NCAT Report 05-06

EVALUATION OF SASOBIT® FOR USE IN WARM MIX ASPHALT

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Sasol Wax Americas, Inc.

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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. One of these processes utilizes Sasobit®, a synthetic long chain Fischer-Tropsch wax. Sasobit® can be blended with the binder at a terminal or in the contractor's tank, introduced in a molten form, added with the aggregate, or pneumatically blown into a drum plant. A laboratory study was conducted to determine the applicability of Sasobit® 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. Superpave gyratory compactor (SGC) results indicated that Sasobit® may lower the optimum asphalt content, so it should be added during the mix design process.

Sasobit® was 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). The addition of Sasobit® does not affect the resilient modulus of an asphalt mix nor does it 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 as well as from the anti-aging properties of Sasobit. There was no evidence of differing strength gain with time for the mixes containing Sasobit® 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 with Sasobit® or any such similar Warm Mix additive may increase the potential for moisture damage. Overall, Sasobit® appears to be a viable tool 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, widen the winter paving window, and facilitate specialized applications, such as airport runway construction, where rapid opening to traffic is essential.

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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 20 percent. North American asphalt mixes are generally heated to 300°F (149°C) or greater, depending mainly on the type 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 (*3*). 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 delays associated with 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 to be tender when placed.

A number of warm asphalt processes have been identified. This report presents an evaluation of one such additive in particular, branded Sasobit®, which is a product of Sasol Wax. It is a fine crystalline, long-chain aliphatic polymethylene hydrocarbon produced from coal gasification 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_2) under catalytic conditions producing a mixture of hydrocarbons having molecular chain lengths of carbon $(C)_5$ to C_{100} plus carbon atoms. The process begins with the generation of synthesis gas 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 C_{45} to C_{100} plus. (*4-6*). By comparison, macrocrystalline bituminous paraffin waxes have carbon chain lengths ranging from C_{25} to C_{50} (*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 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 the added stability (*4,7*). Sasol has developed a technology of co-modification of Sasobit® plus SBS polymers combined with proprietary cross-linking agent as well as technology for transportable Super Concentrates that enhances the high temperature performance grade (PG) while minimizing the affect on the low temperature PG (*8*). The addition of Sasobit® should be engineered to account for affects to the high and low temperature PG.

The ability of Sasobit® to be combined with polymers to achieve target specifications of polymer modified asphalts while still possessing the advantages of warm asphalt mixes has led to the creation of Sasoflex, which is a compound of a plastomer (Sasobit®) with an elastomer (i.e. SBS), made possible through a proprietary chemical cross-linking agent. The plastomer component reduces the viscosity of the mix at the working/paving temperatures and stiffens the binder at the in-service pavement temperatures, while the elastomer component maintains the flexibility at lower temperatures (*8*).

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. Both Sasobit® and Sasoflex can be blended into hot binder at the blending plant without the need for high shear mixing. Figure 1 shows two of the forms in which Sasobit® is available, flakes for molten additions or prills (small pellets) for direct addition to the mix. In commercial applications in Europe, South Africa, and Asia, Sasobit® has been added directly onto the aggregate mix as solid prills or as molten liquid via a dosing meter. Marshall tests performed on mixes produced in this manner indicated no difference in stability or flow as compared to premixing with the binder (*9*). In the United States, Sasobit® has been blended with the binder at the terminal and blown directly into the mixing chamber at the same point cellulose fibers were being added to an SMA (Figure 2). Commercial supplies of Sasobit® are available in 25 kg bags and 600 kg super-sacks (*5*).

Since 1997, over 142 projects were paved using Sasobit® totaling more than 2,716,254 square yards (2,271,499 square meters) of pavement (*10*). Projects were constructed in Austria, Belgium, China, Czech Republic, Denmark, France, Germany, Hungary, Italy, Macau, Malaysia, Netherlands, New Zealand, Norway, Russia, Slovenia, 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.

Figure 1. Sasobit® Flakes (Left) and Prills (Right).

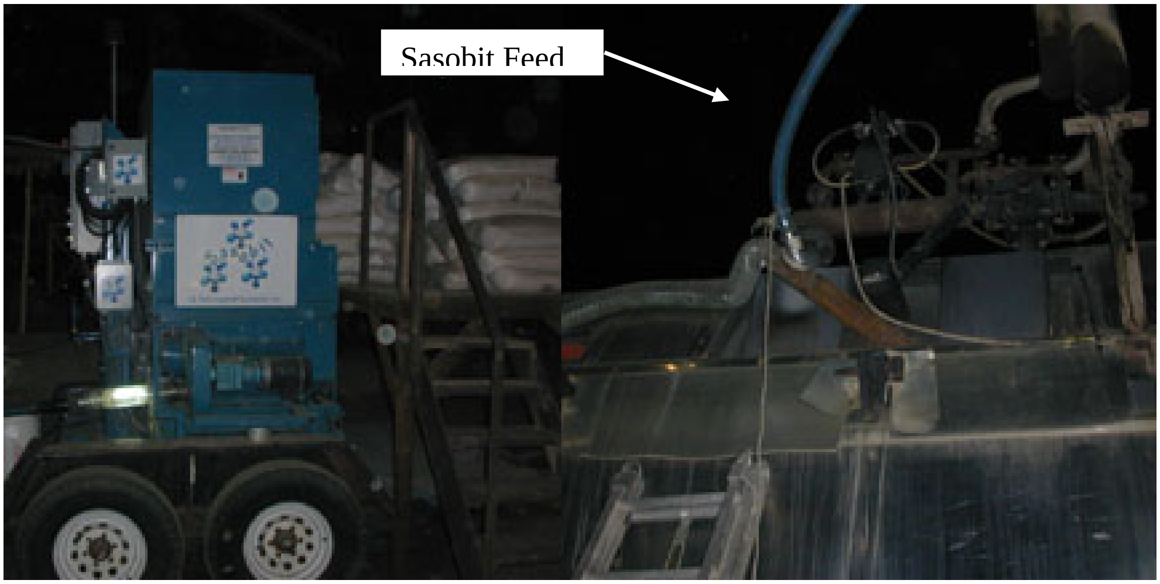

Figure 2. Sasobit® Pneumatic Feed to Mixing Chamber.

OBJECTIVE

The objective of this study was to perform a laboratory study to determine the applicability of Sasobit® in warm mix asphalt applications including 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.

RESEARCH APPROACH

Table 1 shows the experimental design for the laboratory evaluation of Sasobit®. The following sections describe the individual tests that are included in the experimental design.

TABLE 1 Experimental Design for Evaluating the Influence of the Sasobit® on Mixture Volumetrics and Performance

	Number of Samples to be Tested									
	Granite					Limestone				
	PG 64-22		PG 70-22	PG 76-22		PG 64-22		PG 70-22	PG 76-22	
	Control	Sasobit®	Sasoflex	Control	Sasoflex	Control	Sasobit®	Sasoflex	Control	Sasoflex
Mix Design	9	9	9	9	9	9	9	9	9	9
Volumetrics	8	8	8	8	8	8	8	8	8	8
Densification	24	24	24	24	24	24	24	24	24	24
Resilient Modulus	24	24	24	24	24	24	24	24	24	24
APA Rutting	24	24	24	24	24	24	24	24	24	24
Moisture Sensitivity	6	6	6	6	6	6	6	6	6	6
Strength Change with Time	10	10				10	10			

Mix Design

Two aggregate types (granite and limestone) and two asphalt binder grades (PG 64-22 and PG 58-28) were used to evaluate the Sasobit®. From these two binder grades, three different versions of Sasobit® modified binders were developed. The first type was produced by adding 2.5 percent Sasobit® to the PG 58-28 binder to produce a PG 64-22 binder. A second type was produced by adding 4 percent Sasoflex to the PG 58-28, resulting in a PG 70-22. The third binder type was produced from the addition of 4 percent Sasoflex® to the base PG 64-22, resulting in a PG 76-22 binder. The PG 76-22 Sasoflex® modified binder is an example of the Sasol co-modification technology to enhance high temperature PG without downgrading low temperature PG. This third binder was evaluated against a control PG 76-22 binder for this study. 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 N_{design} = 125 gyrations. For the limestone aggregate, the mix design was re-verified using the same design gyration level to determine a new 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 36 mix design combinations (three binder grades, control and Sasobit®/Sasoflex each at four temperatures) are presented in Tables 3 and 4. The data for both aggregates with PG 64-22 and Sasobit® compacted at 190°F (88°C) were not obtained due to lack of material. 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

