Evaluation of Potential Processes for Use in Warm Mix Asphalt

Graham C. Hurley[1] and Brian D. Prowell[2]

Abstract

Several new processes have been developed to reduce the mixing and compaction temperatures of hot mix asphalt without sacrificing the quality of the resulting pavement. Three potential warm mix asphalt processes were evaluated in this study. They were Aspha-min®, Sasobit®, and Evotherm®. A laboratory study was conducted to determine the applicability of these processes to typical paving operations and environmental conditions commonly found in the United States, including the performance of the mixes in quick traffic turn-over situations and high temperature conditions.

All three processes were shown to improve the compactability of mixtures in both the SGC and vibratory compactor. Statistics indicated an overall reduction in air voids. Improved compaction was noted at temperatures as low as 190°F (88°C). Superpave gyratory compactor results indicated that Aspha-min®, Sasobit®, and Evotherm® may lower the optimum asphalt content. The addition of Aspha-min®, Sasobit®, or Evotherm® did not affect the resilient modulus of an asphalt mix nor did they increase the rutting potential of an asphalt mix as measured by the Asphalt Pavement Analyzer. The rutting potential did increase with decreasing mixing and compaction temperatures, which may be related to the decreased aging of the binder resulting from the lower temperatures. There was no evidence of differing strength gain with time for the mixes containing the three processes as compared to the control mixes indicating that a prolonged cure time before opening to traffic is not an issue. The lower compaction temperature used when producing warm asphalt may increase the potential for moisture damage. Overall, Aspha-min®, Sasobit®, and Evotherm® appear to be viable tools for reducing mixing and compaction temperatures that can be readily added to hot mix asphalt. Reductions in mixing and compaction temperatures are expected to reduce fuel costs, reduce emissions,

---

[1] Research Engineer and [2] Assistant Director, National Center for Asphalt Technology

widen the winter paving window and facilitate niche applications such as airport runway construction where rapid open to traffic is essential.

Introduction

A number of new processes and products have become available that have the capability of reducing the temperature at which hot mix asphalt (HMA) is mixed and compacted without compromising the performance of the pavement. These new products can reduce production temperatures by as much as 40 percent. North American asphalt mixes are generally heated to 300°F (149°C) or greater, depending mainly on the grade of binder used; mixes produced with these new products are being produced at temperatures of about 250°F (121°C) or lower. Lower plant mixing temperatures mean fuel cost savings to the contractor and findings have shown that lower plant temperatures can lead to a 30 percent reduction in fuel energy consumption (*1*). Lower temperatures also mean that any emissions, either visible or non-visible, that may contribute to health, odor problems, or greenhouse gas emissions, will also be reduced (*2*). The decrease in emissions represents a significant cost savings, considering that 30-50 percent of overhead costs at an asphalt plant can be attributed to emission control (*1*). Lower emissions may allow asphalt plants to be sited in non-attainment areas, where there are strict air pollution regulations. Having an asphalt plant located in a non-attainment area and producing hot mix with a product that allows for a lower operating temperature will allow shorter haul distances which will improve production and shorten the construction period, thus reducing the possible headache of traffic congestion. Warm asphalt mixes will also allow longer haul distances and a longer construction season if the mixes are produced at more normal operating temperatures. There is another potential added advantage in that oxidative hardening of the asphalt will be minimized with the lower operating temperatures and this may result in changes in pavement performance such as reduced thermal cracking, block cracking, and preventing the mix from being tender when placed.

Of the current processes, this report concentrated on three in particular. The first process is known as Aspha-min®. Aspha-min® is a product of Eurovia Services GmbH, based in Bottrop, Germany. Aspha-min® is a manufactured synthetic sodium aluminum silicate, or better known as zeolite. This zeolite has been hydro-thermally crystallized. Zeolites are framework silicates with large empty spaces in their structures that allow the presence of large cations, such as sodium and calcium. They also allow the presence of large cation groups, such as water molecules. Most zeolites are characterized by their ability to lose and absorb water without damaging their crystal structure. Heat can drive off the water contained in the zeolite, which can then act as a delivery system for the new fluid (*3*).

Eurovia's Aspha-min® contains approximately 21 percent water by mass and is released in the temperature range of 185-360°F (85-182°C). When Aspha-min® is added to the mix at the same time as the binder, water is released. This water release creates a volume expansion of the binder that results in asphalt foam and allows increased workability and aggregate coating at lower temperatures.

During the production of HMA, Eurovia recommends that Aspha-min® be added at a rate of 0.3 percent by mass of the mix, which in previous research has shown a potential 54°F (30°C) reduction in typical HMA production temperatures (*3*). Eurovia also states that all commonly known asphalt and polymer-modified binders can be used, as well as recycled asphalt (RAP). All types of aggregates used in the hot mix industry can also be used, so no changes to a normal mix design process are needed when using zeolite. Aspha-min® zeolite is approximately a 50 mesh material which may be added directly to the pugmill of a batch plant, through the RAP collar, or pneumatically fed into a drum plant using a specially built feeder. To date, four projects have been constructed in the United States as well as a number of projects in Europe.

The second process is branded Sasobit®, which is a product of Sasol Wax. It is a fine crystalline, long-chain aliphatic polymethylene hydrocarbon produced from the gasification of coal or natural gas feedstocks using the Fischer-Tropsch (FT) process (*4*). It is also known as FT hard wax.

In summary, in the Fischer-Tropsch synthesis, coal or natural gas (methane) is partially oxidized to carbon monoxide (CO) which is subsequently reacted with hydrogen (H) under catalytic conditions producing a mixture of hydrocarbons having molecular chain lengths of C5 to C100 plus carbon atoms. The process begins with synthesis gas, which is a combination of carbon monoxide (from coal gasification) and hydrogen (from air separation), then reacted with either an iron or cobalt catalyst to form products such as synthetic naphtha, kerosene, gasoil and waxes. The liquid products are separated and the FT waxes are recovered or hydrocracked into transportation fuels or chemical feedstocks. The Sasobit recovered is in the carbon chain length range of C45 to C100 plus. (*4-6*). By comparison, macrocrystalline bituminous paraffin waxes have carbon chain lengths ranging from C25 to C50 (*7*). The longer carbon chains in the FT wax lead to a higher melting point. The smaller crystalline structure of the FT wax reduces brittleness at low temperatures as compared to bitumen paraffin waxes.

Sasobit® is described as an “asphalt flow improver”, both during the asphalt mixing process and during laydown operations, due to its ability to lower the viscosity of the asphalt binder (*4*). This decrease in viscosity allows working temperatures to be decreased by 32-97°F (18-54°C). Sasobit has a melting 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 the added stability (*4,7*).

During the production of HMA, Sasol recommends that Sasobit® be added at a rate of 0.8 percent or more by mass of the binder, but not to exceed 3 percent. Sasobit® can be blended into hot binder at the blending plant without the need for high shear mixing. In commercial applications in Asia, Europe, South Africa, and the United States, Sasobit® has been added directly onto the aggregate mix as solid prills (small pellets) or as molten liquid via a dosing meter. Marshall tests performed on mixes produced in this manner indicated no difference in Stability or Flow values as compared to premixing with the binder (*8*).

Since 1997, over 142 projects were paved using Sasobit® totaling more than 2,716,254 square yards (2,271,499 square meters) of pavement (*9*). Projects were constructed in Austria, Belgium, China, Czech Republic, Denmark, France, Germany, Hungary, Italy, Macau, Malaysia, Netherlands, New Zealand, Russia, South Africa, Sweden, Switzerland, the United Kingdom, and the United States. The projects included a wide range of aggregate types and mix types, including: dense graded mixes, stone mastic asphalt and Gussaphalt. Sasobit® addition rates ranged from 0.8 to 4 percent by mass of binder.

Evotherm® is a non-proprietary technology based on a chemistry package that includes additives to improve coating and workability, adhesion promoters, and emulsification agents. The total Evotherm package is typically 0.5 percent by weight of emulsion, as was the case for this study. The chemistry is delivered in an emulsion with a relatively high asphalt residue (approximately 70 percent). Unlike traditional asphalt binders, Evotherm® is stored at 176°F (80°C). The water in the emulsion is liberated from the Evotherm® in the form of steam when it is mixed with the heated aggregate. The resulting warm mix appears like hot mix in terms of coating and color.

Two Evotherm field trials have been constructed in South Africa and one in the United States with additional trials planned. The South African trials used dense-graded 12.5 mm NMAS siliceous aggregates and viscosity-graded AC20 and AC10 binders. Parallel-flow drums plants were used to produce dense-graded mix at temperatures as low as 160°F (71°C); and in the field, laydown and compaction temperatures as low as 140°F (60°C) were achieved. The United States trial was constructed near Indianapolis, Indiana. The Indiana mix was a 12.5 mm NMAS Superpave design produced with a dolomitic limestone aggregate. The emulsion was produced from a PG 64-22 base.

Objective

The objective of this study was to perform a laboratory study to determine the applicability of several different processes in warm mix asphalt applications including typical paving operations and environmental conditions commonly found in the United States. The processes were evaluated with respect to compactability, quick turnover to traffic, stiffness, rutting potential, and to moisture susceptibility.

Research Approach

Table 1 shows the experimental design for the laboratory evaluation of the three warm mix additives. The following sections describe the individual tests that are included in the experimental design.

Table 1. Experimental Design for Evaluating the Influence of Warm Asphalt Processes on Mixture Volumetrics and Performance

	Number of Samples Tested							
	Granite				Limestone			
	Control	Zeolite	Sasobit®	Evotherm	Control	Zeolite	Sasobit®	Evotherm
Mix Design	9	9	9	9	9	9	9	9
Volumetrics	8	8	8	8	8	8	8	8
Densification	24	24	24	24	24	24	24	24
Resilient Modulus	24	24	24	24	24	24	24	24
APA Rutting	24	24	24	24	24	24	24	24
Moisture Sensitivity	6	6	6	6	6	6	6	6
Strength Change with Time	10	10	10	10	10	10	10	10

Mix Design

Two aggregate types (granite and limestone) and one asphalt binder grade (PG 64-22) were used to evaluate the processes. However, to achieve the PG 64-22 binder used with the Sasobit®, 2.5 percent Sasobit® was added to a base PG 58-28 binder to produce the PG 64-22 binder. The mix design replicates a 12.5mm nominal maximum aggregate size Superpave coarse-graded crushed granite mix produced by Hubbard Construction, Orlando, Florida. The mix design gradation and optimum asphalt contents are shown in Table 2. The same target gradation was used for the limestone aggregate.

