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Evaluation of Warm Mix Asphalt for Alaska Conditions

Final Report

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In line with a field demonstration project of WMA using Sasobit conducted in Southeast Alaska, this study focused on experimentally assessing the engineering properties of Sasobit modified WMA binders and mixes. Performance tests of binders were conducted according to Superpave specification to assess the correlation between the content of additives, and Superpave performance grade (PG) and stiffness of modified binders. Tests conducted to assess the performance of WMA included 1) permanent deformation (rutting) susceptibility, 2) low temperature cracking performance including tensile strength and tensile creep compliance properties, 3) moisture susceptibility, and 4) dynamic modulus |E*|.

Laboratory investigation of Sasobit-modified binders and WMAs in this study identified a lot of engineering benefits of WMAs using Sasobit over traditional HMA. WMAs using Sasobit with reduced mixing and compaction temperatures, improved workability and rutting resistance, and insignificant effect on moisture susceptibility favorably indicated the suitability of this WMA technology for Alaska conditions. The indirect tension test (IDT) results showed degraded resistance to low temperature cracking of WMA using Sasobit in this study. However, additional tests at lower temperatures, along with a more complete thermal cracking analysis for specific environments of interest should be performed to get a more definitive answer regarding the effects of Sasobit on low temperature cracking.

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Author's Disclaimer

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
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EXECUTIVE SUMMARY

Warm Mix Asphalt (WMA) technologies, recently developed in Europe, are gaining strong interest in the U. S. Field practices. Studies showed that WMA can reduce the high mixing temperatures of regular hot mix asphalt (HMA), increase the temperature gap between production and cessation (allowing increased haul distances), and decrease the binder viscosity allowing effective compaction, which is beneficial for stiff mixes, paving during extreme weather conditions and reduction in compaction effort. However, previous research has not focused much on how WMA functions in cold weather paving and the performance of the WMA in cold regions.

In line with a field demonstration project of WMA using Sasobit conducted in Southeast Alaska, this study focused on experimentally assess the engineering properties of Sasobit modified WMA binders and mixes. In this study, PG 58-28 binder (consistent with that in the field project) was selected to be modified with Sasobit in four different contents, i.e. 0%, 0.8%, 1.5%, and 3.0%, respectively. Performance tests of binders were conducted according to Superpave specification to assess the correlation between the content of additives, and Superpave performance grade (PG) and stiffness of modified binders. Tests conducted to assess the performance of WMA included 1) permanent deformation (rutting) susceptibility by asphalt pavement analyzer (APA) and flow number F_N by simple performance tester (SPT), 2) low temperature cracking performance including tensile strength and tensile creep compliance properties by indirect tension test (IDT), 3) moisture susceptibility by moisture induced sensitivity tests (MIST), and 4) dynamic modulus |E*| by SPT. Performance tests for field-mixed lab-compacted mixes/field-cored samples were also evaluated in the laboratory to compare with the results of lab-mixed lab-compacted mixes.

Results showed that the addition of Sasobit reduced both mixing and compaction temperatures of mixes. Compared with control binder without Sasobit addition, the addition of 3% Sasobit contributed to a decrease of more than 15ºC in mixing temperature and a decrease of 13ºC in the compaction temperature. The Sasobit addition also significantly impacted the PG of binders. With the increase of Sasobit content from 0% to 3%, the high temperature end of asphalt PG increased from 58 to 76, however, the low temperature end also increased from -28ºC to -16ºC as well.

The SPT results showed that |E*| values of lab-mixed lab-compacted mixtures increased with the increase of Sasobit content. The field-mixed lab-compacted mix presented higher |E*| values than the lab-mixed lab-compacted mix with same content of Sasobit (1.5%) and voids in total mix (VTM, 4%). The F_N results were consistent with those of |E*| values. The improved rutting resistance of lab-mixed lab-compacted mixtures with the addition of Sasobit was also found from APA tests, which conformed to |E*| and F_N results. The MIST results exhibited slightly increased TSR values of lab-mixed lab-compacted mixes with the increase of Sasobit content, and the TSR values of field mix and laboratory mix with the same Sasobit content of 1.5% were very close. Within this study, at least the addition of Sasobit did not contribute to moisture damage of WMA compared with the control mix.

