the SGC instead of using 50 blows of the Marshall hammer. In general, the reheated specimens exhibited lower air voids than the hot specimens. This may be attributed to different SGCs being used to compact the hot and reheated samples. Complete test results are presented in Appendix A.

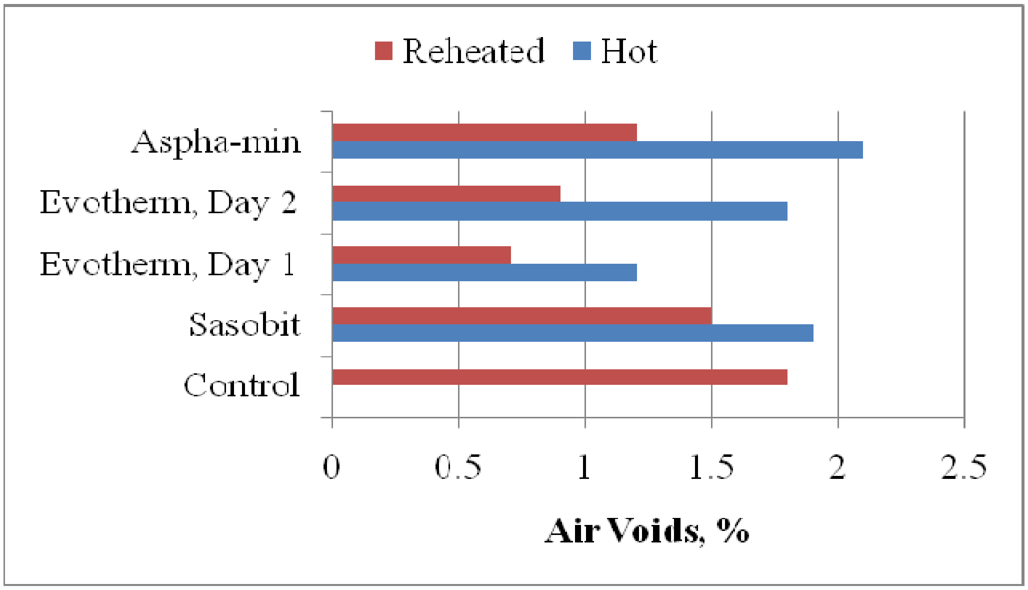

Figure 7. SGC Air Void Contents

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, presented in Table 3, concluded that the WMA technology, whether or not the samples were compacted hot or reheated, and the time of day the sample was obtained were all significant factors in the relative density of the laboratory compacted samples. A Dunnett's test was performed on the ANOVA results to determine how much the inclusion of the different WMA technologies reduced the void content of the compacted samples. From the results, WMA lowered the air void content an average of 0.7 to 1.2 percent at a compaction temperature of 250°F (121°C). This was compared to the control data compacted at a temperature of 300°F (149°C).

Figure 8 presents the main effects plots of the statistical data. This series of plots graphically represent the mean trends in the statistical data. From the plots, it can be seen that both reheating the samples and the time during the day the sample was obtained significantly impacted the air void contents of the compacted samples. In an attempt to explain why the second daily samples resulted in higher air voids, the measured asphalt contents for each sample were evaluated. This data is presented in Appendix B. Asphalt content was determined according to ASTM D2172, Method A, Centrifuge Method. It was determined that the asphalt content of the second sample was consistently lower than the first sample, which can result in higher air void contents of the compacted samples.

Table 3. Analysis of Variance Densification Results

Source	DF	Adj. MS	F-statistic	p-value	Significant[1]
WMA Process	3	3.45	40.78	<0.0001	Yes
Reheating	1	9.45	111.63	<0.0001	Yes
Sample time	1	5.39	63.74	<0.0001	Yes
Error	95	0.08			
Total	100				

Note: [1] indicates significant at the 95 percent confidence interval.