Table 2. Target Gradations and Asphalt Contents

	% Passing		
Sieve Size	JMF[1]	Granite	LMS[2]
19.0	100.0	99.0	100.0
12.5	90.0	87.9	90.9
9.5	83.0	79.9	83.6
4.75	52.0	49.6	52.7
2.36	34.0	32.2	32.6
1.18	25.0	23.6	23.7
0.600	19.0	18.6	17.5
0.300	13.0	14.7	12.3
0.150	5.0	5.3	6.0
0.075	2.9	2.9	3.1
AC, %	5.3	5.1	4.8

1: Job Mix Formula; 2: Limestone

The job mix formula asphalt content was verified for the granite aggregate using a design gyration level of 125 gyrations. For the limestone aggregate, the mix design was conducted using the same design gyration level to determine an optimum asphalt content. Once the mix designs were verified at 300°F (149°C), each combination was then compacted at three lower temperatures (265, 230, and 190°F (129, 110, 88°C)). Volumetric properties for each of the 32 mix design combinations (one binder grade, two aggregates, three processes and one control mix type, and four compaction temperatures) are presented in Tables 3 and 4. The data for both aggregates with Sasobit® compacted at 190°F (88°C) were not obtained due to lack of material. These data points will be obtained when more material is available. Each result represents the average of two samples. From the results of the mix design verifications using the control mixtures, asphalt contents of 5.1 and 4.8 percent were determined for the granite and limestone aggregate, respectively. These asphalt contents were used throughout the remainder of the study, whenever test specimens were made.

Table 3. Volumetric Mix Design Data for Granite Aggregate

Additive	Temperature, F	AC, %	G_{mm}	% G_{mm} @ N_i	G_{mb}	Air Voids, %	VMA	VFA
Control	300	5.1	2.467	88.0	2.365	4.1	13.6	69.6
Control	265	5.1	2.467	88.2	2.371	3.9	13.3	71.0
Control	230	5.1	2.467	87.7	2.360	4.4	13.8	68.4
Control	190	5.1	2.467	87.5	2.356	4.5	13.9	67.6
Zeolite	300	5.1	2.457	88.8	2.376	3.3	13.9	76.4
Zeolite	265	5.1	2.457	88.9	2.382	3.0	13.6	77.7
Zeolite	230	5.1	2.457	88.7	2.378	3.2	13.1	75.5
Zeolite	190	5.1	2.457	88.3	2.368	3.6	13.5	73.2
Sasobit	300	5.1	2.461	88.4	2.375	3.5	13.9	74.8
Sasobit	265	5.1	2.461	88.0	2.377	3.4	13.8	75.5
Sasobit	230	5.1	2.461	88.0	2.360	4.1	14.4	71.7
Sasobit	190	5.1	2.461	NA	NA	NA	NA	NA
Evotherm	300	5.1	2.465	88.7	2.389	3.1	12.7	75.7
Evotherm	265	5.1	2.465	88.5	2.387	3.2	12.8	75.2
Evotherm	230	5.1	2.465	88.4	2.384	3.3	12.9	74.5
Evotherm	190	5.1	2.465	88.6	2.390	3.0	12.7	76.0

Table 4. Volumetric Mix Design Data for Limestone Aggregate

Additive	Temperature, F	AC, %	G_{mm}	% G_{mm} @ N_i	G_{mb}	Air Voids, %	VMA	VFA
Control	300	4.8	2.544	85.4	2.433	4.4	15.0	70.8
Control	265	4.8	2.544	85.1	2.430	4.5	15.1	70.3
Control	230	4.8	2.544	85.3	2.435	4.3	14.9	71.3
Control	190	4.8	2.544	85.5	2.439	4.1	14.8	72.1
Zeolite	300	4.8	2.544	85.8	2.442	4.0	14.7	72.8
Zeolite	265	4.8	2.544	85.8	2.449	3.7	14.4	74.3
Zeolite	230	4.8	2.544	85.7	2.444	3.9	14.6	73.2
Zeolite	190	4.8	2.544	84.8	2.418	4.9	15.5	68.2
Sasobit	300	4.8	2.545	86.1	2.459	3.4	14.1	76.1
Sasobit	265	4.8	2.545	86.3	2.463	3.2	14.0	76.7
Sasobit	230	4.8	2.545	86.3	2.465	3.1	13.9	77.4
Sasobit	190	4.8	2.545	NA	NA	NA	NA	NA
Evotherm	300	4.8	2.547	86.0	2.472	3.0	13.6	78.4
Evotherm	265	4.8	2.547	85.6	2.458	3.5	14.1	75.3
Evotherm	230	4.8	2.547	86.2	2.477	2.8	13.5	79.6
Evotherm	190	4.8	2.547	85.2	2.451	3.8	14.4	73.9

Observations from Tables 3 and 4 indicate that the different processes had little effect on the maximum specific gravity (G_{mm}) of the mixture. Previous research has indicated that the Superpave gyratory compactor (SGC) was insensitive to compaction temperature (*10,11*). In Tables 3 and 4 there are very slight trends of increasing air voids with decreasing temperature for some of the combinations. Out of the 22 combinations that data was determined for, only one had a higher air void level than its corresponding control mixture. An Analysis of Variance (ANOVA) test was conducted on the gyratory data to confirm the belief that the gyratory compactor is not sensitive to compaction temperature. The results are shown in Table 5. From these results, the gyratory compactor is statistically insensitive to the change in compaction temperature. It can also be seen from the data that the different additives are significant in the densification of hot mix asphalt. Consequently, the addition of the Aspha-min® zeolite appears to reduce the design asphalt content by approximately 0.1 to 0.4 percent, while the addition of Sasobit® or Evotherm® appear to reduce the design asphalt content by approximately 0.1 to 0.5. Similar reductions were noted in previous research on Sasobit®(*4*). However, as stated previously, the asphalt contents presented in Table 2 were used for the production of the remaining test samples to reduce the number of variables.

Table 5. ANOVA Results for Gyratory Data

Source	DF	Adj. MS	F-stat	p-value	Significant
Temperature	2	0.0154	0.14	0.872	No
Additive	3	1.3526	12.16	0.000	Yes
Aggregate	1	0.0704	0.63	0.437	No
Error	17	0.1112			
Total	23				

Densification

Once the optimum asphalt contents and volumetric properties for each aggregate/binder combination were determined, test samples were then produced to evaluate the mixes' ability to be compacted over a range of temperatures. These test samples were prepared using oven dried aggregate. Before test samples were made, the anticipated number of test specimens were batched and then randomized for each of the different sets to reduce the variability. This was achieved by compacting a set of six samples per mix at the three lower temperatures mentioned previously (265, 230, and 190°F (129, 110, 88°C)), as well as a set compacted at 300°F (149°C). The mixing temperature was approximately 35°F (14°C) above the compaction temperature. Each sample was aged for two hours at its corresponding compaction temperature prior to compaction. No coating problems were observed for any of the warm mix processes. Test samples were compacted using a vibratory compactor, as seen in Figure 1. The vibratory compactor was selected for several reasons. One reason was that the literature suggested that the Superpave gyratory compactor was insensitive to temperature changes. A second reason was that it was found to be easier to produce samples for the Asphalt Pavement Analyzer

(APA) with the vibratory compactor than with a Marshall hammer (the Marshall hammer is known to be sensitive to compaction temperature). A third reason was that the vibratory compactor applies a vertical load, frequency, and amplitude that is comparable to those found in a typical vibratory roadway compactor.

Test samples, 6 inches in diameter and 3.75 inches tall, were compacted in the vibratory compactor for a time period of 30 seconds. This was the length of time that produced an air void content of 7 percent in preliminary testing using the PG 64-22 control mixture with the granite aggregate at 300°F (149°C). Once the air void content was determined, these same samples were then used to determine the resilient modulus and APA rut resistance of each mix at the various compaction temperatures.

Figure 1. Vibratory Compactor used for Compaction of Test Samples

Resilient Modulus

Resilient modulus is a measure of the stiffness of the hot mix asphalt. The indirect resilient modulus was determined according to ASTM D 4123, *Indirect Tension Test for Resilient Modulus of Bituminous Mixtures*. The testing was conducted at 73°F (23°C) as recommended by Lottman (*12*). Since resilient modulus is a non-destructive test, additional testing was conducted on the same set of test samples for each mix combination.

APA Rutting

Once the resilient modulus testing was completed, each mixture set was placed in the APA to determine the rut resistance of each aggregate/binder combination for the different compaction temperatures. 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.

Strength Gain

An evaluation of strength change with time was also conducted because of the possible changes in the stiffness of the asphalt due to the lower production temperatures when using the warm asphalt additives. If they improve the workability of a mixture, there may be concern that the workability would not dissipate prior to being opened to traffic, thus creating the potential for rutting. Ten samples of each mix were prepared for short-term and long-term mix aging per AASHTO PP2, using both the granite and limestone aggregates. Mixture strength was evaluated based on indirect tensile strength at 77°F (25 °C). The indirect tensile strength of the mixture is sensitive to binder (or mastic) stiffness. Indirect tensile strength testing was performed on samples after the aging periods shown in Table 6.