In a summary, laboratory investigation of Sasobit-modified binders and WMAs in this study identified a lot of engineering benefits of WMAs using Sasobit over traditional HMA. WMAs using Sasobit with reduced mixing and compaction temperatures, improved workability and rutting resistance, and insignificant effect on moisture susceptibility favorably indicated the suitability of this WMA technology for Alaska conditions. The IDT results showed degraded resistance to low temperature cracking of WMA using Sasobit in this study. However, additional tests at lower temperatures, along with a more complete thermal cracking analysis

for specific environments of interest should be performed to get a more definitive answer regarding the effects of Sasobit on low temperature cracking.

The limited tests of field specimens in this study generally displayed higher variance/ inconsistency in results than those of lab-mixed lab-compacted specimens. Therefore, closer correlation between lab results and field performance data are suggested in the future study. Studies should also include long-term performance and associated life cycle cost analyses.

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CHAPTER I

INTRODUCTION

GENERAL

The asphalt industry and its agency partners are constantly looking for ways to improve pavement performance, increase construction efficiency, conserve resources and advance environmental stewardship (Newcomb 2007). In order to achieve these goals, warm mix asphalt (WMA) technologies, now under evaluation worldwide, tend to reduce the viscosity of asphalt and provide the mixing and compacting temperatures in the range of 20-55°C lower than typical hot mix asphalt (HMA) (D'Angelo et al. 2008). A number of benefits are well recognized as driving the development of WMA, which are mainly addressed as 1) improved environmental aspects and sustainable development particularly due to the reduction of energy consumption and resulting reduction in CO_2 emission, 2) improvement in field compaction due to the reduction of viscosity, thus to extend the paving season and allow the possibility for longer haul distance, and 3) welfare of the asphalt worker due to the reduction of odor emission, etc.

Among various WMA technologies, Sasobit is described as an "asphalt flow improver" due to its ability to lower the viscosity of the asphalt binder (Damm et al. 2002). A number of research and field trials have been conducted on the performance of WMA with Sasobit additive. The general consensus is that WMA with Sasobit additive is expected to provide performance equal to or better than HMA (Hurley and Prowell 2005a, AAT 2005, Diefenderfer et al. 2007, D'Angelo et al. 2008). Although studies have been reported in both laboratory and field studies, there are few studies focused on the performance of WMA with Sasobit in paving projects in such an extreme cold weather condition as in Alaska. A full scale field trial using Sasobit modified binder and mixes was constructed in the summer of 2008 in Southeast Alaska on the Petersburg-Mitkof Highway Upgrade Project, Phase II. In line with this field trial, this study evaluated the performance of both binders and mixtures modified with Sasobit, as presented in this report.

PROBLEM STATEMENT

In cold regions asphalt mixes can be difficult to compact, particularly if the asphalt layers are thin and cool weather is present. Contractors at time struggle to achieve the density standards. Without adequate compaction, pavements are prone to distresses thus reducing pavement life. Field practices and studies including several on-going National Cooperative Highway Research Program (NCHRP) and other state research projects showed that using WMA can reduce the high mixing temperatures of regular HMA, increase the temperature gap between production and cessation (allowing increased haul distances), and decrease the binder viscosity allowing effective compaction, which is beneficial for stiff mixes, paving during extreme weather conditions and reduction in compaction effort.

However, previous research has not focused much on how WMA functions in cold weather paving and the performance of the WMA in cold regions, with respect to the material types and climatic conditions typical of Alaska and other cold regions. In line with the field trial using Sasobit modified WMA conducted in the summer of 2008 at Southeast region of Alaska, research is needed to monitor and evaluate WMA binders and mixes in cold weather conditions. How Sasobit additive affects WMA performance regarding low temperature performance, rutting resistance, and moisture susceptibility is needed to be investigated. A comparison of the performance of field samples and lab mixtures is also necessary to determine the suitability of WMA technology for

Alaska conditions.

OBJECTIVES

The major objectives of this study are 1) to experimentally assess the engineering properties of Sasobit modified WMA binders and mixes, and 2) to facilitate the determination of suitability of the WMA technology for Alaska conditions.