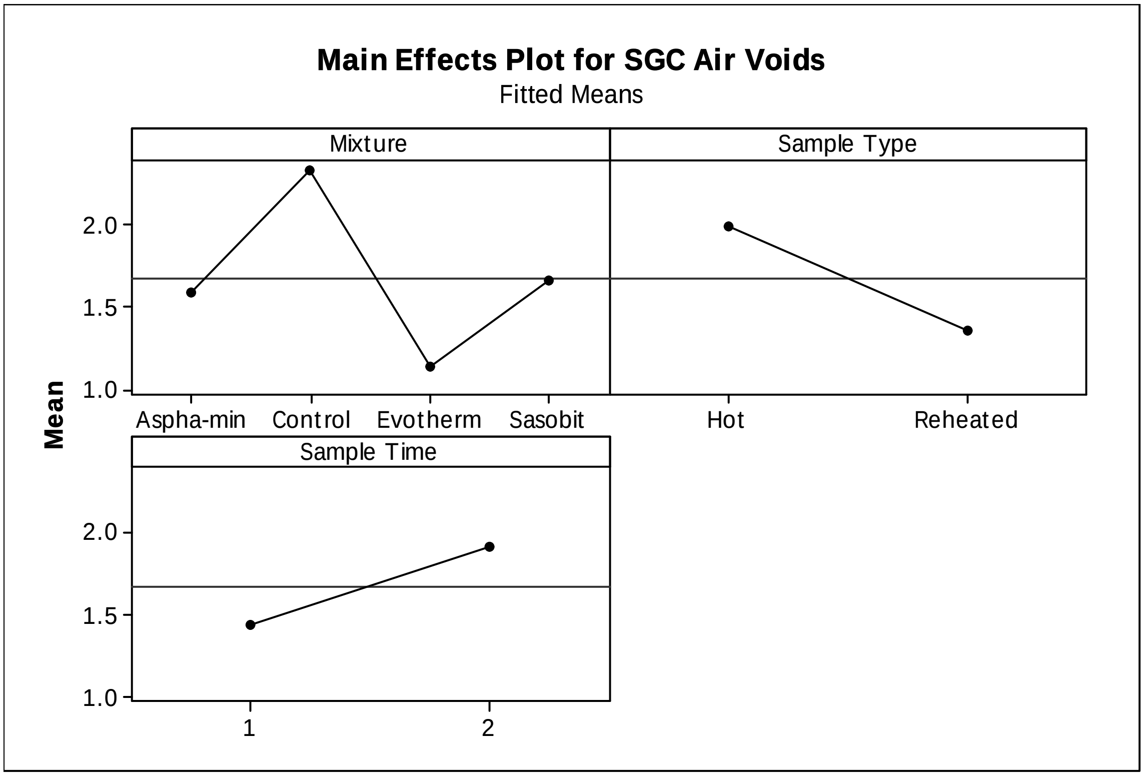

Figure 8. Main Effects Plots for Densification

Asphalt Pavement Analyzer

Once the air void contents of the specimens compacted to 75 gyrations were determined, each mixture set was tested in the APA to determine the laboratory rut resistance of each asphalt mixture. 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 (5-7).Test results from the APA are shown in Figure 9. The data illustrates 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 reduction in air voids of the reheated samples. It can also be seen from Figure 9 that the Evotherm™ mix samples had the highest measured rut depths.

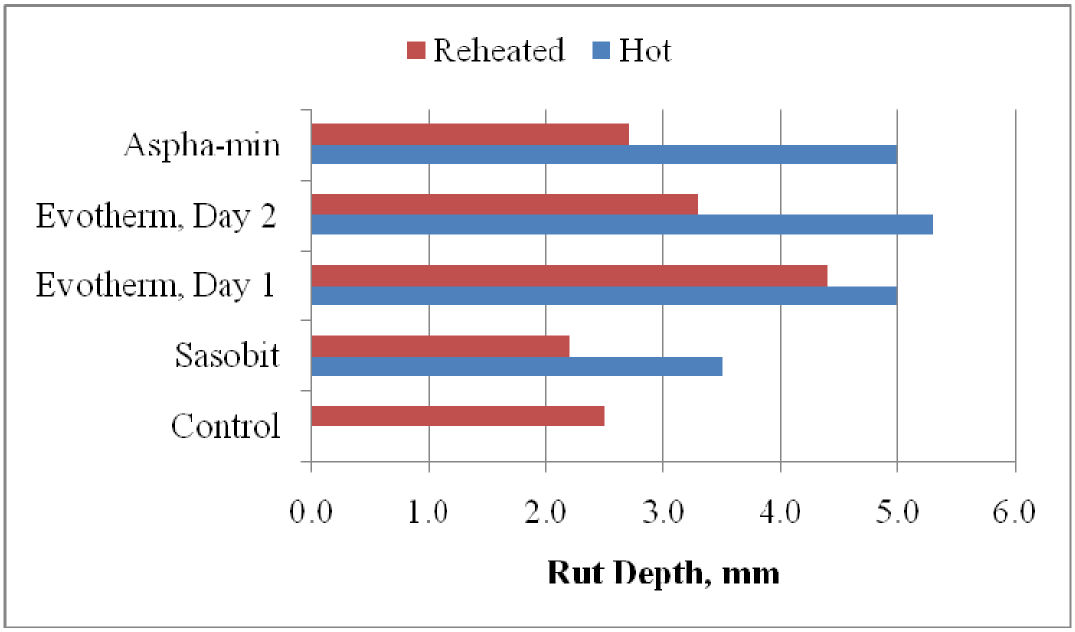

Figure 9. Asphalt Pavement Analyzer Rut Depth Results

Table 4 presents the ANOVA results for the measured APA rut depths. The ANOVA results show that both the WMA technology and sample type (hot or reheated) significantly affected the measured rut depths. A Dunnett's test was performed on the ANOVA results to determine what effect the WMA technologies had on the measured rut depths. The results from the Dunnett's test indicated that only the Evotherm™ had a significant effect on the measured rut depths; the Aspha-min® and Sasobit® samples were not statistically different than the control section APA results. For the Evotherm™, the measured rut depths were significantly higher than the control; averaging 1.2 mm higher than the measured rut depths for the control mix.

Table 4. Analysis of Variance Asphalt Pavement Analyzer Results

Source	**DF**	**Adj. MS**	**F-statistic**	**p-value**	**Significant**[1]
WMA Process	3	14.89	16.93	<0.0001	Yes
Reheating	1	53.10	60.39	<0.0001	Yes
Sample time	1	0.09	0.11	0.744	No
Error	95	0.88			
Total	100				

Note: [1] indicates significant at the 95 percent confidence interval.