Asphalt	Sasol Type	Temperature, F	AC, %	G_{mm}	% G_{mm} @ N_i	G_{mb}	Air Voids, %	VMA	VFA
PG 64-22	Control	300	5.1	2.467	88.0	2.365	4.1	13.6	69.6
PG 64-22	Control	265	5.1	2.467	88.2	2.371	3.9	13.3	71.0
PG 64-22	Control	230	5.1	2.467	87.7	2.360	4.4	13.8	68.4
PG 64-22	Control	190	5.1	2.467	87.5	2.356	4.5	13.9	67.6
PG 64-22	Sasobit	300	5.1	2.461	88.4	2.375	3.5	13.9	74.8
PG 64-22	Sasobit	265	5.1	2.461	88.0	2.377	3.4	13.8	75.5
PG 64-22	Sasobit	230	5.1	2.461	88.0	2.360	4.1	14.4	71.7
PG 64-22	Sasobit	190	5.1	2.461	NA	NA	NA	NA	NA
PG 70-22	Sasoflex	300	5.1	2.458	88.8	2.378	3.2	13.8	76.5
PG 70-22	Sasoflex	265	5.1	2.458	88.7	2.374	3.4	14.0	75.4
PG 70-22	Sasoflex	230	5.1	2.458	87.7	2.356	4.2	14.6	71.6
PG 70-22	Sasoflex	190	5.1	2.458	87.1	2.349	4.5	14.6	72.6
PG 76-22	Control	300	5.1	2.457	88.0	2.369	4.0	14.1	71.5
PG 76-22	Control	265	5.1	2.457	88.5	2.355	4.5	14.6	69.1
PG 76-22	Control	230	5.1	2.457	86.7	2.334	5.4	15.4	64.8
PG 76-22	Sasoflex	300	5.1	2.458	88.1	2.365	3.8	14.3	73.6
PG 76-22	Sasoflex	265	5.1	2.458	88.5	2.371	3.5	14.0	74.9
PG 76-22	Sasoflex	230	5.1	2.458	87.6	2.343	4.7	15.1	68.9

TABLE 4 Volumetric Mix Design Data for Limestone Aggregate

Asphalt	Sasol Type	Temperature, F	AC, %	G_{mm}	% G_{mm} @ N_i	G_{mb}	Air Voids, %	VMA	VFA
PG 64-22	Control	300	4.8	2.544	85.4	2.433	4.4	15.0	70.8
PG 64-22	Control	265	4.8	2.544	85.1	2.430	4.5	15.1	70.3
PG 64-22	Control	230	4.8	2.544	85.3	2.435	4.3	14.9	71.3
PG 64-22	Control	190	4.8	2.544	85.5	2.439	4.1	14.8	72.1
PG 64-22	Sasobit	300	4.8	2.545	86.1	2.459	3.4	14.1	76.1
PG 64-22	Sasobit	265	4.8	2.545	86.3	2.463	3.2	14.0	76.7
PG 64-22	Sasobit	230	4.8	2.545	86.3	2.465	3.1	13.9	77.4
PG 64-22	Sasobit	190	4.8	2.545	NA	NA	NA	NA	NA
PG 70-22	Sasoflex	300	4.8	2.538	86.5	2.465	2.9	13.9	79.3
PG 70-22	Sasoflex	265	4.8	2.538	86.2	2.450	3.5	14.4	76.0
PG 70-22	Sasoflex	230	4.8	2.538	86.2	2.444	3.7	14.6	74.6
PG 70-22	Sasoflex	190	4.8	2.538	84.9	2.421	4.6	15.4	70.2
PG 76-22	Control	300	4.8	2.546	85.8	2.444	4.0	14.1	76.1
PG 76-22	Control	265	4.8	2.546	85.8	2.442	4.0	14.7	72.4
PG 76-22	Control	230	4.8	2.546	86.5	2.426	4.7	15.2	69.2
PG 76-22	Sasoflex	300	4.8	2.543	86.4	2.459	3.3	14.1	76.6
PG 76-22	Sasoflex	265	4.8	2.543	86.3	2.453	3.6	14.3	75.2
PG 76-22	Sasoflex	230	4.8	2.543	85.8	2.441	4.0	14.7	72.8

Observations from Tables 3 and 4 indicate that the addition of Sasobit® 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 (*11*, *12*). In Tables 3 and 4 there are very slight trends of increasing air voids with decreasing temperature for some of the combinations. The addition of Sasobit resulted in lower air voids than the corresponding control mixture in all 18 aggregate, binder, and temperature combinations. Consequently, the addition of Sasobit® or Sasoflex appears to reduce the design asphalt content. 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. Similar reductions were noted in previous research (*4*). Beyond the effects of improved compaction, the addition of Sasobit® is not expected to impact the calculation of volumetric properties.

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). Only the PG 64-22 and PG 70-22 mixes (both control and warm mixes) were evaluated at 190°F (88°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. Test samples were compacted using a vibratory compactor, as seen in Figure 3. 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.

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 level of 7 percent in preliminary testing using the PG 64-22 control mixture with the granite aggregate. Once the air void level 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.

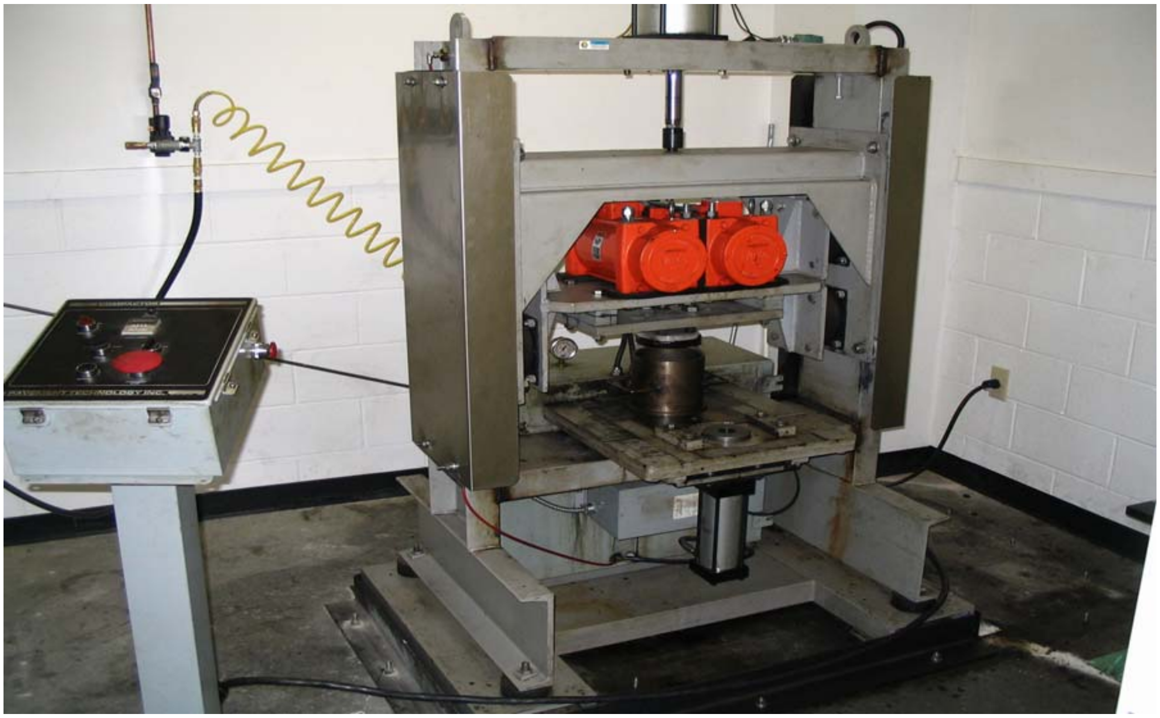

Figure 3. Vibratory Compactor used for Compaction of Test Samples.