Table 6. Strength Gain Experiment Aging Periods

Set	Short Term Aging (hours) at 250°F (121 °C) (prior to compaction)	Long Term Aging (days) of Compacted Samples at 185°F (85 °C)
1	2	0
2	4	0
3	2	1
4	2	3
5	2	5

Moisture Sensitivity

If the moisture contained in the aggregate does not completely evaporate during mixing due to the low mix temperatures, water may be retained in the aggregate which could in turn lead to increased susceptibility to moisture damage. Therefore, additional test samples were produced and tested according to ASTM D 4867, *Effect of Moisture on Asphalt Concrete Paving Mixtures*, to assess the potential for moisture susceptibility of each mixture combination. The ASTM procedure is similar to the AASHTO T283 procedure except for the aging times. Several agencies have already eliminated the 72-96 hour room temperature cure period found in the AASHTO procedure.

To simulate the actual mixing process of a typical drum plant, a bucket mixer and a propane torch were used to heat the aggregate and mix the samples for making the TSR test samples. This was selected based on a methodology developed to study the effects of residual moisture on compaction (tender mixes) (*13*). The bucket mixer used can be seen in Figure 2. Before the aggregate was combined with the binder, 3 percent water in addition to the absorption value of each aggregate was added to the mix before it was heated. For example, the granite aggregate had an absorption value of 1.1 percent, so a total of 4.1 percent water by aggregate weight was added to the oven dry material before the binder was added.

The addition of the aggregate to the bucket mixer took place in two steps because it was found that when the entire gradation was added at once, by the time the aggregate was heated to the intended mixing temperature, which was 275°F (135°C), all of the fine material had segregated to the bottom of the bucket. So when the binder was added to the aggregate, the fine material was not fully coated. This was alleviated by adding the coarse and fine aggregate separately. The appropriate percentage of moisture was added to the fine aggregate portion, then set aside. The coarse aggregate was added to the bucket, and appropriate percentage of moisture was introduced to the coarse aggregate (Figure 2) and then it was heated to 250°F (121°C) (Figure 3). Then the fine aggregate portion was added to the bucket and the aggregate was heated back to the intended mixing temperature. When reached, the dust proportion of the blend and the binder was added to the bucket and allowed to thoroughly coat the aggregate. Each bucket mix produced three test samples. During the mixing process, the mix temperature decreased, so each test sample was placed in an oven until the compaction temperature (250°F (121°C)) was reached, usually about 10-15 minutes. This process is shown in Figures 2-4.

Figure 2. Introduction of Moisture to Aggregate for TSR Samples

Figure 3. Heating of Wet Aggregate to Mixing Temperature

Figure 4. Warm Mix Asphalt in Bucket Mixer

TEST RESULTS AND DISCUSSION

Densification

As mentioned earlier, samples were compacted in the vibratory compactor over a range of temperatures. The densification results for both the granite and limestone mixes are shown in Figures 5 and 6. The data for the replicates are provided in the Appendix, Tables A1 through A8. From observation of the results in Figures 5 and 6, the addition of zeolite, Sasobit®, and Evotherm improves compaction over the control mixture for all binder, aggregate, and temperature combinations. Observation of Figures 5 and 6 also show that the air void content for the control mixtures increased from 300°F (149°C) to 265°F (129°C), but did not increase at the lower compaction temperatures. This is probably due to less aging of the binder or possibly from the coarse nature of the mix. To verify if the coarse nature of the mix had an influence on the densification of the mixtures, a fine gradation was evaluated in the vibratory compactor at the different compaction temperatures, and their bulk specific gravities was determined. The results indicated a gradual increase in the air void content with the decrease in compaction temperature, so the coarse nature of the mix is believed to have some influence in the fluctuation of the densification at the lower compaction temperatures.

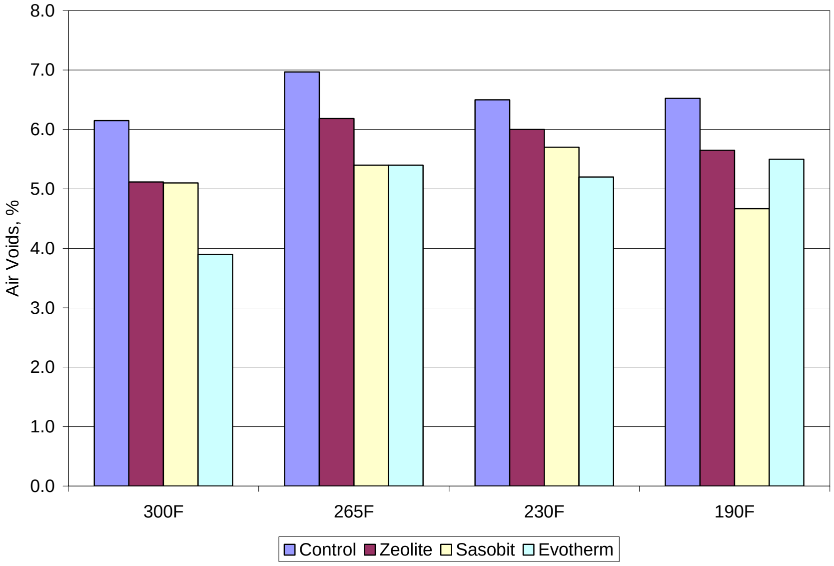

Figure 5. Densification Results over Range of Compaction Temperatures – Granite Mix

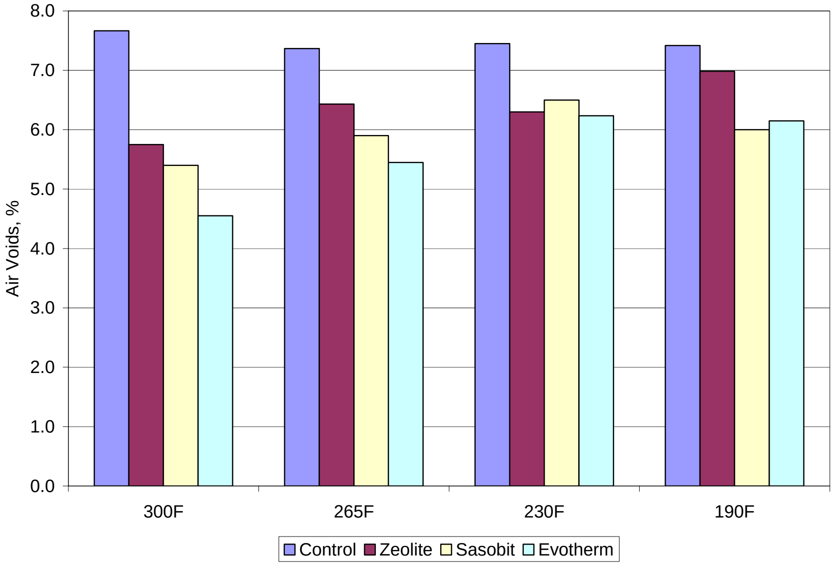

Figure 6. Densification Results over Range of Compaction Temperatures – Limestone Mix

Analysis of Variance (ANOVA) was used to analyze the densification data with air voids as the response variable and aggregate type, presence of additive, and compaction temperature as factors. The results from the ANOVA are presented in Table 7. From the results, all factors along with all possible interactions are statistically significant.

Table 7. ANOVA Densification Results

Source	DF	Adj. MS	F-stat	p-value	Significant*
Temp	3	8.8115	31.33	0.000	Yes
Additive	3	18.8782	67.13	0.000	Yes
Agg	1	28.5208	101.42	0.000	Yes
Temp*Additive	9	2.2346	7.95	0.000	Yes
Temp*Agg	3	1.3168	4.68	0.004	Yes
Additive*Agg	3	1.4257	5.07	0.002	Yes
Temp*Additive*Agg	9	0.5641	2.01	0.042	Yes
Error	160	0.2812			
Total	191				

* = Significant at the 95 percent confidence interval

A Tukey's post-ANOVA test was then conducted on the data for several reasons. One was to compare the different additives to the control and to each other, to see if any additive was statistically different from another additive. A second reason was to determine how much each additive lowered the air void content, based on the fact that the optimum asphalt content might be altered by the addition of a warm asphalt additive, discussed earlier in the report. Based on the results from the Tukey's test, Evotherm lowered the air void content the most, with Sasobit® next, and zeolite lowering the air void content the least. Statistically speaking, all additives significantly lowered the air void content, compared to the control. However, Evotherm was significantly different than the Sasobit® and zeolite, while the Sasobit® and zeolite were statistically different than the control; they were not statistically different than one another.

Interaction plots for the densification data are shown in Figure 7. Interaction plots are just another way to graphically visualize the data. From these plots, a couple of conclusions can be made. One, the granite aggregate consistently produced lower air void contents, based on both compaction temperature and the presence of any additive. And two, Evotherm produced lower air void contents over the range of compaction temperatures.

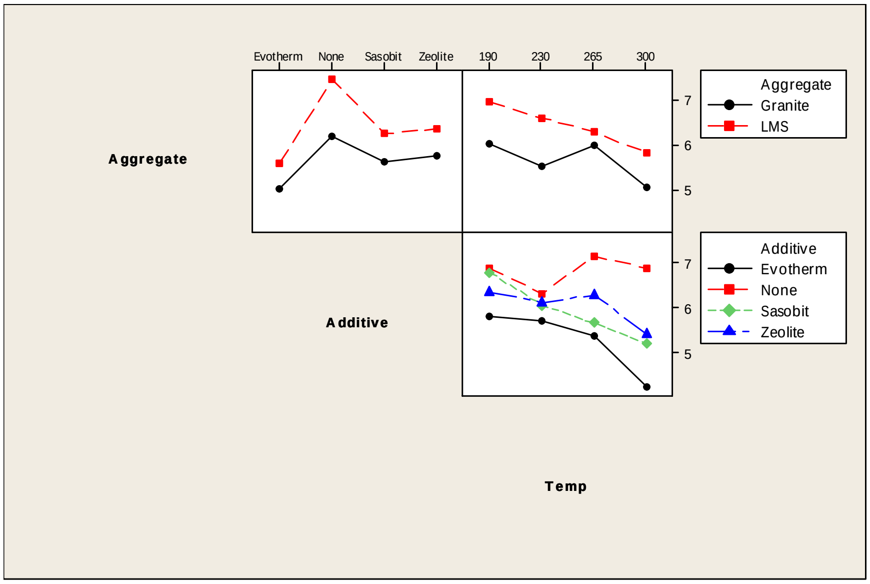

Figure 7. Interaction Plots for Densification Data

Numerically speaking, Evotherm lowered the air void content by an average of 1.5 percent, with a 95 percent confidence interval of 1.2 to 1.8 percent. For the Sasobit®, it lowered the air void content by 0.9 percent, with a 95 percent confidence interval of 0.6 to 1.2 percent. Zeolite lowered the air void content by an average of 0.8 percent, with a 95 percent confidence interval of 0.5 to 1.1 percent. All results were compared to the control mixtures data compacted at 300°F (149°C). It is ultimately believed that the addition of any additive will ease the field compaction of hot mix asphalt, based upon the statistical findings from the densification data.