The main effects plots for the APA rut depths are presented in Figure 10. From the plots, it was observed that the Sasobit® resulted in, numerically, the lowest measured rut depths; it is believed that this was due to the fact that the Sasobit® stiffens the asphalt binder, increasing its resistance to rutting. In an attempt to explain why the Evotherm™ rut depths were significantly higher, the field compaction and plant discharge temperatures were evaluated to determine if a trend between temperatures and measured rut depths existed. Even though no plant discharge was recorded for the control data (Figure 3), it can be inferred that the plant discharge temperatures were the highest, since the compaction temperatures were the highest. Lower production temperatures should result in less aging of the asphalt binder and therefore lower binder stiffness. From Figure 3, it can be seen that the Evotherm™ had the lowest plant discharge and compaction temperatures, which possibly led to Evotherm™ having the highest measured rut depths in the APA. During the field trial, the Ohio Research Institute for Transportation and the Environment (ORITE) constructed parallel test sections in their Accelerated Pavement Load Facility (APLF) to evaluate the performance of the WMA sections over various loads and environmental conditions. The results generated from the APLF should be a more accurate indicator of the actual resistance to permanent deformation of the different WMA technologies evaluated.

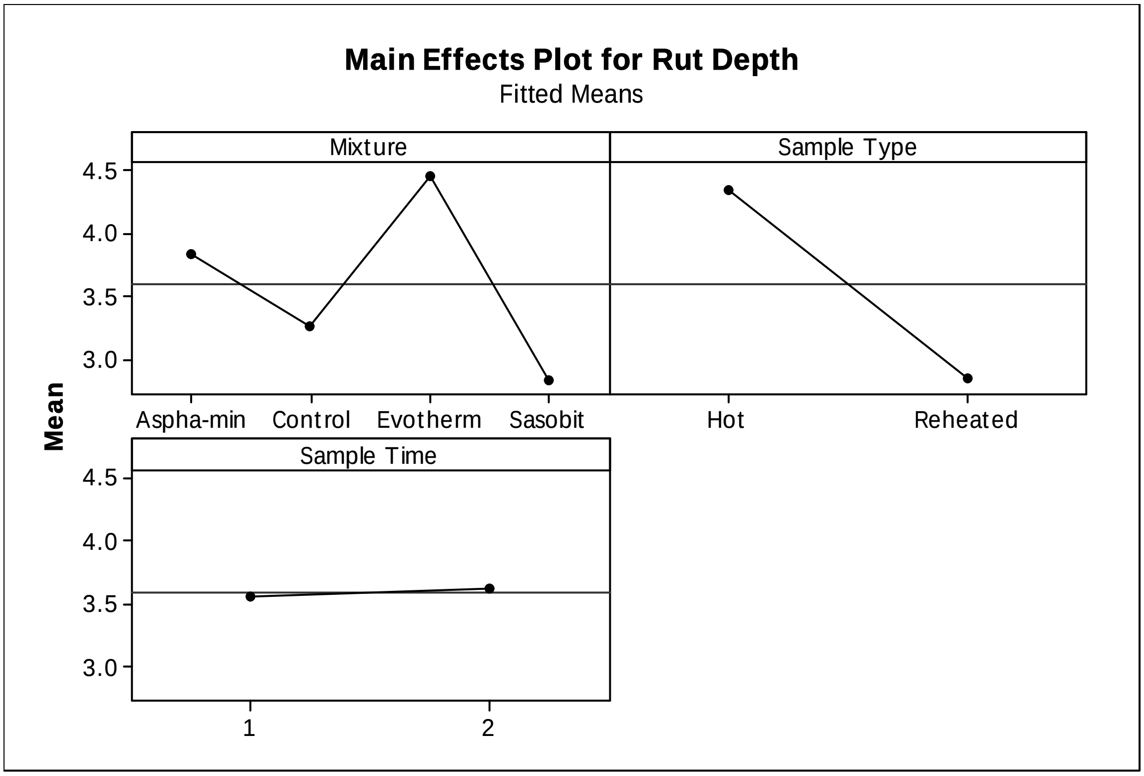

Figure 10. Main Effects Plots for Measured APA Rut Depths

Moisture Resistance

Specimens of each mixture were tested according to AASHTO T 283 (i.e. TSR) to assess moisture damage susceptibility of the asphalt mixtures. TSR testing was conducted on both hot compacted and reheated samples compacted to 7±1.0% air voids. This was done to see if moisture dissipation had an effect on the moisture resistance of the WMA mixtures, especially the Aspha-min® and Evotherm™, which use water to deliver the technology. The data for each test section has been divided into the separate samples taken during the day, as well as whether or not the samples were compacted hot or were reheated. The results are summarized in Tables 5 and 6. Complete TSR test results are presented in Appendix C. Figure 11 presents the average of all the data obtained. From the data, it can be seen that only 3 out of 17 tests had a TSR value that satisfied the Ohio DOT minimum required TSR value of 0.80 (including the control mixture). There is concern with WMA that incomplete drying of the aggregates may increase the potential for moisture damage. This may have been the reason that the majority of the TSR tests failed to meet the TSR criterion. Weather data from nearby Zanesville, OH indicates that during the three-week period the field trial was conducted, 4.25 inches of rain fell (*14*). No preventative measures (paving under stockpiles, covered stockpiles, etc.) were in place to minimize moisture in the aggregate stockpiles.