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 (*13*). 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) to minimize variables in the data. 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 operating temperatures from the Sasobit®. If the Sasobit® improves 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 PG 64-22 binder and 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 5.

TABLE 5 Strength Gain Experiment Aging Periods

Set	Short Term Aging (hours) at 230°F (110 °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 left in close contact with the aggregate surface, which could 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 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) (*14*). The bucket mixer used can be seen in Figure 4. 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. The addition of 3 percent water above the absorption value was selected as typical of stockpile moisture contents. 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 moved 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 4) and then it was heated to 250°F (121°C) (Figure 5). 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 4-6.

Figure 4. Introduction of Moisture to Aggregate for TSR Samples.

Figure 5. Heating of Wet Aggregate to Mixing Temperature.

Figure 6. Hot Mix Asphalt in Bucket Mixer.

TEST RESULTS AND DISCUSSION

Binder Tests

Binder testing was conducted according to AASHTO MP1. The binder test results for both the control and Sasobit® modified binders are shown in Table 6. Sasobit® is reported to reduce the aging effect of the binder. As a reminder, the PG 64-22 with Sasobit® and the PG 70-22 with Sasoflex both contained the PG 58-28 as their base binder. The relative change between the original and RTFO DSR test results is an indication of the aging the binder undergoes during the construction process. From the data in Table 6, the PG 64-22 with Sasobit® and the PG 70-22 with Sasoflex both exhibited reduced aging when compared to their base binder. The RTFO DSR result for the PG 58-28 base binder was 174 percent of the original DSR value, compared to 121 percent for the PG 64-22 with Sasobit® and 69 percent for the PG 70-22 with Sasoflex. This indicates the reduced aging of the binder with the addition of Sasobit®.

Figure 7 shows a plot of viscosity versus temperature for the PG 64-22 modified with Sasobit® compared to the PG 64-22 control. Figure 7 demonstrates how Sasobit® can reduce viscosity in the mixing and compaction temperature range while producing approximately the same (or in some cases greater) viscosity at in-service pavement temperatures. The compaction temperature for the Sasobit® modified PG 64-22 is approximately 32°F (18°C) less than the compaction temperature for the PG 64-22 control.

TABLE 6 Binder Test Results

Test	PG 58-28 (Base)	PG 64-22 (Control and Base)	PG 64-22 (Sasobit®)	PG 70-22 (Sasoflex)	PG 76-22	PG 76-22 (Sasoflex)
Modifier	None	None	2.5% Sasobit®	4% Sasoflex	None	4% Sasoflex
Test Temp., °C	58	64	64	70	76	76
Original DSR, G*/sin δ, kPa	1.015	1.815	1.790	2.689	1.290	1.461
RTFO DSR, G*/sin δ, kPa	2.781	3.868	3.950	4.548	3.096	2.682
Test Temp., °C	19	25	25	28	31	31
PAV DSR. G*sinδ, kPa	4138	3554	2906	2448	1059	2635
Test Temp., °C	-18	-12	-12	-12	-12	-12
BBR Creep Stiffness (S), MPa	248	208	164	153	165	251
BBR m-value	0.316	0.317	0.306	0.328	0.315	0.292[1]

[1]Does not meet the minimum requirements of AASHTO M320 (m-value > 0.300)

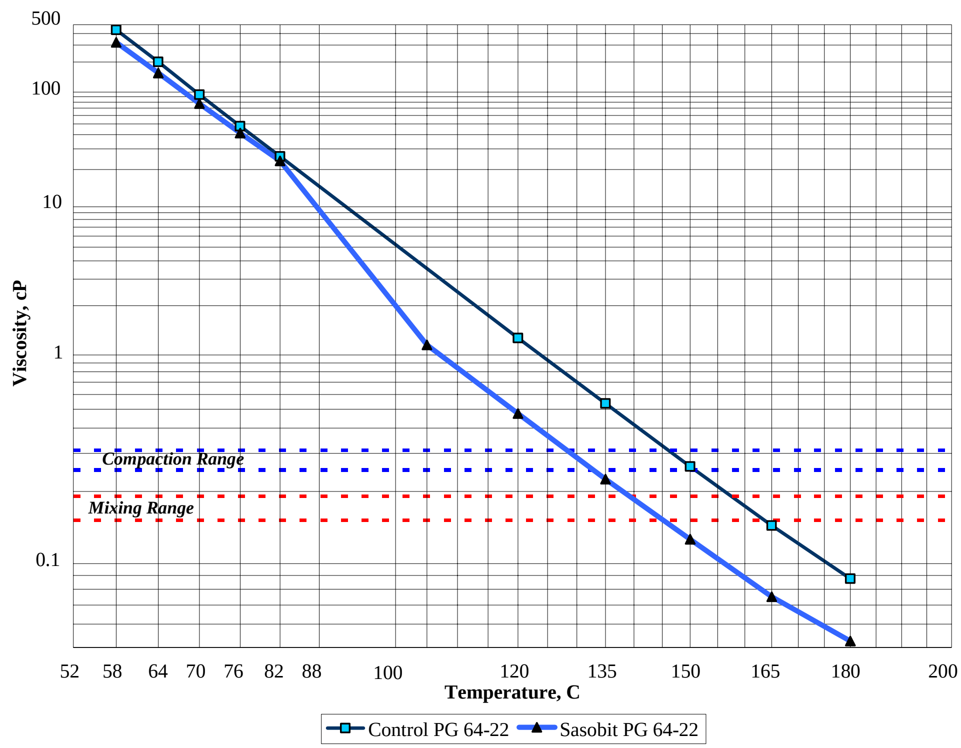

Figure 7. Mixing and Compaction Temperature for PG 64-22 Binders.

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 8 and 9. From observation of the results in Figures 8 and 9, the addition of Sasobit® improves compaction over the control mixture for all binder, aggregate, and temperature combinations except for four cases. This is most likely to be due to the inclusion of the SBS, which may have stiffened the binder enough to increase the air void levels. The improved compaction is more pronounced with the PG 64-22, possibly because there is no SBS to counter the viscosity reducing effect of Sasobit® and has a higher recommended compaction temperature. Observation of Figure 8 also shows that the air void content 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.

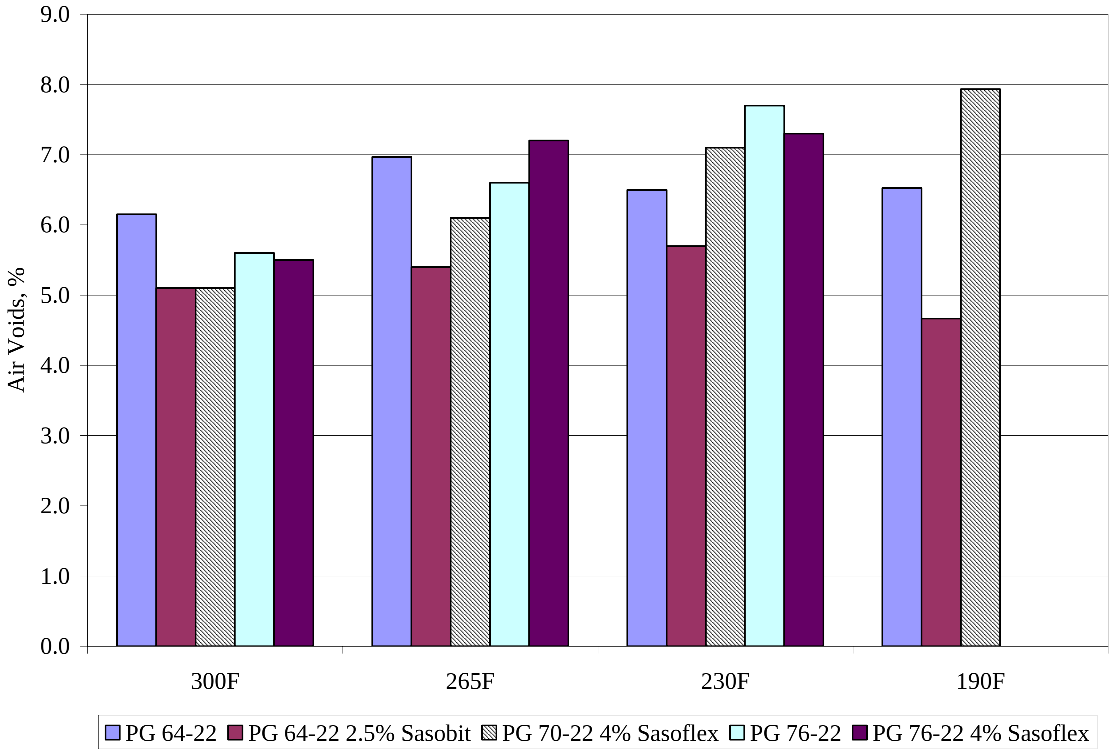

Figure 8. Densification Results over Range of Compaction Temperatures – Granite Mix.