Resilient Modulus

The data for the resilient modulus tests are provided in the Appendix, Tables A1 through A8. An ANOVA was performed to determine which factors (aggregate type, additive, and compaction temperature) significantly affect the measured resilient modulus. These results are presented in Table 8. Based on the results, only two factors (compaction temperature and additive) and two interactions (between compaction temperature and additive and between additive and aggregate type) had a significant effect on the resilient modulus.

Table 8. ANOVA Results for Resilient Modulus

Source	DF	Adj. MS	F-stat	p-value	Significant*
Temp	3	5.68E+10	5.51	0.001	Yes
Additive	3	2.96E+10	2.87	0.038	Yes
Agg	1	2.23E+10	2.16	0.143	No
Temp*Additive	9	2.90E+10	2.81	0.004	Yes
Temp*Agg	3	7.92E+09	0.77	0.514	No
Additive*Agg	3	4.08E+10	3.96	0.009	Yes
Temp*Additive*Agg	9	1.18E+10	1.14	0.336	No
Error	160	1.03E+10			
Total	191				

* = Significant at the 95 percent confidence interval

Tukey's post-ANOVA test was conducted on the resilient modulus data to compare the different additives to the control and to each other, as was done for the densification data. From these results, it was concluded that Evotherm increased the measured resilient modulus the most, with zeolite next. Sasobit® actually decreased the measured resilient modulus, according to the data. However, none of the additives significantly affected the measured resilient modulus values, one way or the other, based on the Tukey's rankings.

Interaction plots for the measured resilient modulus data are shown in Figure 8. Interaction plots are just another way to graphically visualize the data. From these plots, a couple of conclusions can be made. First, the limestone aggregate consistently produced higher resilient modulus values for two of the three additives and over the range of compaction temperatures. And second, Evotherm produced higher resilient modulus values over the range of compaction temperatures, except for the 300°F (149°C) compaction temperature, but an oultier may possibly be skewing the zeolite test results.

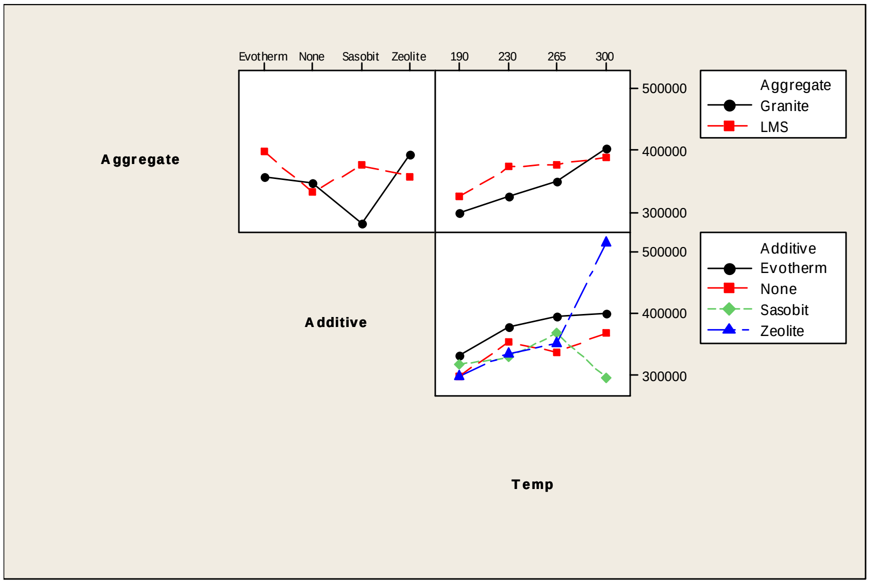

Figure 8. Interaction Plots for Resilient Modulus

APA Rutting

Once each set of test samples were tested to determine its resilient modulus value, they were placed in an oven at 147°F (64°C) for a minimum of six hours to ensure that they were equilibrated to the APA test temperature. They were then placed in the Asphalt Pavement Analyzer to determine their rutting potential at a temperature of 147°F (64°C). The rutting results for the granite and limestone aggregates are shown in Figures 9 and 10 with the supporting data for the replicates shown in the Appendix, Tables A1 through A8.

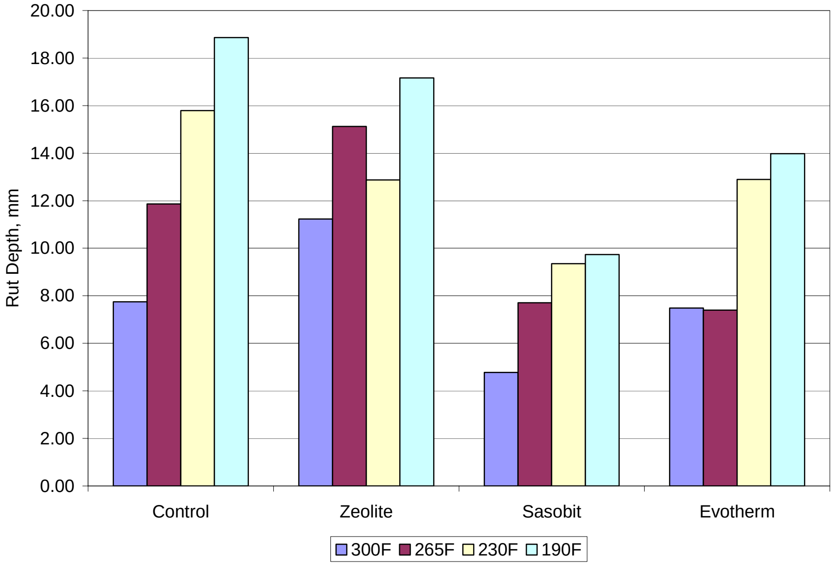

Figure 9. APA Rutting Results for Granite Aggregate

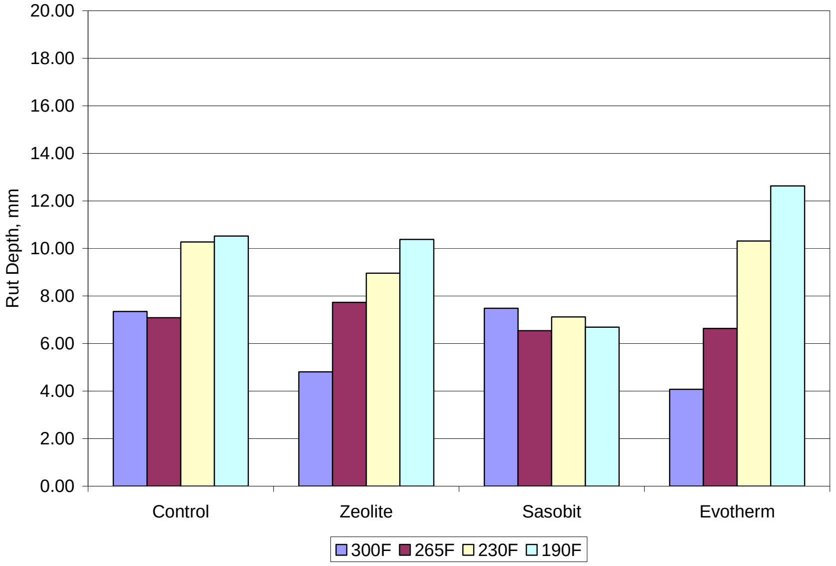

Figure 10. APA Rutting Results for Limestone Aggregate

Analysis of variance results from the rutting data are presented in Table 9. Based on these results, all factors and interactions except for the one three-way interaction between compaction temperature, additive, and aggregate type were found to be significant.

Table 9. ANOVA Results for APA Rutting

Source	DF	Adj. MS	F-stat	p-value	Significant*
Temp	3	483.59	36.64	0.000	Yes
Additive	3	37.67	2.85	0.039	Yes
Agg	1	591.93	44.85	0.000	Yes
Temp*Additive	9	32.23	2.44	0.012	Yes
Temp*Agg	3	40.73	3.09	0.029	Yes
Additive*Agg	3	64.88	4.92	0.003	Yes
Temp*Additive*Agg	9	24.82	1.88	0.058	No
Error	160	13.20			
Total	191				

* = Significant at the 95 percent confidence interval

A Tukey's post-ANOVA test was performed on the rutting results to compare the different additives. The results from the Tukey's suggested that the Evotherm lowered the rut depths the most (by an average of 1.8 mm); Sasobit® decreased the rut depths by 1.4 mm, while the zeolite decreased the rutting potential by an average of 0.2 mm. However, none of the additives significantly increased or decreased the rutting potential compared to the hot mix asphalt control samples, based on Tukey's rankings.

Interaction plots for the measured rutting data are shown in Figure 11. From these plots, a couple of conclusions can be made. First, the limestone aggregate consistently produced lower rutting values for the control and all additives and over the range of compaction temperatures. And second, the additives produced lower rutting values over the range of compaction temperatures, except for the zeolite at the 265°F (129°C) compaction temperature, but this may be caused by variability in the test data.