Table 5. Tensile Strength Ratio Results, Samples Compacted with No Reheating

Mix Type	**Date**	**Sample**	**Indirect Tensile Strength**		**TSR, %**
			Unconditioned, psi	**Conditioned, psi**	
Sasobit®	9/18	1	99.6	68.1	68
	9/18	2	97.4	72.5	74
Evotherm™	9/7	1	89.5	73.4	82
	9/7	2	85.4	54.4	64
	9/8	1	80.5	59.0	73
	9/8	2	74.0	64.3	87
Aspha-min®	9/11	1	132.9	93.9	71
	9/11	2	135.6	99.9	74

Table 6. Tensile Strength Ratio Results, Samples Compacted After Reheating

Mix Type	**Date**	**Sample**	**Indirect Tensile Strength**		**TSR, %**
			Unconditioned, psi	**Conditioned, psi**	
Control	8/30	1	162.9	126.7	78
Sasobit®	9/18	1	125.3	88.7	71
	9/18	2	128.1	101.1	79
Evotherm™	9/7	1	117.0	99.8	85
	9/7	2	117.3	49.0	42
	9/8	1	137.5	81.0	59
	9/8	2	130.2	51.0	39
Aspha-min®	9/11	1	158.3	86.8	55
	9/11	2	152.7	114.3	75

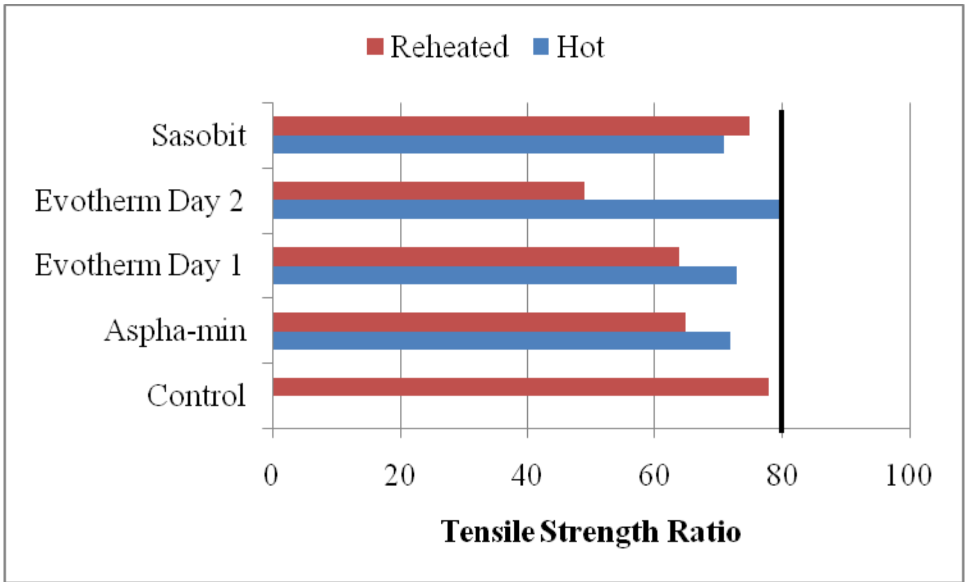

Figure 11. Tensile Strength Ratio Results

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 both hot compacted and reheated mix samples. This test is typically used to predict rutting and stripping potential of HMA, but has been found to be sensitive to other factors, including binder stiffness, short-term aging, compaction temperature, and anti-stripping treatments (*15*). 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 from the Hamburg wheel tracking device are presented in Tables 7 and 8 (compacted hot and reheated, respectively). In most cases, the stripping inflection point indicates whether the mixture will be prone to moisture damage or not. From these data, it can be seen that, based on the stripping inflection point, the reheated samples provided better results, in three of four cases, than the samples that were compacted prior to reheating. This has also been seen in previous field trials. With the exception of the Evotherm™ sample taken on the second day of production, the tests on reheated WMA samples performed better than the control mixture.

Table 7. Hamburg Wheel Tracking Device Results, Samples Compacted with No Reheating

Mix Type	Date	Avg. VTM, %	Stripping Inflection Point, cycles	Rutting Rate, mm/hr	Total Rutting @ 10,000 cycles, mm
Control	8/28/06	No Samples Available			
Sasobit®	9/18/06	7.7	8,900*	1.72	10.4
Evotherm™	9/7/06	7.7	6,500	2.71	17.7
Evotherm™	9/8/06	6.6	6,350	3.02	39.5
Aspha-min®	9/11/06	7.2	6,800	2.61	22.2

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.

Table 8.Hamburg Wheel Tracking Device Results, Samples Compacted After Reheating

Mix Type	Date	Avg. VTM, %	Stripping Inflection Point, cycles	Rutting Rate, mm/hr	Total Rutting @ 10,000 cycles, mm
Control	8/28/06	7.2	7,950	1.45	13.4
Sasobit®	9/18/06	7.4	> 10,000	1.16	7.0
Evotherm™	9/7/06	6.5	> 10,000	2.99	15.4
Evotherm™	9/8/06	7.5	5,600	3.36	41.1
Aspha-min®	9/11/06	7.7	> 10,000	3.44	15.6

Dynamic Modulus

Dynamic modulus tests were conducted on field mixed, laboratory compacted samples using an IPC Global AMPT (Asphalt Mixture Performance Tester). A minimum of three specimens per mix per sample collected was tested. For the WMA mixes, there were both hot and reheated specimens while the control mix only had reheated specimens. Testing was conducted at seven frequencies at each of three temperatures. Dynamic modulus master curves generated for each of the test sections are presented in Figures 12 and 13. The reference temperature for the master curves is 70°F (21.1°C). Figure 12 displays the master curves for the samples that were compacted on-site, while Figure 13 displays the master curves for the samples that were reheated prior to compaction.