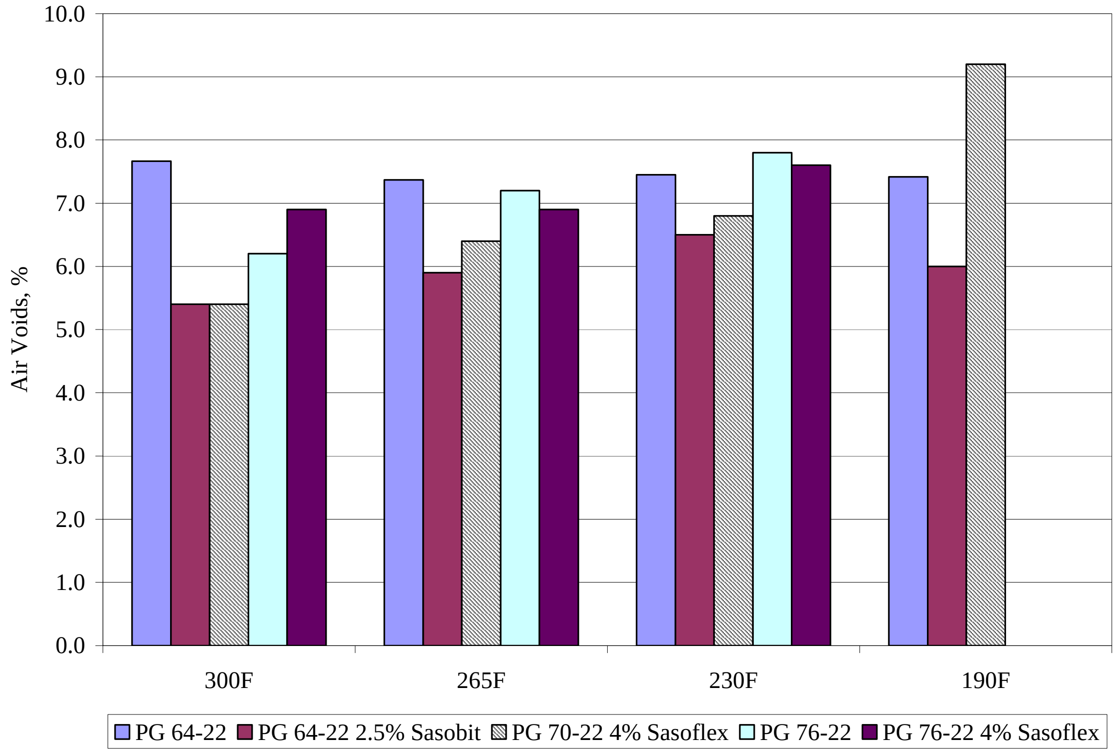

Figure 9. Densification Results over Range of Compaction Temperatures – Limestone Mix.

Analysis of Variance (ANOVA) was used to analyze the densification data with air voids as the response variable and aggregate type, binder grade, presence of Sasobit®, and compaction temperature as factors. Binder grade was evaluated separately to determine if it was a significant factor. From the results, binder grade was not a significant factor in the densification of the different asphalt mixes. With respect to the influence of binder aging on densification, it is significant that values for Sasobit® are lower than the control over all combinations in the experimental design.

Tables 7 through 9 present the analysis results separated into the three different binder grades. Of the main factors for the PG 64-22, the effect of aggregate type, presence of Sasobit®, and compaction temperature were all significant, as well as all of the interactions except for the two-way interaction between aggregate type and Sasobit®. Aggregate type was the most significant factor followed by whether or not Sasobit® was included. A Tukey's post ANOVA test performed on the densification results showed that Sasobit® reduced the air void content by an average of 0.87 percent with a 95 percent confidence interval of 0.49 to 1.25 percent. For the PG 70-22, all factors and interactions except for the presence of Sasobit® and the two-way interaction between compaction temperature and aggregate type were significant, with the aggregate type being the most significant. By adding Sasobit® to the PG 70-22 binder, the average air void content was reduced by 0.11 percent with a 95 percent confidence interval of -0.51 to 0.28 percent as compared to the PG 64-22 control. This indicates that a grade stiffer binder (PG 70-22) modified with Sasoflex was more compactable than the PG 64-22 control. From Table 9, only compaction temperature and aggregate type were significant for the PG 76-22 binder type; compaction temperature was the most significant factor. PG 76-22 with Sasoflex reduced the air void level by an average of 0.07 percent with a 95 percent confidence interval of -0.26 to 0.41 percent

TABLE 7 Analysis of Variance Densification Results for PG 64-22 Binder

Source	DF	Adj. MS	F-stat	p-value	Significant*
Temp	3	3.0869	9.56	0.000	Yes
Additive	1	18.2004	56.38	0.000	Yes
Agg	1	46.4817	144.00	0.000	Yes
Temp*Additive	3	4.1962	13.00	0.000	Yes
Temp*Agg	3	5.7469	17.80	0.000	Yes
Additive*Agg	1	0.2604	0.81	0.372	No
Temp*Additive*Agg	3	7.3874	22.89	0.000	Yes
Error	80	0.3228			
Total	95				

Note: * indicates significant at the 95 percent confidence interval.

TABLE 8 Analysis of Variance Densification Results for PG 70-22 Sasoflex Modified Binder compared to PG 64-22 Control

Source	DF	Adj. MS	F-stat	p-value	Significant*
Temp	3	11.2598	27.25	0.000	Yes
Additive	1	0.3151	0.76	0.385	No
Agg	1	16.0884	38.93	0.000	Yes
Temp*Additive	3	13.2409	32.04	0.000	Yes
Temp*Agg	3	0.6576	1.59	0.198	No
Additive*Agg	1	5.2734	12.76	0.001	Yes
Temp*Additive*Agg	3	2.1648	5.24	0.002	Yes
Error	80	0.4132			
Total	95				

Note: * indicates significant at the 95 percent confidence interval.

TABLE 9 Analysis of Variance Densification Results for PG 76-22 Binder

Source	DF	Adj. MS	F-stat	p-value	Significant*
Temp	3	14.7039	32.04	0.000	Yes
Additive	1	0.0939	0.20	0.653	No
Agg	1	3.38	7.36	0.009	Yes
Temp*Additive	3	0.5839	1.27	0.288	No
Temp*Agg	3	1.4517	3.16	0.049	No
Additive*Agg	1	0.0022	0.00	0.945	No
Temp*Additive*Agg	3	1.0972	2.39	0.100	No
Error	60	0.4589			
Total	71				

Note: * indicates significant at the 95 percent confidence interval.

Resilient Modulus

An Analysis of Variance (ANOVA) was performed to determine which factors (aggregate type, Sasobit®, and compaction temperature) significantly affect the measured resilient modulus. Binder type was evaluated separately, and was determined not to be a significant factor in determining resilient modulus. The results for the binder types are presented in Tables 10 through 12. Based on the results, only the interaction between aggregate type and the presence of Sasoflex was a significant factor in the determination of resilient modulus. It can also be noted that the addition of Sasobit® to the asphalt did not significantly affect the resilient modulus. So the addition of Sasobit® does not significantly increase or decrease the stiffness of hot mix asphalt for any compaction temperature.