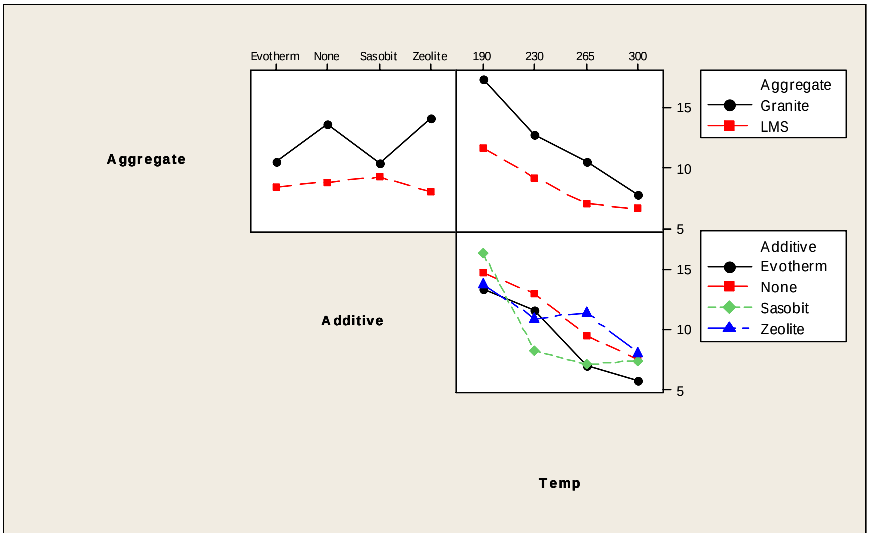

Figure 11. Interaction Plots for APA Rutting

Strength Gain

The strength gain experiment was conducted to evaluate the rutting potential immediately after construction. The results from the strength gain experiment for both aggregates are presented in Figures 12 and 13. The results indicated that although the strength varied over the different aging times, there was no change in strength for either the control mix or for the warm mix at a particular age time. This means that there is no evidence to support the need for a cure time before traffic can be allowed on the asphalt mixture containing Aspha-min®. The data for the Sasobit® generally indicated reduced aging of the binder, except for the long term aging samples for the limestone aggregate. Previous research conducted at 41°F (5°C) on a Stone Matrix Asphalt (SMA) mixture containing Sasobit® indicated no difference in tensile strength between the control and warm mixes *(14)*. Also, based on the rutting data discussed earlier, there is no evidence to support the need for a cure time before traffic can be allowed on the asphalt mixture containing Sasobit®. This is consistent with the reported congealing point (212°F (100°C)) for Sasobit® (*4*). Schumann Sasol (now Sasol Wax) reports that a project in Italy was opened to traffic five hours after paving began (*15*). Sasobit® is also being used in the repaving of Frankfurt airport. Twenty-four inches of HMA is placed in a 7.5 hour window. The runway is then reopened to jet aircraft at a temperature of 185 °F (85°C). Evotherm® shows evidence of strength gain with time, but the strengths at all but one aging period for the granite aggregate are numerically superior to that of the control mixture; for the limestone aggregate, the Evotherm® resulted on lower, but comparable values to the control mixture.

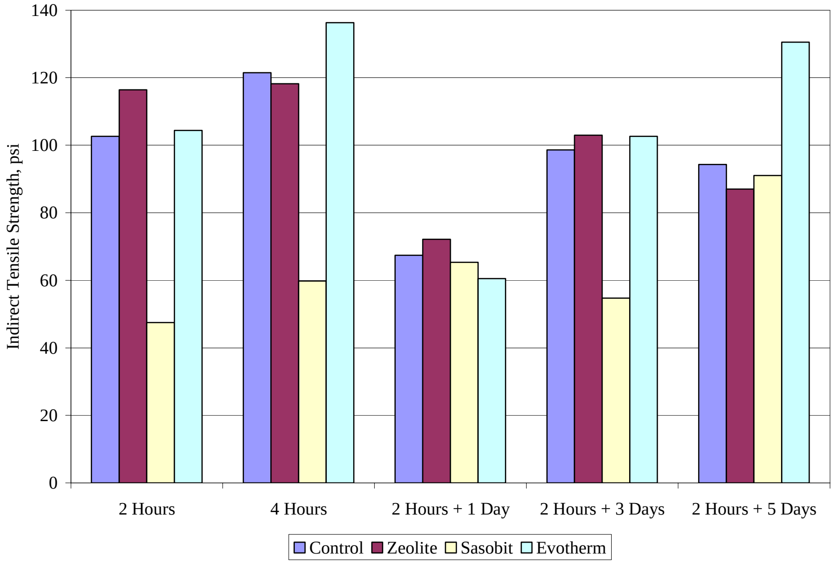

Figure 12. Strength Gain Results – Granite

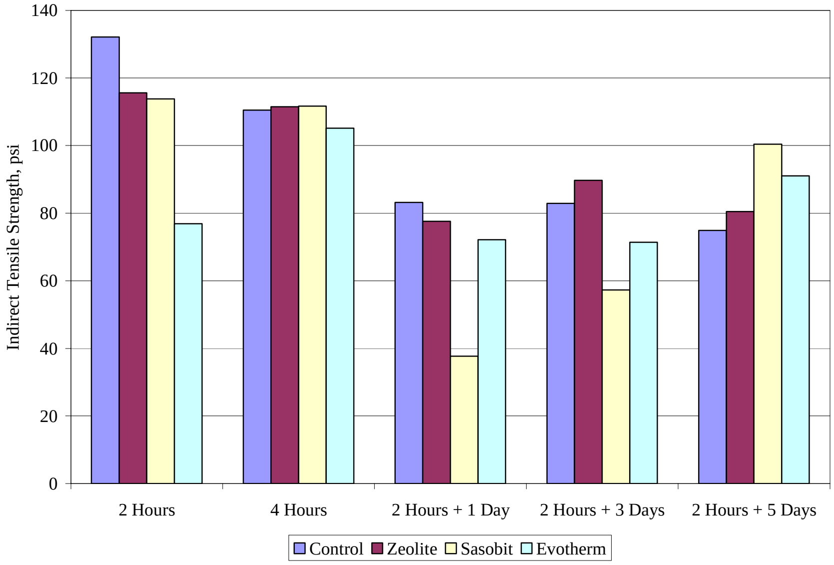

Figure 13. Strength Gain Results - Limestone

Critical Compaction Temperature

In order to accurately evaluate the warm asphalt additives, a comparison was made between the test results for each of the different additives and the test results for the control mix at a normal compaction temperature, this being at 300°F (149°C) for this particular study.

The reason for this comparison was to determine a critical compaction temperature; a minimum compaction temperature to where warm mix laid at any temperature below this compaction temperature, the performance of in-place asphalt will not be as good as hot mix asphalt laid at normal compaction temperatures. The test results for these comparisons can be seen in Table 10. In Table 10, the row labeled "none" refers to hot mix asphalt without any warm mix additives added. It does not mean hot mix that was mixed and compacted at normal temperatures and let cooled to the particular compaction temperature, but rather mixed and compacted at the two different temperatures evaluated, these being 265°F (129°C) and 230°F (110°C).

Observation of the results for the densification data indicated, all processes were either statistically the same, or significantly improved the compaction of the samples, down to 230°F (110°C). All equal signs seen in Table 10 indicate that there is no statistical difference between the process in question and hot mix asphalt at 300°F (149°C). The less than (<) sign means the performance is not as good as typical hot mix asphalt, where the greater than (>) sign indicates performance that is better than HMA. The values in parentheses indicate the p-value of each comparison, to illustrate the significance of the comparison. For example, at the 230°F (110°C) compaction temperature, all process significantly improved the densification, but based on the individual p-values, Evotherm® improved the densification the most.

Regarding resilient modulus, all processes neither significantly increased nor decreased the measured resilient modulus values, down to 230°F (110°C). This holds true for the mix type with no additive as well. This suggests that no additive will affect the stiffness of an asphalt mixture.

Based on the results for the APA rutting tests, Sasobit® neither increased nor decreased the rutting potential, down to 230°F (110°C). For the zeolite, there was a significant increase in the rutting results for both compaction temperatures. Observation of the p-values suggests that the rutting was more significant at the 265°F (129°C) compaction temperature; however, this may be due to some testing variability from the APA device. The test results for the Evotherm suggest that there may be an increased potential for rutting at the 230°F (110°C) compaction temperature.

Table 10. Results of Comparison of Additives to Hot Mix

	Air Voids		Resilient Modulus		APA Rutting	
	265	**230**	**265**	**230**	**265**	**230**
None	= (0.8895)	= (0.1161)	= (0.9695)	= (0.9969)	= (0.3071)	< (0.0002)
Zeolite	= (0.2250)	> (0.0122)	= (0.9968)	= (0.9391)	< (0.0025)	< (0.0420)
Sasobit	> (0.0006)	> (0.0059)	= (1.0000)	= (0.8911)	= (0.9926)	= (0.9752)
Evotherm	> (0.0000)	> (0.0001)	= (0.9801)	= (0.9987)	= (0.9833)	< (0.0087)

Moisture Sensitivity

As was mentioned before, ASTM D 4867 was used to determine the moisture sensitivity test results. A compaction temperature of 250°F (121°C) was selected based on compaction, modulus, and rutting results to be an acceptable temperature for all three processes. The results for both aggregates are shown in Table 11. Also included in Table 11 are test results from TSR samples that were prepared from oven dry aggregate in the gyratory compactor after being aged at 300°F (149°C) for two hours, except for the Sasobit®, which was aged at 250°F (121°C), as stated in ASTM D 4867. This testing was conducted to see what kind of behavior the additives exhibited in the mixture. From the test results for samples prepared with oven dry aggregate in Table 11, the presence of zeolite decreased the TSR value, but still resulted in an acceptable value, while the Sasobit® lowered the TSR value to an unacceptable value.