Table 9 presents the ANOVA results performed on the dynamic modulus test data. Of importance within Table 9 is the observation that the WMA technologies significantly affected the dynamic modulus results, and that there was no statistical difference in the measured dynamic modulus results from samples compacted hot and reheated prior to compaction. This ensures that accurate dynamic modulus data can be obtained for an individual asphalt pavement using reheated material, allowing the samples to be produced at a later date. A Dunnett's test was performed to determine how much the WMA technologies affected the measured dynamic modulus results. Compared to the control mix, WMA technologies lowered the dynamic modulus an overall average of approximately 89,000 psi, which ranges from 11–23 percent lower, depending on the WMA technology. This percent reduction is based on the dynamic modulus data recorded at 70°F (21.1°C) and 10 Hz.

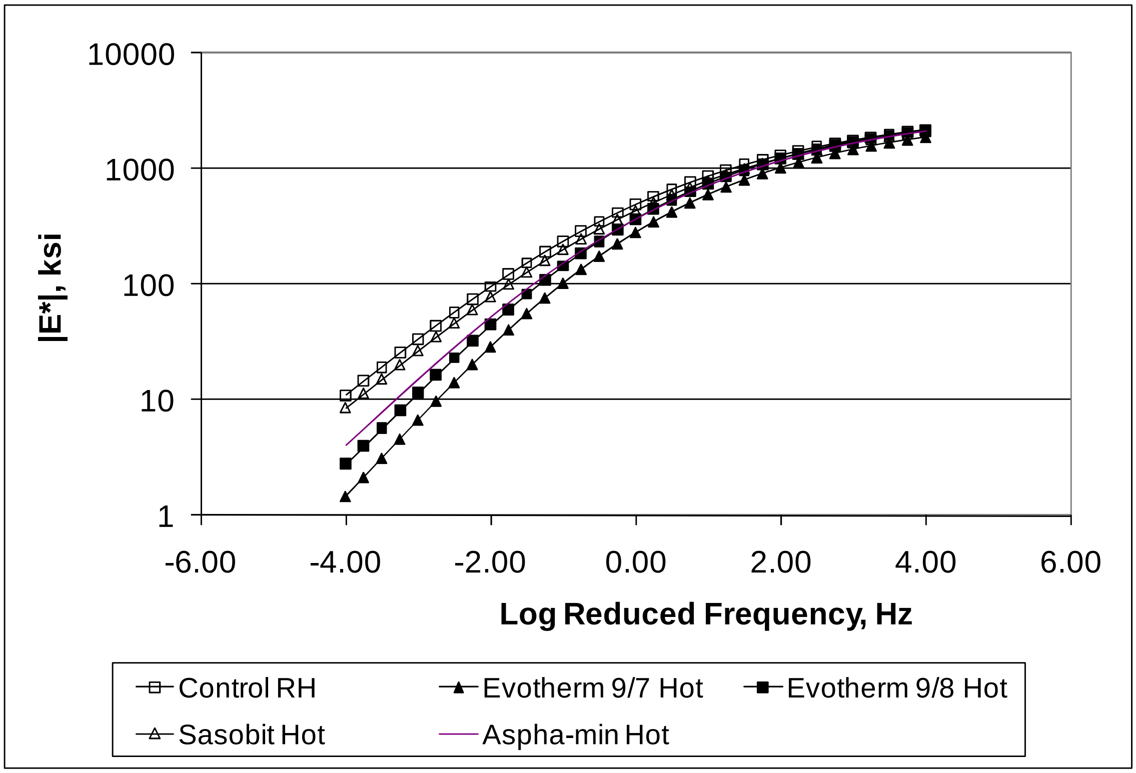

Figure 12. Dynamic Modulus Master Curves, Samples Compacted Prior to Reheating

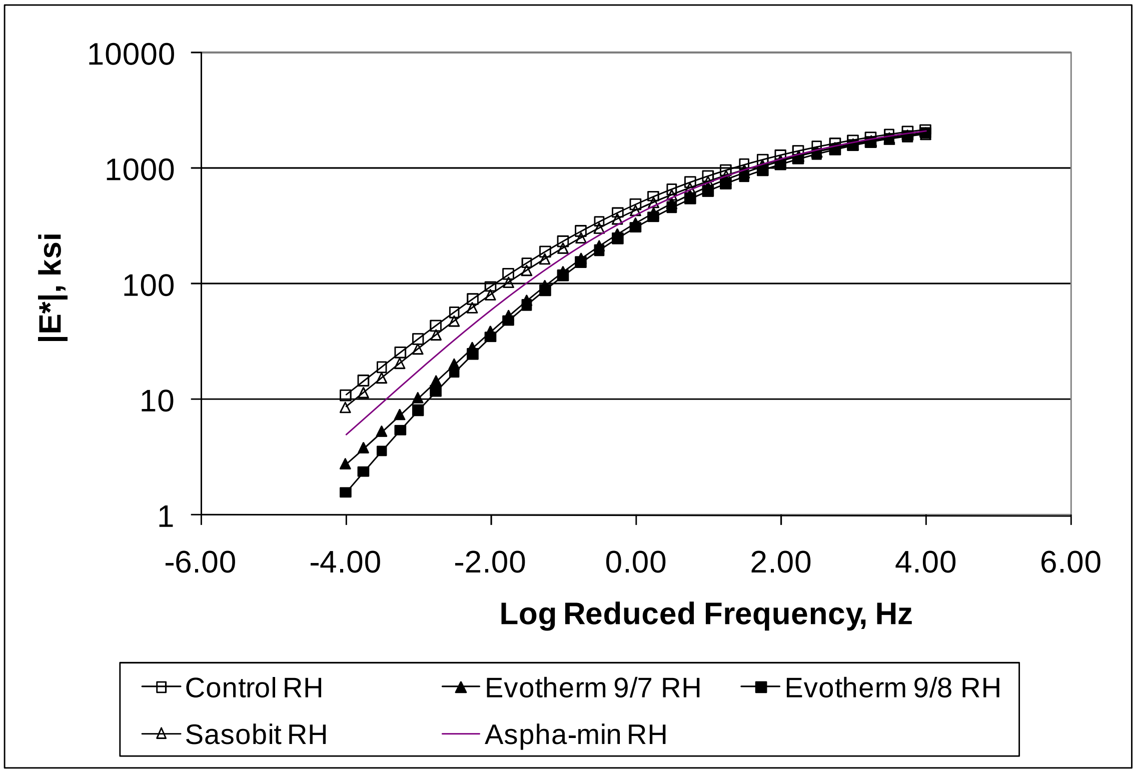

Figure 13. Dynamic Modulus Master Curves, Samples Compacted After Reheating

Table 9. Analysis of Variance of Dynamic Modulus Results

Source	**DF**	**Adj. MS**	**F-statistic**	**p-value**	**Significant**[1]
WMA Process	3	2.06E+11	13.62	<0.0001	Yes
Reheating	1	1.23E+9	0.08	0.776	No
Temperature	2	1.39E+14	9145.52	0.000	Yes
Frequency	6	5.47E+12	360.87	0.000	Yes
Error	820	1.52E+12			
Total	832				

[1] Indicates significant difference at the 95 percent confidence interval.

Since the dynamic modulus is highly dependent on temperature and frequency, an additional set of statistical analyses were performed to evaluate the differences within each temperature and frequency category. Categorizing the data by temperature and frequency allowed for 23 replicates per category. The only factor considered within each category was WMA process. The results of the ANOVAs are listed in Table 10. The results of the analysis indicate that there is no statistical difference between the various mixes at the low temperature, 40°F (4.4°C) at all frequencies. However, as the test temperature increases, the mixes begin to yield dynamic modulus results that differ from one another. Mean comparisons were also conducted within each category to determine which WMA process(es) differed from the control HMA in terms of dynamic modulus results. Table 11 summarizes the results of the mean dynamic modulus comparisons by temperature and frequency. The results indicate that at the higher temperatures and lower frequencies, there are significant differences