TABLE 10 ANOVA Results for Resilient Modulus – PG 64-22

Source	DF	Adj. MS	F-stat	p-value	Significant*
Temp	3	4.44E+09	0.45	0.718	No
Additive	1	5.48E+08	0.06	0.814	No
Agg	1	7.73E+9	0.78	0.379	No
Temp*Additive	3	1.73E+10	1.75	0.163	No
Temp*Agg	3	1.84E+10	1.87	0.142	No
Additive*Agg	1	2.62E+10	2.65	0.108	No
Temp*Additive*Agg	3	9.82E+9	0.99	0.400	No
Error	80	9.88E+09			
Total	95				

Note: * indicates significant at the 95 percent confidence interval.

TABLE 11 ANOVA Results for Resilient Modulus – PG 70-22

Source	DF	Adj. MS	F-stat	p-value	Significant*
Temp	3	1.80E+10	1.71	0.171	No
Additive	1	4.92E+09	0.47	0.496	No
Agg	1	4.02E+10	3.83	0.054	No
Temp*Additive	3	7.65E+08	0.07	0.974	No
Temp*Agg	3	1.58E+10	1.50	0.220	No
Additive*Agg	1	7.52E+10	7.17	0.009	Yes
Temp*Additive*Agg	3	8.00E+09	0.76	0.518	No
Error	80	1.05E+10			
Total	95				

Note: * indicates significant at the 95 percent confidence interval.

TABLE 12 ANOVA Results for Resilient Modulus – PG 76-22

Source	DF	Adj. MS	F-stat	p-value	Significant*
Temp	3	4.03E+10	5.02	0.010	Yes
Additive	1	1.93E+10	2.39	0.127	No
Agg	1	3.45E+09	0.43	0.515	No
Temp*Additive	3	1.04E+10	1.29	0.283	No
Temp*Agg	3	1.95E+10	2.43	0.097	No
Additive*Agg	1	7.14E+10	8.88	0.004	Yes
Temp*Additive*Agg	3	1.45E+09	0.18	0.836	No
Error	60	8.04E+09			
Total	71				

Note: * indicates significant at the 95 percent confidence interval.

Interaction plots for resilient modulus are shown in Figure 10. From these plots, several conclusions can be made. First, the limestone aggregate consistently produced the highest resilient modulus values. Comparing the different mixes, there was little difference in the resilient modulus, but the PG 76-22 with Sasoflex resulted in the highest values. Second, the resilient modulus decreased as the compaction temperature decreased. The effect of temperature is more pronounced with the PG 76-22 binders. It is believed that this is related to the decreased aging of the binder (lower asphalt stiffness) with decreasing compaction temperatures.

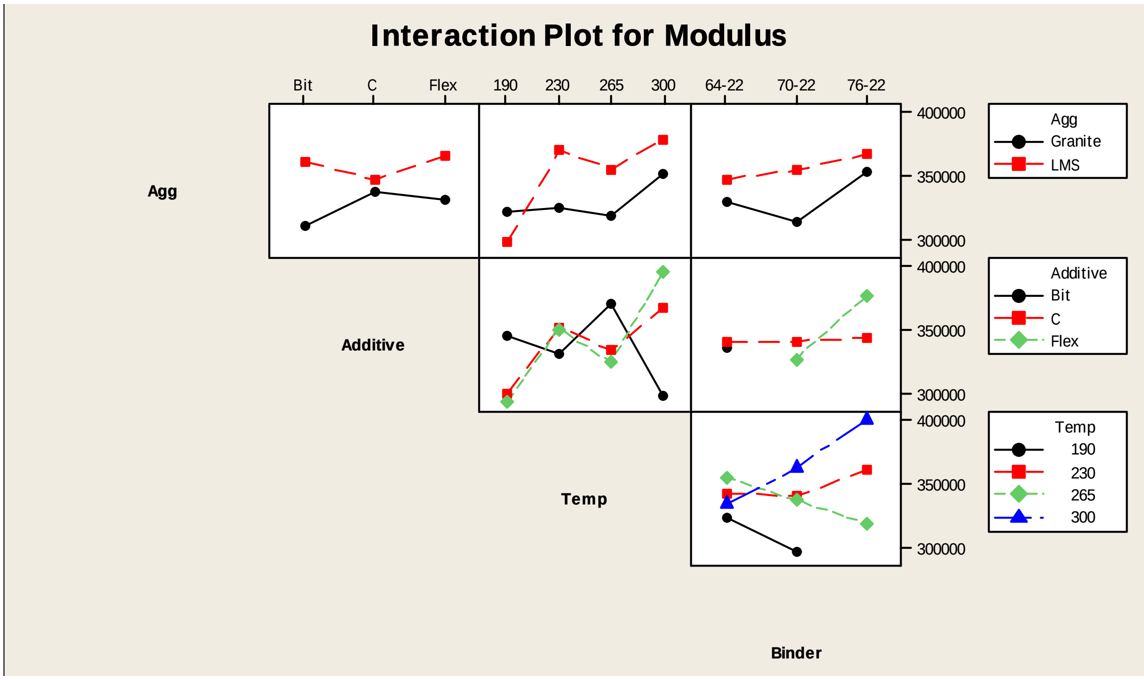

Figure 10. Interaction Plots for Resilient Modulus.

Further analysis was conducted to determine if there was a statistical difference in the resilient modulus values at the different compaction temperatures. This was accomplished by use of Tukey's Method. From the results, there was no statistical difference in the compaction temperature for the PG 64-22 binder; for the PG 70-22 binder, there was a statistical difference in the compaction temperature between 265°F (129°C) and 230°F (110°C). There was no significant difference in the compaction temperature for resilient modulus values for the PG 76-22 binder type.

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 11 and 12. The whisker marks in both figures indicate the standard deviation for each set of rut samples.

An ANOVA was performed to determine which factors (aggregate type, binder type, Sasobit®, and compaction temperature) significantly affect the measured rut depth. As with the densification and resilient modulus data, binder type was evaluated separately and was found to be a significant factor in determining rut depth. Each of the six samples tested in the APA was treated as a replicate. Results from the ANOVA tests are presented in Tables 13 through 14 for the PG 64-22 and PG 76-22 binders. ANOVA results are not presented for the PG 70-22 modified with Sasoflex since there was no PG 70-22 control. As expected, the PG 70-22 modified with Sasoflex performed better than the PG 64-22 control. The results show that all