Table 11. Tensile Strength Results for Granite and Limestone

Aggregate	Mix Type	Indirect Tensile Strength		TSR, %
		Unsaturated, psi	Saturated, psi	
Granite	Control	126.6	123.4	0.97*
Granite	Zeolite	155.0	126.3	0.81*
Granite	Sasobit®	59.5	40.6	0.68**
Granite	Zeolite	67.2	40.4	0.60**
Granite	Control	75.9	88.3	1.16
Granite	Zeolite	72.5	48.7	0.67
Granite	Sasobit®	53.2	38.0	0.71
Granite	Evotherm	70.8	67.7	0.96
Limestone	Control	109.5	71.2	0.65
Limestone	Zeolite	86.6	44.2	0.51
Limestone	Sasobit®	53.9	49.1	0.91
Limestone	Evotherm	75.0	46.8	0.62

Note: * Indicates Samples were prepared in SGC following ASTM D 4867

Note: ** Indicates Samples were prepared in SGC following ASTM D 4867 with 250°F compaction temperature

Once this testing was concluded, TSR samples were then produced at a lower compaction temperature (250°F (121°C)) using the bucket mixer, as previously discussed in this report. Initially, testing was performed without the presence of any type of anti-stripping agent. Results from this testing showed that the zeolite lowered the TSR value as compared to the control mixture (Table 8); the resulting TSR value does not satisfy the recommended minimum value for Superpave mixes (minimum of 0.80). The test results also exhibited some variability in the data from one aggregate type to the next. For example, the Sasobit® increased the resistance to moisture for the limestone, but decreased the resistance for the granite, compared to their corresponding control mixes, whereas the Evotherm® did the opposite, increasing the TSR with the granite aggregate and decreasing the TSR with the limestone aggregate compared to the corresponding control. It is believed that the testing precision is decreased when the tensile strength values are low, which is apparent in this case.

Figure 14 presents a sample containing Aspha-min® exhibiting a cohesive failure. It is believed that the binder was somewhat emulsified due to the moisture released from the Aspha-min®, causing the cohesive failure. It is possible that a cure time would dissipate the moisture in the binder, eliminating the potential of a cohesive failure.

In Figure 15, the conditioned control sample exhibited an adhesive failure. But the unconditioned control samples also exhibited visual stripping resulting from adhesive failures. It is expected that the adhesive failure resulted from moisture remaining in the aggregate from the lower mixing and compaction temperature. However, the cohesive failure in the samples containing the Aspha-min® resulted in lower tensile strengths.

Figure 14. Example of Cohesive Stripping Failure – Granite

Figure 15. Example of Adhesive Stripping Failure – Granite

It is believed that the failing TSR values were possibly due to several factors, those being moisture retained in the aggregate, or due to residual moisture left behind by the microscopic foaming process of the zeolite. To evaluate these hypotheses, additional TSR tests were conducted with the granite aggregate as shown in Table 12. To determine if the lower TSR values were caused by moisture in the aggregate, TSR testing was conducted using oven dry aggregate. The aggregate was placed in a 250°F (121°C) oven prior to mixing to make sure there was no internal moisture present. Test results from the oven dry aggregate also resulted in failing TSR values; therefore the decrease in tensile strength is not believed to be solely due to internal aggregate moisture.

To determine if the moisture resistance could be increased, anti-stripping agents were then evaluated. First, one type of liquid anti-stripping agent, ARMAZ LOF 6500, was used with the control and zeolite mixtures. This additive is routinely used with the granite aggregate source. For the control mixture, the liquid anti-strip visually reduced the adhesive failure, increased the unsaturated tensile strengths while the saturated tensile strengths remained the same as the control mixture without liquid anti-strip. For the mixture with zeolite, the liquid anti-strip increased the unsaturated tensile strengths, but it decreased the saturated tensile strengths, thus resulting in a low TSR value (0.38). The decrease in the saturated tensile strength may possibly be due to a reduction in binder viscosity from the liquid anti-stripping agent.

Table 12. Additional Tensile Strength Results for Granite Aggregate

Anti-Stripping Additive	Mix Type	Indirect Tensile Strength		TSR
		Unsaturated, psi	Saturated, psi	
0.75% LOF 6500	Control	104.7	90.5	0.86
0.75% LOF 6500	Zeolite	96.0	36.2	0.38
1% Lime	Zeolite	110.6	85.5	0.77
1.5% Lime	Zeolite; Two-stage addition	79.9	69.3	0.87
1.5% Lime	Zeolite; All Added Dry	90.2	67.3	0.75
0.4% Magnabond	Sasobit	17.5	16.5	0.94

Hydrated lime was then evaluated. Hydrated lime was used in two different percentages (1 and 1.5 percent), while for the 1.5 percent added hydrated lime, it was evaluated in two methods – all added dry and in a two stage addition (0.5 percent added to wet aggregate and the remaining percent added to the dry aggregate). For the addition of just the one percent hydrated lime, it was added to the dry aggregate. From the results in Table 12, the hydrated lime increased the TSR value to just below the minimum requirement for Superpave mixes.

As was mentioned before, the use of 1.5 percent hydrated lime was evaluated in two methods. First, 0.5 percent was added to the wet aggregate. This was performed to try and improve the adhesive failure exhibited in the previous trials. The remaining percent was added to the dry aggregate to possibly solve the cohesive failure seen in the previous trial as well. From the test results, this added amount of hydrated lime produced an acceptable TSR value. But the split addition process may possibly add unnecessary cost, so the 1.5 percent hydrated lime was evaluated again, but added all at once to the dry aggregate. Results indicated a decrease in TSR value to an unacceptable value.

Regarding the Sasobit®, Sasol recommended adding a liquid anti-stripping agent that has been commonly used in commercial paving applications. Kling Beta 2912 is manufactured by AKZO Nobel and is more commonly known as Magnabond. Additional TSR testing was conducted using Magnabond at a percentage of 0.4 by weight of binder. These test results are also included in Table 12. The results indicated a substantial increase in the TSR value, compared to the test results from the PG 64-22 binder with only Sasobit® added. The additional TSR testing using the liquid anti-stripping agent resulted in an acceptable value, based on Superpave requirements. However, the individual tensile strengths (both unsaturated and saturated) were substantially lower than the other strengths obtained.

Mead Westvaco developed an alternate formulation with different adhesion promoters for the limestone aggregate. The TSR tests were repeated using the bucket mixer as described previously using this alternate formulation. The unsaturated strength of the samples produced with the new formulation were 85.6 psi, and the saturated strength was 93.5 psi resulting in a TSR of 1.09. From the results, the resistance to moisture increased by approximately 50 percent compared to the original formulation. The conditioned samples exhibited no visible stripping, neither adhesive nor cohesive.

Hamburg Wheel-Tracking Device

To validate the TSR results, test samples were prepared and tested in the Hamburg wheel-tracking device. This device is used to predict moisture damage of hot mix asphalt. It also has been found to be sensitive to several factors, including asphalt cement stiffness, length of short-term aging, compaction temperature, and anti-stripping treatments (*16*). All these factors have previously been observed as possible problem areas in the evaluation of warm asphalt mixes, so the test results from the Hamburg wheel-tracking device may be vital in accurately establishing a good performing warm asphalt mix.

Test results from the Hamburg wheel-tracking device are presented in Table 13. Also included are the corresponding TSR values for each of the mix types. From these test results, the Hamburg test results varied in relation to the test results from the TSR testing. In some cases, the Hamburg confirmed the data determined from the TSR test (Evotherm), while in other cases the Hamburg data showed a decrease in the moisture resistance of a particular mix. This is mainly true for the mixes containing Sasobit®. The Hamburg test results also confirmed the conclusion that the mixture containing zeolite had a lower resistance to moisture than the control mixture. This is based on the stripping inflection point. When describing the stripping inflection point, it is the number of passes at which the deformation of the sample is the result of moisture damage and not rutting alone. Illustration of the stripping inflection point is shown in Figure 16. It is related to the resistance of the mix to moisture damage. The lower the stripping inflection point is an indication of a decrease in the resistance to moisture for an asphalt mix. Stripping inflection points over 10,000 cycles, in a general sense, represent good mixes.

Table 13. Hamburg Wheel Tracking Device Results

Aggregate	Mix Type	Treatment	Stripping Inflection Point, cycles	Rutting Rate, mm/hr	TSR
Granite	Control	None	6500*	1.841	1.16
Granite	Sasobit®	None	3975	2.961	0.71
Granite	Zeolite	None	3450	5.139	0.67
Granite	Evotherm	None	NA	1.708	0.96
Granite	Zeolite	1.5% Hydrated Lime 2 Stage Addition	8500*	1.912	0.87
Granite	Zeolite	1.5% Hydrated Lime All Added Dry	NA	0.687	0.75
Granite	Sasobit®	0.4% Magnabond	NA	0.164	0.94
Limestone	Control	None	2500	4.284	0.65
Limestone	Zeolite	None	1700	2.835	0.51
Limestone	Sasobit®	None	2900	3.976	0.91
Limestone	Evotherm	None	2550	3.178	0.62

Note: * individual sample did not have a stripping inflection point; reported value is average of 10,000 cycles and recorded stripping inflection point of second sample; NA = No stripping inflection point determined

The rutting rate determined from the Hamburg test results correlated well with the stripping inflection point; that as the inflection point increased, indicating an increase in moisture resistance, the rutting rate decreased. Rutting rate is defined as the slope of the secondary consolidation tangent, as seen in Figure 16. The addition of Sasobit® improved the rutting rate in all cases as compared to the control mixes, except for the granite aggregate using PG 64-22. This corresponds to the findings with the APA. The test results indicated that the addition of liquid anti-stripping agent in combination with Sasobit® produced the lowest rutting rate, which in turn will result in an added benefit of decreased rutting potential of asphalt mixes produced at lower operating temperatures.

The Hamburg results also indicated the split addition of 1.5 percent hydrated lime improved both the stripping inflection point and the rutting rate, when compared to the results with just zeolite added. In terms of rutting rate, this was an improvement of 63 percent. The addition of 1.5 percent dry lime resulted in no occurrence of a stripping inflection point 10,000 cycles and further improvement in the rutting rate.