between the control HMA and both Aspha-min® and Evotherm™ mixes. The mean dynamic modulus results for the Sasobit® mix did not differ significantly from the control HMA. Most likely the Sasobit behaved most similarly to the HMA since the wax stiffened the binder. The Aspha-min® and Evotherm™ did not stiffen the binder, therefore the dynamic modulus results for those two mixes were lower than the HMA due to the reduced aging of the binder.

Table 10. Analysis of Variance of Dynamic Modulus Results by Temperature and Frequency

Temperature °C	Frequency Hz	p-value	Statistically Different[1]
4.4	0.5	0.3279	No
	1	0.3453	No
	2	0.3455	No
	5	0.3105	No
	10	0.2810	No
	20	0.2590	No
	25	0.2533	No
21.1	0.5	0.0023	Yes
	1	0.0089	Yes
	2	0.0278	Yes
	5	0.0827	Yes
	10	0.1497	No
	20	0.2266	No
	25	0.2514	No
37.8	0.5	<0.0001	Yes
	1	<0.0001	Yes
	2	<0.0001	Yes
	5	0.0016	Yes
	10	0.0087	Yes
	20	0.0419	Yes
	25	0.0687	No

[1] Indicates statistical difference at 95 percent confidence interval.

Table 11. Mean Comparisons of Dynamic Modulus Data by Temperature and Frequency

Temperature	Frequency	Significantly Different from HMA Control[1]		
		Aspha-min	Evotherm	Sasobit
4.4	0.5	No	No	No
	1	No	No	No
	2	No	No	No
	5	No	No	No
	10	No	No	No
	20	No	No	No
	25	No	No	No
21.1	0.5	No	Yes	No
	1	No	Yes	No
	2	No	No	No
	5	No	No	No
	10	No	No	No
	20	No	No	No
	25	No	No	No
37.8	0.5	Yes	Yes	No
	1	Yes	Yes	No
	2	Yes	Yes	No
	5	No	Yes	No
	10	No	Yes	No
	20	No	No	No
	25	No	No	No

[1] Indicates significant difference at 95 percent confidence interval.

EMISSIONS TESTING

Table 12 presents the plant's burner fuel usage results for each of the three WMA technologies used in this evaluation. During the production of the Aspha-min® and Sasobit® mixtures, fuel usage was reduced 8.8 and 17.9 percent, respectively. For the Evotherm™ mixture, an increase in fuel usage was determined. It is believed that this is due to the water in the Evotherm™ emulsion. At 6.1 percent asphalt, each ton of the asphalt mixture would have 122 lbs of binder. If the binder residue is 69 percent of the Evotherm™ emulsion, then 176.8 lbs of emulsion (122 / 0.69), 54.8 lbs of which is water, would be required for each ton of WMA. It takes 970 BTU to convert one lb of water to steam. Thus, converting the water in the emulsion to steam requires 54.8 x 970 = 53,156 BTU per ton of WMA. A cubic foot (cf) of natural gas produces approximately 1030 BTU. Therefore, 53,156 / 1030 = 51.6 cf of natural gas would be required to turn the water into steam for the emulsion used in one ton of Evotherm™ WMA. This approximates the difference in natural gas usage between the control and Evotherm™ sections.