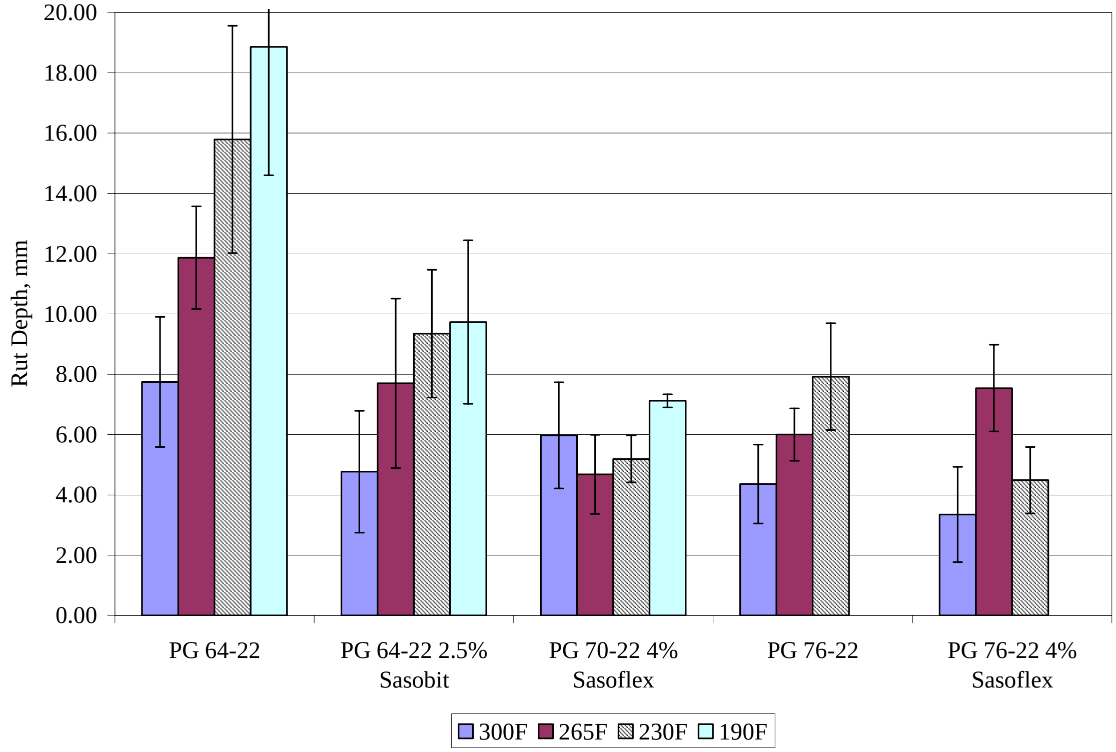

Figure 11. APA Rut Depths for the Granite Aggregate.

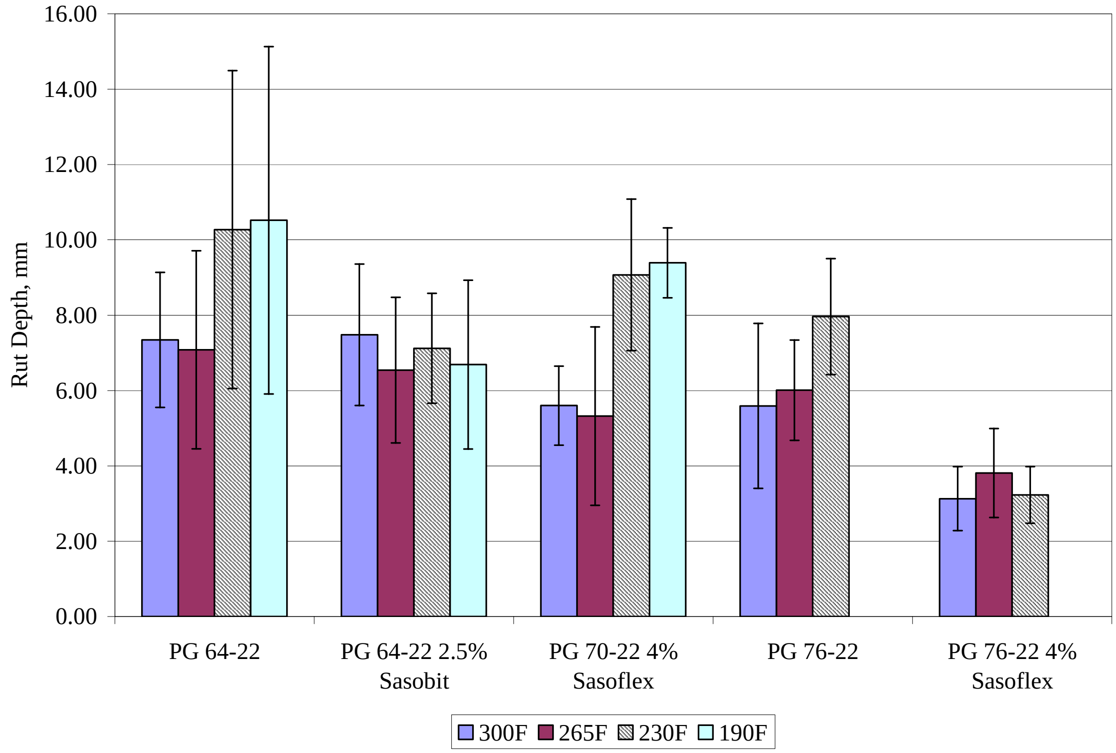

Figure 12. APA Rut Depths for the Limestone Aggregate.

TABLE 13 ANOVA Results for Rut Depth – PG 64-22

Source	DF	Adj. MS	F-stat	p-value	Significant*
Temp	3	108.772	12.47	0.000	Yes
Additive	1	230.392	26.42	0.000	Yes
Agg	1	114.101	13.09	0.001	Yes
Temp*Additive	3	32.894	3.77	0.014	Yes
Temp*Agg	3	59.380	6.81	0.000	Yes
Additive*Agg	1	159.650	18.31	0.000	Yes
Temp*Additive*Agg	3	7.109	0.82	0.489	No
Error	80	8.720			
Total	95				

Note: * indicates significant at the 95 percent confidence interval.

TABLE 14 ANOVA Results for Rut Depth – PG 76-22

Source	DF	Adj. MS	F-stat	p-value	Significant*
Temp	3	24.925	13.02	0.000	Yes
Additive	1	75.707	39.55	0.000	Yes
Agg	1	7.729	4.04	0.049	Yes
Temp*Additive	3	21.59	11.28	0.000	Yes
Temp*Agg	3	8.34	4.36	0.017	Yes
Additive*Agg	1	21.028	10.99	0.002	Yes
Temp*Additive*Agg	3	2.775	1.45	0.243	No
Error	60	1.914			
Total	71				

Note: * indicates significant at the 95 percent confidence interval.

factors and interactions were significant except for the three way interaction between compaction temperature, Sasobit®, and aggregate type for the PG 64-22 and the PG 76-22. The addition of Sasobit®/Sasoflex did have a significant effect on the measured rut depth for both the PG 64-22 and the PG 76-22 binders.This means that the use of Sasobit® and/or Sasoflex would significantly decrease the rutting potential of an asphalt mixture.

Interaction plots for rut depth are illustrated in Figure 13. The interaction plots graphically show how the factors affect the rutting potential. From observation of the interaction plots, several conclusions can be made. First, the limestone rutted less than the granite. Second, the addition of Sasobit®/Sasoflex decreased the rutting potential over the control mixes, particularly at the lower compaction temperatures. Third, the stiffer binders (PG 70-22 and PG 76-22) rutted less than the softer binder (PG 64-22). And fourth, the rut depths increased as the compaction temperature decreased for all factor level combinations. The effect of temperature on rut depth is larger for the control (PG 64-22 and PG 76-22) samples. This may be due to the anti-aging characteristics of Sasobit®.

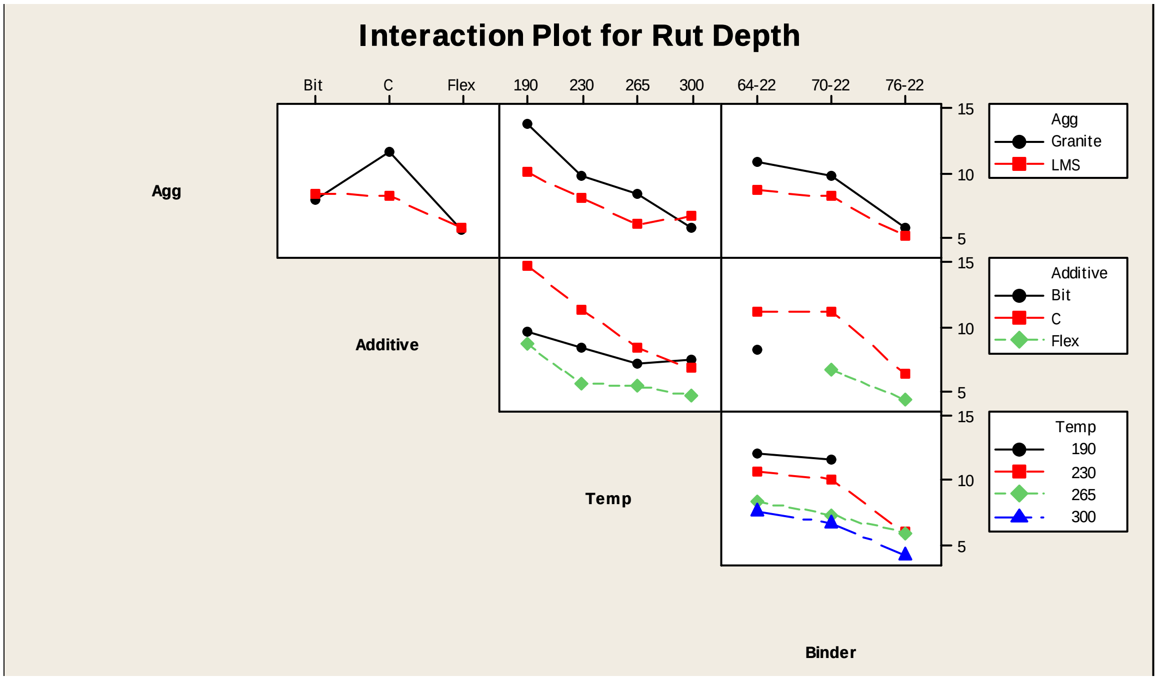

Figure 13. Interaction Plots for Rut Depth.