The results from the Hamburg wheel-tracking device correlated well with the TSR values, validating the earlier claim that the addition of zeolite increased the potential for moisture damage. The Hamburg results for the addition of 1.5 percent dry lime indicate a mixture resistant to moisture susceptibility while the TSR results were marginal. Generally, the Hamburg wheel-tracking test is considered to be the more accurate predictor of moisture damage as compared to the TSR test. Lime will also stiffen the binder (*17*), thus also providing a benefit in the rutting potential of warm mixtures that are compacted at a lower temperature (less than 250°F (121°C)).

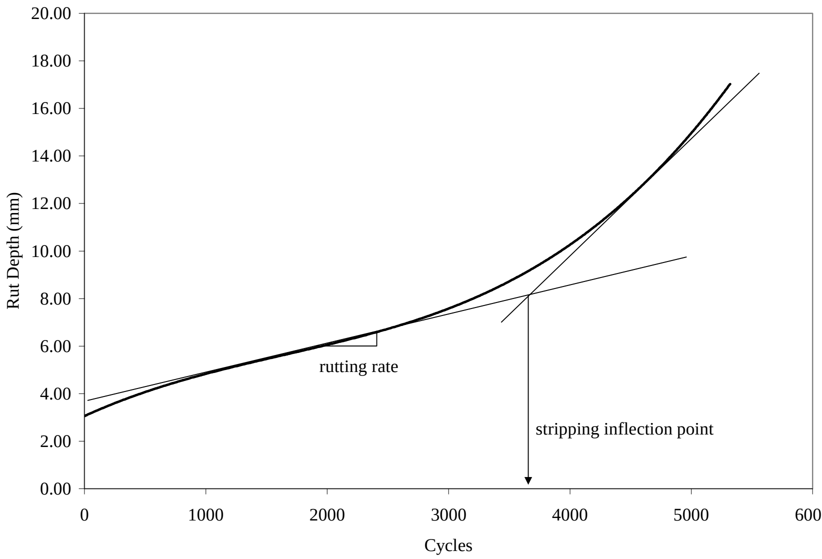

Figure 16. Hamburg Test Results, Defining Rutting Rate and Stripping Inflection Point

Conclusions

Based on the results from the lab testing using all three warm asphalt additives, the following conclusions were made:

- The gyratory compactor was not sensitive to the reduction in compaction temperature. Therefore, all test samples to simulate field compactability were compacted in the vibratory compactor.
- The addition of any warm mix processes lowers the measured air voids in the gyratory compactor. While this may indicate a reduction in the optimum asphalt content, at this time it is believed that additional research is required

and that the optimum asphalt content of the mixture determined without any additives included should be used. It should be noted that the optimum asphalt content of the mixture without the addition of any additive was used for all of the testing completed in this study.

- All processes improved the compactability of the mixtures in both the SGC and vibratory compactor. Statistics indicated an average reduction in air voids up to 0.77 percent for the Aspha-min® zeolite, 0.89 percent for the Sasobit®, and up to 1.53 percent for the Evotherm in the vibratory compactor. Improved compaction was noted at temperatures as low as 190°F (88°C) for all three additives.
- The addition of any warm mix process evaluated in this study does not affect the resilient modulus of an asphalt mix compared to mixtures having the same PG binder. Improved density improves the measured resilient modulus. Therefore, there would not be any effect on pavement thickness design when using warm asphalt mixes.
- The addition of Sasobit®, zeolite, or Evotherm does not increase the rutting potential of an asphalt mix. The rutting potential increased with decreasing mixing and compaction temperatures and this may be related more to the decreased aging of the binder. However, the mixes containing Sasobit® were less sensitive (in terms of rutting) to the decreased production temperatures than the control mixes were.
- The indirect tensile strengths for mixes containing Sasobit® were lower, in some cases, as compared to the control mixes. This reduction in tensile strength is believed to be related to the anti-aging properties of Sasobit® observed in the binder testing. Other laboratory tests (APA and Hamburg) indicated good rutting resistance for the mixes containing Sasobit®.
- There was no evidence of differing strength gain with time for the mixes containing any additives as compared to the control mixes. The addition of Aspha-min® or Evotherm may not require a cure time for the asphalt mixture prior to opening to traffic. Field data from Europe supports the fact that the addition of Sasobit® does not require a cure time for the asphalt mixture prior to opening to traffic, as well.

- The lower compaction temperature used when producing warm asphalt with any such warm mix additive may increase the potential for moisture damage. The lower mixing and compaction temperatures can result in incomplete drying of the aggregate. The resulting water trapped in the coated aggregate may cause moisture damage. Reduced tensile strength and visual stripping were observed in both the control and warm asphalt mixes produced at 250°F (121°C).
- Various anti-stripping agents were evaluated to mitigate the potential for moisture damage. Hydrated lime used with zeolite appeared to be effective with the granite aggregate. The addition of 1.5 percent hydrated lime resulted in improved cohesion and moisture resistance over the warm mixtures without hydrated lime. The addition of AKZO Nobel Magnabond (Kling Beta 2912) improved the TSR values to acceptable levels for the Sasobit®. An alternate Evotherm formulation provided good moisture resistance for the limestone aggregate.
- Hamburg wheel-tracking tests indicated good performance in terms of moisture susceptibility and rutting for the mixtures containing Sasobit® and Magnabond. Hamburg results also suggested the lime will also assist in the rutting resistance of warm mixtures with Aspha-min® compacted at lower temperatures due to the lime stiffening the asphalt binder.

Recommendations

Based on the research conducted to date, the following is recommended when using any warm mix additive to reduce hot mix asphalt production temperatures:

- The modified binder including Sasobit® needs to be engineered to meet the desired Performance Grade. As an example in this study, a PG 58-28 was used as the base asphalt with the addition of 2.5 percent Sasobit® to produce a PG 64-22.

- The optimum asphalt content should be determined without the addition of any warm mix additive. Additional samples should then be produced so the field target density can be adjusted (e.g. If the laboratory air void content with any additive included was decreased in the lab by 0.5 percent, then the field target density should be increased by 0.5 percent).
- Based on the compaction and rutting results, a minimum field mixing temperature of 275°F (135°C) and a minimum field compaction temperature of 250°F (121°C) is recommended If the mixing temperature is below 275°F (135°C), then the high temperature grade should be bumped by one grade. Performance testing can be conducted to predict field performance. Field compaction will dictate the true minimum compaction temperature depending on a number of factors.
- Tensile strength ratio testing should be conducted at the anticipated field production temperatures. If test results determined are not favorable, anti-stripping agents should be added to the mix as an anti-stripping agent to increase the tensile strength ratio.
- More research is needed to further evaluate field performance, the selection of the optimum asphalt content, and the selection of binder grades for lower production temperatures.

Acknowledgements

The authors would like to thank Hubbard Construction Company, MeadWestvaco Asphalt Innovations, Sasol America, NAPA and FHWA for funding this study.

References

1. The Asphalt Pavement Association of Oregon, "Warm Mix Asphalt Shows Promise for Cost Reduction, Environmental Benefit"; Centerline, The Asphalt Pavement Association of Oregon, Salem, OR; Fall 2003.
2. Stroup-Gardiner, M and C. Lange. *Characterization of Asphalt Odors and Emissions.* Proceedings of the Ninth International Conference on Asphalt Pavements. Copenhagen, Denmark. August 2002.
3. U. S. Department of Transportation Federal Highway Administration. Warm Mix Technologies and Research. www.fhwa.dot.gov/pavement/wma.html. Accessed February 17, 2004.
4. Damm, K-W, J. Abraham, T. Butz, G. Hildebrand and G. Riebeschl. *Asphalt Flow Improvers as ‚Intelligent Fillers' for Hot Asphalts – A New Chapter in Asphalt Technology.* In Journal of Applied Asphalt Binder Technology, April 2002, Pp 36-69.
5. U. S. Department of Transportation Federal Highway Administration. "Warm Mix Technologies and Research". www.fhwa.dot.gov/pavement/wma.html. Accessed February 17, 2004.
6. Zhou, Z., Y. Zhang, J. W. Tierney and I. Wender. *Producing Fuels from Fischer-Tropsch Waxes.* In Petroleum Technology Quarterly, Winter 2004.
7. Butz, T., I. Rahimian, and G. Hildebrand. *Modifications of Road Bitumens with The Fischer-Tropsch Paraffin Sasobit®.* In Journal of Applied Asphalt Binder Technology, October 2001. Pp 70-86.
8. Brits, C. H. *Sasobit Investigation*. Report No. 100035/S9/2004/11/05/CHB/av/1, Geostrada Engineering Materials Laboratory, South Africa, 2004.
9. Sasol Wax. "Roads and Trials with Sasobit®" http://www.sasolwax.com/data/sasolwax_/Bitumen%20Modification/Roads%20and%20trials%20e.pdf Accessed, May 13, 2005.
10. Bahia, H. U., and D. I. Hanson. "A Project NCHRP 9-10 Superpave Protocols for Modified Asphalt Binders," Draft Topical Report (Task 9), Prepared for National

Cooperative Highway Research Program, Transportation Research Board, National Research Council, May 2000.

11. Huner, M. H. and E. R. Brown, "Effects of Re-Heating and Compaction Temperature on Hot Mix Asphalt Volumetrics." NCAT Report No. 01-04, National Center for Asphalt Technology, Auburn, AL, 2001.
12. Lottman, R. P., "Predicting Moisture-Induced Damage to Asphaltic Concrete," National Cooperative Highway Research Program Report 246, Transportation Research Board, National Research Council, Washington, DC, 1982.
13. Huber, G. A., R. L. Peterson, J. A. Scherocman, J. D'Angelo, M. Anderson, and M. S. Buncher. *Determination of Moisture in Hot-Mix Asphalt and Relationship with Tender Mixture Behavior in the Laboratory*. Transportation Research Record 1813 Transportation Research Board, National Academy of Sciences, Washington D. C. 2002. Pp 95-102.
14. Butz, T. "Sasobit®: Characterization of Properties and Effects on Binder and Asphalt", 41st Conference of the Association of Road and Traffic Engineers, Saxonia, Leizig, Germany, 2005.
15. Schumann Sasol. "State Road, Piemont Italy." Product Information, Hamburg, November 2001.
16. Aschenbrener, Tim, *Evaluation of Hamburg Wheel-Tracking Device to Predict Moisture Damage in Hot Mix Asphalt*, Transportation Research Record 1492 Transportation Research Board, National Academy of Sciences, Washington D.C. 1995. Pp 193-201.
17. Little, D. and J. Epps "The Benefits of Hydrated Lime in Hot Mix Asphalt." National Lime Association, 2001.