Table 12. Fuel Usage Results for Each WMA Technology

Mix	Initial Natural Gas Reading, cf (thousands)	Final Natural Gas Reading, cf (thousands)	Daily Tons Produced	Natural Gas Used per Ton, cf/ton	Percent Change from Control, %
Control	557,015	557,402	1367.24	288	
Evotherm™	558,171	558,583	1207.05	341	+ 15.4
Aspha-min®	559,174	559,457	1139.22	263	- 8.8
Sasobit®	559,832	560,030	835.11	237	- 17.9

Fuel savings have been noted in other WMA projects using Evotherm™ emulsion. However, these mixes were produced at lower temperatures. In this project, the discharge of the mix from the coater into the vertical bucket elevator controlled the production temperature. When temperatures were reduced much below 275°F (135°C), the WMA did not flow into the vertical bucket elevator. Lower production temperatures would have reduced the fuel needed to heat the aggregate and most likely cancelled out the additional fuel needed to turn the water in the emulsion into steam. MeadWestvaco has largely transitioned from the Evotherm™ emulsion system to the Evotherm DAT technology which introduces much less water into the mixer. The Evotherm DAT technology is also more economical than the Evotherm emulsion due to the lower costs associated with shipping the DAT product.

During construction of each test section, EES Group, Inc. performed industrial hygiene testing at several points on the paver, as well as a few background locations. This was done to perform a comparative analysis between the control mixture and the different WMA technologies. The results from the industrial hygiene survey are presented in Table 13. All three WMA technologies drastically reduced both the total particulates and benzene soluble matter (BSM) when compared to the control mixture, averaging close to 75 percent reduction in emissions around the paving operations.

Table 13. Industrial Hygiene Results for Total Particulate and Benzene Soluble Matter

Mixture	Total Particulate, mg/m^3	Percent Reduction, Total Particulate	BSM, mg/m^3	Percent Reduction, BSM
Control	1.25		1.05	
Evotherm™	0.29	77	0.29	72
Sasobit®	0.33	74	0.21	80
Aspha-min®	0.41	67	0.20	81

Table 14 presents the results from asphalt plant stack emissions testing performed during construction of the control and WMA test sections. Testing was conducted by Chief Environmental Group, LTD., located in Zanesville, Ohio (*16*). Data were obtained for several criteria pollutants emitted from a typical HMA plant: SO_2 (sulfur dioxide), NO_x (oxides of nitrogen), CO (carbon monoxide), and VOC's (volatile organic compounds). As would be expected with natural gas combustion and limestone aggregates, SO_2 emissions were negligible, making differences between mixes inconclusive (*17*).

Both the Sasobit® and Aspha-min® had substantial reductions in CO, NO_x, and VOC emissions as compared to the control. For the Evotherm™, the VOC results were 159 percent higher than the control mixture while CO and NO_x emissions were reduced. This increase in VOC emissions exceeds that which could be attributed to increased fuel usage, discussed previously and may be attributed to vaporizing emulsion water. Twenty pounds of VOC emissions per hour is four times state-of-the-art performance requirements in some states and would exceed permitted limits at many plants (*17*).

One would expect CO emissions to track natural gas used per ton and any CO reduction to reflect lower fuel usage attributed to reduced mix temperature. That CO dropped with Evotherm™ (-20.3%) even as fuel use increased (+15.4%) suggests that the burner was tuned after the control runs. It is highly unlikely that a 9 to 18% reduction in fuel use with Sasobit® and Aspha-min® would result in a 60% reduction in CO. Consequently the reported reduction in CO emissions cannot be attributed to warm mix technology (*17*).

Table 14. Asphalt Plant Stack Emissions Results (*16*)

	Control	**Evotherm™**	**Aspha-min®**	**Sasobit®**
Date	8/30/2006	9/7/2006	9/11/2006	9/16/2006
Production Rate, TPH	165	167	168	167
Fuel	Natural Gas	Natural Gas	Natural Gas	Natural Gas
Calculated Stack Moisture, %	22.3	29.5	24.4	24.8
Carbon Dioxide, %	3.5	4.2 (+ 20.0%)	2.8 (- 20.0%)	2.0 (- 42.9%)
Oxygen, %	15.7	15.0	15.8	15.7
Sulfur Dioxide, lbs/hr	0.24	0.37	0.04	0.04
Nitric Oxide, lbs/hr	5.2	5.1 (- 1.9%)	3.6 (- 30.8%)	4.1 (- 21.2%)
Carbon Monoxide, lbs/hr	63.1	50.3 (- 20.3%)	24.0 (- 62.0%)	23.2 (- 63.2%)
VOC, lbs/hr (USEPA Method 25A)	7.8	20.2 (+159%)	2.9 (- 62.8%)	3.8 (- 51.3%)

FIELD PERFORMANCE

Ohio University has been monitoring the project's performance as part of a research project sponsored by the Ohio DOT. In-place density results as a function of time are shown in Figure 14 (*18*-*19*). Cores were not taken from the roadway immediately after construction. The as-constructed density may be inferred from the 3-month between the wheel path (BWP) core results. The as-constructed densities of all three WMA technologies are better than the control. The Evotherm™ densities were the best. As expected, the mixes have densified with time in the wheel path (WP). After 18 months, the in-place air voids are above 3 percent, even though the laboratory voids were low.