Further data analysis was performed to determine if there is a significant difference in the rut depths at the four compaction temperatures. This was accomplished by using the Tukey's method. From the results, it was determined that samples at 300°F (149°C) had the least rutting. Rut depths at 265°F (129°C) and 230°F (110°C) were not statistically different from one another for the PG 64-22 and PG 70-22 binder, but were statistically different for the PG 76-22 binder. These rut depths were also all greater than the rut depths at 300°F (149°C). The samples compacted at 190°F (88°C) had the highest rut depths. This difference in rut depths is not believed to be due to air voids. Instead it is believed to be related to the decreased aging of the binder at the lower compaction temperatures. The high temperature binder grade may need to be bumped for mixing temperatures less than 265°F (129°C) to counteract the tendency for increased rutting with decreasing production temperatures.

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 14 and 15. The results indicated that the strength varied both over the different age times and between the control mix and warm mix at a particular age time. The data for the Sasobit® sample generally indicated a 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 indicated no difference in tensile strength between the control and warm mixes *(15)*. Also, based on the rutting data discussed earlier, there is no evidence to support the

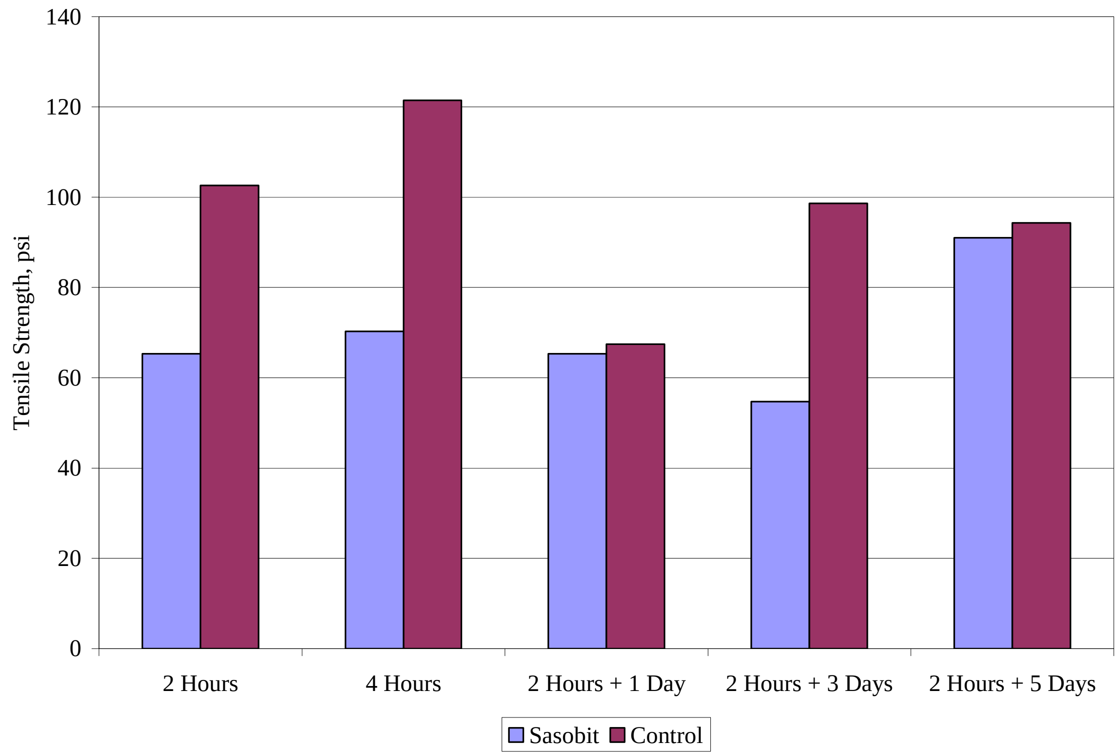

Figure 14. Strength Gain Results – Granite Aggregate.

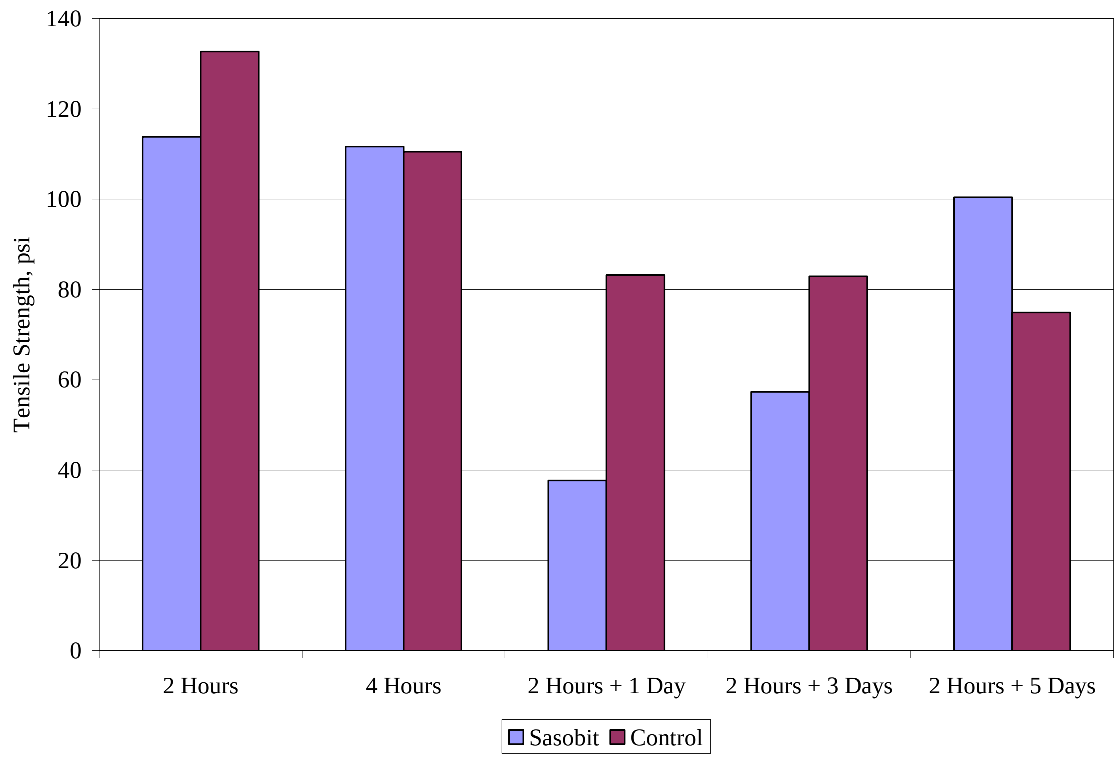

Figure 15. Strength Gain Results – Limestone Aggregate.

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 (*16*). Sasobit® was also used in the repaving of Frankfurt airport. Twenty-four inches of HMA were placed in a 7.5 hour window. The runway was then reopened to jet aircraft at a temperature of 185 °F (85°C).