Appendix

Table A1. Test Results for Granite HMA

Compact. Temp. °F	AVC Air Voids, %	Resilient Modulus, psi	APA Rut Depth, mm
300	7.5	467,171	10.4
300	6.0	294,065	8.1
300	6.3	572,998	9.2
300	5.3	420,863	7.6
300	6.1	215,163	7.0
300	5.7	218,717	4.1
Average	6.2	364,830	7.7
Std Dev.	0.7	145,399	2.2
265	5.9	272,652	13.4
265	5.5	239,237	12.5
265	9.7	289,367	9.0
265	7.1	577,025	12.1
265	7.0	281,952	13.4
265	6.6	366,632	10.9
Average	7.0	337,811	11.9
Std Dev.	1.5	124,486	1.7
230	4.3	315,579	18.9
230	5.8	310,433	10.8
230	5.5	426,761	18.1
230	5.4	349,150	15.9
230	4.9	485,897	19.5
230	5.5	276,334	11.6
Average	5.2	360,692	15.8
Std Dev.	0.5	79,815	3.8

Table A2. Test Results for Granite WMA with Zeolite

Compact. Temp. °F	AVC Air Voids, %	Resilient Modulus, psi	APA Rut Depth, mm
300	5.0	687,767	10.1
300	5.6	682,167	11.7
300	5.8	487,386	13.8
300	5.2	433,168	15.5
300	4.7	529,635	10.4
300	4.4	477,301	5.9
Average	5.1	549,571	11.2
Std Dev.	0.5	109,286	3.3
265	5.7	509,675	10.6
265	5.2	272,691	15.1
265	5.7	543,764	14.3
265	6.2	280,185	12.9
265	7.1	290,417	22.0
265	7.2	254,065	15.8
Average	6.2	358,466	15.1
Std Dev.	0.8	131,313	3.9
230	6.8	401,439	12.8
230	6.5	169,512	9.8
230	6.2	320,211	14.1
230	5.0	596,461	8.9
230	5.9	300,014	13.9
230	5.6	458,273	17.8
Average	6.0	374,318	12.9
Std Dev.	0.6	146,646	3.2

Table A3. Test Results for Granite WMA with Sasobit

Compact. Temp. °F	AVC Air Voids, %	Resilient Modulus, psi	APA Rut Depth, mm
300	5.3	256,341	6.7
300	5.3	345,309	2.2
300	5.4	216,508	7.1
300	4.9	296,066	5.4
300	4.2	408,657	2.8
300	5.3	291,797	4.5
Average	5.1	302,446	4.8
Std Dev.	0.5	67,503	2.0
265	5.2	294,986	4.4
265	6.0	220,596	10.2
265	6.0	199,955	10.0
265	5.5	459,184	10.4
265	5.0	376,923	6.2
265	4.9	232,128	5.0
Average	5.4	297,295	7.7
Std Dev.	0.5	102,136	2.8
230	5.2	245,023	11.5
230	6.0	400,953	11.4
230	5.8	230,897	6.0
230	5.6	196,361	8.4
230	6.0	288,890	8.6
230	5.5	270,607	10.3
Average	5.7	272,122	9.4
Std Dev.	0.3	70,788	2.1

Table A4. Test Results for Granite WMA with Evotherm

Compact. Temp. °F	AVC Air Voids, %	Resilient Modulus, psi	APA Rut Depth, mm
300	4.0	494,925	6.4
300	4.1	255,852	7.0
300	4.1	325,132	8.4
300	3.2	398,841	6.7
300	4.1	422,122	8.6
300	4.1	471,223	7.7
Average	3.9	394,683	7.5
Std Dev.	0.4	90,320	0.9
265	5.0	396,105	6.4
265	5.8	721,394	7.0
265	5.1	302,279	4.8
265	5.1	252,856	8.6
265	5.6	264,369	8.3
265	5.5	502,908	9.3
Average	5.4	406,652	7.4
Std Dev.	0.3	180,682	1.7
230	5.7	305,878	10.1
230	6.9	256,110	12.3
230	5.3	286,165	14.7
230	4.5	364,771	10.1
230	4.5	360,688	16.6
230	4.5	230,165	13.6
Average	5.2	300,630	12.9
Std Dev.	1.0	54,599	2.6

Table A5. Test Results for Limestone HMA

Compact. Temp. °F	AVC Air Voids, %	Resilient Modulus, psi	APA Rut Depth, mm
300	8.0	298,143	5.4
300	7.1	327,752	7.8
300	6.6	497,695	7.8
300	7.7	295,254	6.8
300	8.2	396,668	10.4
300	8.4	420,900	5.9
Average	7.7	372,735	7.3
Std Dev.	0.7	80,123	1.8
265	7.3	337,083	5.7
265	7.5	435,035	4.1
265	7.4	287,729	6.3
265	7.3	337,065	10.1
265	7.5	338,496	10.6
265	7.2	303,359	5.7
Average	7.4	339,795	7.1
Std Dev.	0.1	51,236	2.6
230	7.7	398,798	7.6
230	7.3	222,463	5.0
230	7.7	302,232	9.9
230	7.5	316,623	8.7
230	7.1	454,714	16.1
230	7.4	390,027	14.4
Average	7.5	347,476	10.3
Std Dev.	0.2	83,153	4.2

Table A6. Test Results for Limestone WMA with Zeolite

Compact. Temp. °F	AVC Air Voids, %	Resilient Modulus, psi	APA Rut Depth, mm
300	6.1	478,491	4.4
300	6.5	350,333	3.9
300	5.7	475,634	8.3
300	5.7	666,245	7.4
300	5.2	322,710	2.9
300	5.3	604,166	2.1
Average	5.8	482,930	4.8
Std Dev.	0.5	135,372	2.5
265	7.2	418,459	6.7
265	5.9	309,849	5.7
265	6.9	329,377	4.5
265	6.3	315,048	9.8
265	6.0	378,661	7.3
265	6.3	324,986	12.5
Average	6.4	346,063	7.7
Std Dev.	0.5	43,127	2.9
230	6.1	434,645	10.9
230	6.3	282,399	13.0
230	5.9	278,984	7.8
230	6.6	378,760	5.2
230	6.3	205,147	9.6
230	6.4	206,560	7.4
Average	6.3	297,749	9.0
Std Dev.	0.2	92,500	2.8

Table A7. Test Results for Limestone WMA with Sasobit

Compact. Temp. °F	AVC Air Voids, %	Resilient Modulus, psi	APA Rut Depth, mm
300	5.4	337,358	8.4
300	5.5	297,320	14.7
300	5.6	471,217	4.8
300	5.3	255,892	7.9
300	5.4	181,684	9.0
300	5.1	209,677	15.9
Average	5.4	292,191	10.1
Std Dev.	0.2	104,360	4.3
265	6.2	636,016	8.4
265	5.5	446,225	6.9
265	6.4	253,693	5.8
265	5.7	332,667	3.1
265	5.3	542,245	8.0
265	6.4	434,460	7.1
Average	5.9	440,884	6.5
Std Dev.	0.5	137,965	1.9
230	7.1	298,667	5.2
230	5.9	333,557	7.2
230	6.7	444,113	8.1
230	6.6	600,905	8.3
230	6.5	330,688	5.5
230	6.0	317,233	8.5
Average	6.5	387,527	7.1
Std Dev.	0.5	116,373	1.5

Table A8. Test Results for Limestone WMA with Evotherm

Compact. Temp. °F	AVC Air Voids, %	Resilient Modulus, psi	APA Rut Depth, mm
300	4.8	347,682	2.4
300	4.8	563,202	5.1
300	4.7	271,011	3.2
300	4.5	537,561	4.3
300	4.2	375,629	4.3
300	4.3	337,883	5.1
Average	4.6	405,495	4.1
Std Dev.	0.3	117,647	1.1
265	5.7	310,068	9.0
265	5.2	279,233	6.9
265	5.4	410,908	4.4
265	5.3	538,571	4.6
265	5.4	430,599	6.7
265	5.7	336,251	8.2
Average	5.5	384,272	6.6
Std Dev.	0.2	95,404	1.9
230	6.5	435,817	14.0
230	6.0	453,508	12.2
230	6.4	716,368	6.1
230	6.0	379,249	11.3
230	5.9	352,414	11.5
230	6.6	424,074	6.9
Average	6.2	460,238	10.3
Std Dev.	0.3	130,948	3.1

Table A9. Indirect Tensile Strength (psi) as a Function of Aging Time

Granite	2 Hours	4 Hours	2 Hours + 1 Day	2 Hours + 3 Days	2 Hours + 5 Days
Control	102.6	121.5	67.4	98.6	94.3
Zeolite	116.4	118.2	72.2	103.0	87.0
Sasobit	47.5	59.8	65.3	54.7	91.0
Evotherm	104.4	136.3	60.5	102.6	130.5
Limestone	2 Hours	4 Hours	2 Hours + 1 Day	2 Hours + 3 Days	2 Hours + 5 Days
Control	132.1	110.5	83.2	82.9	74.9
Zeolite	115.6	111.5	77.6	89.7	80.5
Sasobit	113.8	111.7	37.7	57.3	100.4
Evotherm	76.9	105.1	72.2	71.4	91.0