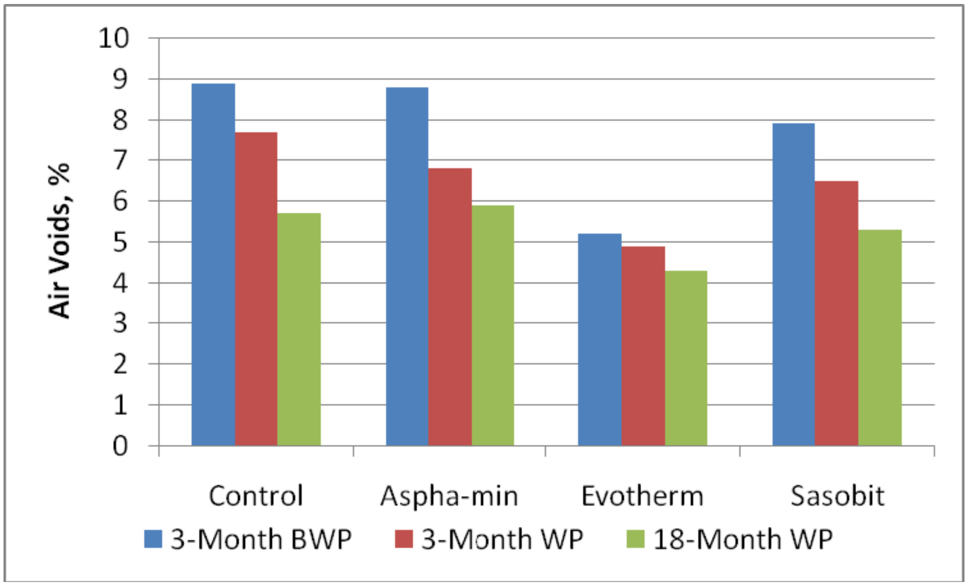

Figure 14. In-Place Air Voids with Time (*18*, *19*)

The Ohio DOT reported that the WMA test sections are showing signs of various degrees of raveling. Figures 15-17 show photographs of each of the three WMA test sections. It is believed that the Sasobit® section was photographed while in the shade; therefore the photo is darker than the other two photos. In terms of ranking, from visual observation, the Evotherm™ has the smallest degree of raveling, with Sasobit® showing the highest degree of raveling (*20*). This is evidenced by the loss of aggregate from the roadway surface. The raveling may be an indication of moisture damage occurring in the WMA. The raveling may also result from paving practices, particularly those related to the mix dragging out under the screed and the ensuing hand work. The early portion of the Sasobit® was placed at temperatures even lower than those reported in Figure 3. This may have contributed to the raveling in the Sasobit® section.

Figure 15. Evotherm™ WMA Test Section (*20*)

Figure 16. Aspha-min® WMA Test Section (*20*)

Figure 17. Sasobit® WMA Test Section (20)

CONCLUSIONS

In August and September 2006, WMA field evaluations were constructed on SR 541 in Kimbolton, Ohio. These test sections were used to evaluate the field performance of three WMA technologies, namely Evotherm™, Sasobit®, and Aspha-min®. Specific conclusions generated from this evaluation include:

- WMA test sections were placed at compaction temperatures ranging from 30 to 60°F lower than the control test section,
- Laboratory air voids for the WMA sections were, on average, 0.7 to 1.2 percent lower than the control section, representing a statistically significant reduction in air voids, 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 compared to the control. For the Sasobit® and Aspha-min®, the measured rut depths were statistically equal to the control,
- AASHTO T 283 testing indicated an increase in moisture damage potential for all three WMA technologies. However, stripping inflection points from Hamburg wheel-tracking tests indicate improved performance for three of four WMA samples compared to the control mixture for the reheated specimens. The exception is the second day's Evotherm™ samples. In terms of total rutting from the Hamburg Test, the Aspha-min®

and Evotherm™ results were greater than the control while the Sasobit® results were less than the control. There were insufficient replicates to make statistical comparisons,

- The dynamic modulus of the Aspha-min® and Evotherm™ WMA technologies were statistically lower than the dynamic modulus results from the control for certain temperatures and frequencies. The differences occurred at the intermediate temperature and low frequencies for the Evotherm™ WMA and the high temperature and lower frequencies for both the Aspha-min® and Evotherm™ WMA. It was also determined that the dynamic modulus results were statistically not different for samples compacted both prior to and after reheating,
- Based on an industrial hygiene survey, WMA reduced the emissions at the paver, on average, 67 to 81 percent, based on total particulates and benzene soluble matter for all three WMA technologies,
- Stack emissions testing indicated a reduction of emissions produced for both the Aspha-min® and Sasobit® WMA technologies, while the Evotherm™ produced higher emissions than the other technologies and the control section. The increased CO_2 and VOC emissions for the Evotherm™ WMA are believed to be a result of higher fuel usage during the construction of the Evotherm test section. The Evotherm™ production temperatures were higher than normal to address flow into the plant's vertical bucket elevator, and
- The as-constructed, in-place densities for all three WMA technologies were better than the density of the HMA control even with the lower compaction temperatures.

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APPENDIX A