Moisture Sensitivity

As was mentioned before, ASTM D 4867 was used to determine the moisture sensitivity test results. The results for both aggregates are shown in Table 15. The test results exhibited some variability in the data from one aggregate type to the next. For example, the PG 76-22 Sasoflex increased the resistance to moisture for the granite, but decreased the resistance for the limestone. Observation of the results also concluded that the addition of Sasobit®/Sasoflex both increased and decreased the moisture susceptibility, depending on the type binder and aggregate, compared to their corresponding control mixture.

Observing the test results individually, only four out of the ten mixes had TSR values that met Superpave criteria. Superpave suggests a TSR value of at least 80 percent. It is believed that the testing precision is decreased when the tensile strength values are low, which is apparent in this case.

After the initial test plan was concluded regarding moisture sensitivity, 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 15. The results indicated a substantial increase in the TSR value, compared to the test results from the PG 64-22 binder

TABLE 15 Tensile Strength Results for Granite and Limestone Aggregates

Aggregate	Mix Type	Unsaturated, psi	Saturated, psi	TSR, %
Granite	PG 64-22 Control	89.8	68.2	0.76
Granite	PG 64-22 Sasobit®	53.2	38.0	0.71
Granite	PG 70-22 Sasoflex	106.2	50.4	0.47
Granite	PG 76-22 Control	137.3	68.4	0.50
Granite	PG 76-22 Sasoflex	99.1	79.2	0.80
Granite	PG 64-22 Sasobit® with 0.4% Magnabond	17.5	16.5	0.94
Limestone	PG 64-22 Control	109.5	71.2	0.65
Limestone	PG 64-22 Sasobit	53.9	49.1	0.91
Limestone	PG 70-22 Sasoflex	118.6	62.4	0.53
Limestone	PG 76-22 Control	97.3	84.7	0.87
Limestone	PG 76-22 Sasoflex	145.3	80.9	0.56

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.

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 (*17*). 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 form the Hamburg wheel-tracking device are presented in Table 16. 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, while in other cases the Hamburg data showed an improvement in the moisture resistance of a particular mix. This is mainly true for the mixes containing Sasoflex. 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. Stripping inflection points over 10,000 cycles, in a general sense, represent good mixes. The lower the stripping inflection point is an indication of a decrease in the resistance to moisture for an asphalt mix.

Table 16 Hamburg Wheel-Tracking Device Results

Aggregate	Mix Type	Binder	Treatment	Stripping Inflection Point, cycles	Rutting Rate, mm/hr	Unsaturated Tensile Strength, psi	Saturated Tensile Strength, psi	TSR
Granite	Control	PG 64-22	None	6500*	1.841	75.9	88.3	1.16
Granite	Sasobit®	PG 64-22	None	3975	2.961	53.2	38.0	0.71
Granite	Sasoflex	PG 70-22	None	NA	0.314	106.2	50.4	0.47
Granite	Control	PG 76-22	None	NA	0.708	137.3	68.4	0.50
Granite	Sasoflex	PG 76-22	None	9250*	0.310	99.1	79.2	0.80
Granite	Sasobit®	PG 64-22	0.4% Magnabond	NA	0.164	17.5	16.5	0.94
Limestone	Control	PG 64-22	None	2500	4.284	109.5	71.2	0.65
Limestone	Sasobit®	PG 64-22	None	2900	3.976	53.9	49.1	0.91
Limestone	Sasoflex	PG 70-22	None	8750*	0.905	118.6	62.4	0.53
Limestone	Control	PG 76-22	None	5750	1.535	97.3	84.7	0.87
Limestone	Sasoflex	PG 76-22	None	NA	0.857	145.3	80.9	0.56

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® or Sasoflex 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.

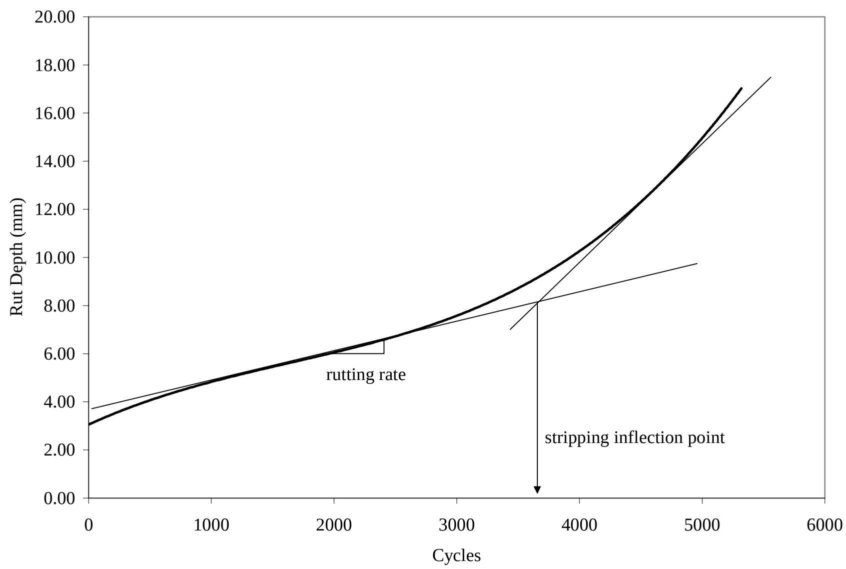

Figure 16. Hamburg Test Results, Defining Rutting Rate and Stripping Inflection Point.

CONCLUSIONS

Based on the results from the lab testing using Sasobit®, the following conclusions were made:

- The addition of Sasobit® 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 the Sasobit® should be used. It should be noted that the optimum asphalt content of the mixture without the addition of the Sasobit® was used for all of the testing (with and without Sasobit®) completed in this study. Reducing the optimum asphalt content may negate the improved compaction resulting from the addition of Sasobit®.

- Sasobit® improved the compactability of the mixtures in both the SGC and vibratory compactor. Statistics indicated an average reduction in air voids up to 0.87 percent. Improved compaction was noted at temperatures as low as 190°F (88°C) for the mixes produced with Sasobit® and 230°F (110°C) for the mixtures containing Sasoflex.

- The addition of Sasobit® does not affect the resilient modulus of an asphalt mix compared to mixtures having the same PG binder.

- The addition of Sasobit® generally decreased the rutting potential of the asphalt mixes evaluated. 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®. 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.

- 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. Both tensile strength ratio and Hamburg tests were conducted to assess moisture susceptibility. Reduced tensile strength and visual stripping were observed in both the control and Sasobit® mixes produced at 250°F (121°C). However, the addition of AKZO Nobel Magnabond (Kling Beta 2912) improved the TSR values to acceptable levels. Hamburg wheel-tracking tests indicated good performance in terms of moisture susceptibility and rutting for the mixtures containing Sasobit® and Magnabond as well as the mixtures containing Sasoflex.

RECOMMENDATIONS

Based on the research conducted to date, the following are recommended when using Sasobit® or Sasoflex to reduce hot mix asphalt production temperatures:

- The modified binder including Sasobit® or Sasoflex 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 with a neat binder having the same grade as the Sasobit® modified binder. Additional samples should then be produced with the Sasobit® modified binder so the field target density can be adjusted (e.g. If the air void content with the Sasobit® included was decreased in the lab by 0.5 percent, then the field target air voids should be decreased by 0.5 percent).

- Based on the compaction and rutting results, a minimum mixing temperature of 265°F (129°C) and a minimum compaction temperature of 230°F (110°C) is recommended. If the mixing temperature is below 265°F (129°C), then the high temperature grade should be bumped by one grade to counteract the tendency for increased rutting susceptibility with decreasing production temperatures. Performance testing can be conducted to predict field performance. Field compaction will dictate the true minimum compaction temperature depending on a number of factors.

- Moisture sensitivity testing should be conducted at the anticipated field production temperatures. If test results determined are not favorable, an anti-striping agent should be added to the mix to increase the resistance to moisture. AKZO Nobel Magnabond was effective in this study and other work conducted by Sasol Wax Americas.

- 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.

AKNOWLEDGEMENTS

The authors thank Dr. Mary Stroup-Gardiner for her assistance in the development of the experimental design for this project. The authors also thank Sasol Wax, Americas for sponsoring this study.

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