RESEARCH METHODOLOGY

To meet the objectives of this study, the following major tasks were conducted:

- Task 1: Literature review
- Task 2: Experimental design and material collection
- Task 3: Laboratory performance tests for binders
- Task 4: Laboratory performance tests for mixtures
- Task 5: Data processing and analyses
- Task 6: Project summary and recommendations

Task 1: Literature review

A comprehensive literature review of current research efforts and progress in the area of WMA with Sasobit was conducted during the whole process of the project. The purpose of the review was mainly to gather information on key subjects that pertain to this study such as WMA projects in the nation and some projects overseas to determine both positive and negative attributes in using WMA, binder and mixture characterization, and experimental results and field performance. This task is presented in Chapter II.

Task 2: Experimental design and material collection

Based on the literature review in Task 1, a detailed laboratory testing plan was developed to assess the material properties of WMA including binder characterization and mixes performance. Materials used for WMA and control mixes (without the sasobit additive), consistent with those used in the field trial, were collected including Sasobit, local aggregates and neat asphalt binder. Loose mixtures and cores were collected from the field as well. This task is presented in Chapter III.

Task 3: Laboratory performance tests for binders

In this study, PG 58-28 binder was selected to be modified with Sasobit in four different contents, i.e. 0%, 0.8%, 1.5%, and 3.0% by weight of the asphalt binder, respectively. Performance tests of binders were conducted according to Superpave specification in the laboratory in order to 1) assess the constructability of WMAs used in the field, and 2) evaluate the correlation between the content of additives, and Superpave performance grade and stiffness of modified binders. Those tests included: 1) rotational viscosity test for constructability performance, 2) dynamic shear rheometer (DSR) for both rutting and fatigue performance, and 3) bending beam rheometer (BBR) for low temperature performance. Binders at three critical stages were tested, including 1) un-aged original asphalt binders, 2) binders after short term aging by Rolling Thin Film Oven (RTFO), and 3) binders after long term aging by pressure-aging vessel (PAV). Chapter III describes the work on this task.

Task 4: Laboratory performance tests for mixtures

WMA specimens were prepared by mixing local aggregates and PG 58-28 binder modified with four different Sasobit contents (i.e. 0%, 0.8%, 1.5%, and

3.0%, respectively) in the laboratory. Loose mixtures and cores were also collected from the field for laboratory performance tests. The volumetric properties of all mixes were validated to meet the design criteria of voids in total mix (VTM) before tests according to AASHTO test specifications.

Tests conducted to assess the performance of WMA included 1) permanent deformation (rutting) susceptibility by asphalt pavement analyzer (APA) and flow number F_N by simple performance tester (SPT), 2) low temperature cracking performance including tensile strength and tensile creep compliance properties by indirect tension test (IDT), 3) moisture susceptibility by moisture induced sensitivity tests (MIST), and 4) dynamic modulus |E*| by SPT. Performance tests for field-mixed lab-compacted mixes and field-cored samples were also evaluated by IDT, APA, SPT and MIST in the laboratory to compare with the results of lab-mixed lab-compacted mixes. Chapter III provides the report of this task.

Task 5: Data processing and analyses

Both laboratory and field performance data were statistically processed and analyzed. Based on the statistical analyses and interpretation, the significance of using WMA technology was determined. The difference and correlation between the test results of field and laboratory mixes were analyzed as well. The work in this task is included in Chapter IV.

Task 6: Project summary and recommendations

Based upon the above tasks, a summary of research results and findings from this study was provided in this task. Recommendations regarding the feasibility of using WMA for Alaska conditions were made, as well as those for future work, as presented in Chapter V.

CHAPTER II

LITERATURE REVIEW

A comprehensive literature review was conducted to gather information on key subjects that pertain to this study such as WMA projects in the nation and some projects overseas to determine both positive and negative attributes in using WMA, binder and mixture characterization, and experimental results and field performance. The literature findings were summarized and documented in this chapter.

WMA TECHNOLOGIES

Adopted from Europe, WMA technologies entail the use of additives in asphalt binders designed to soften the binder, allowing workability and compactibility at lower temperature (a processing temperature range of 250°F ~ 275°F) than with traditional HMA (a discharge temperature of between 280°F and 320°F) (Figure 2.1).

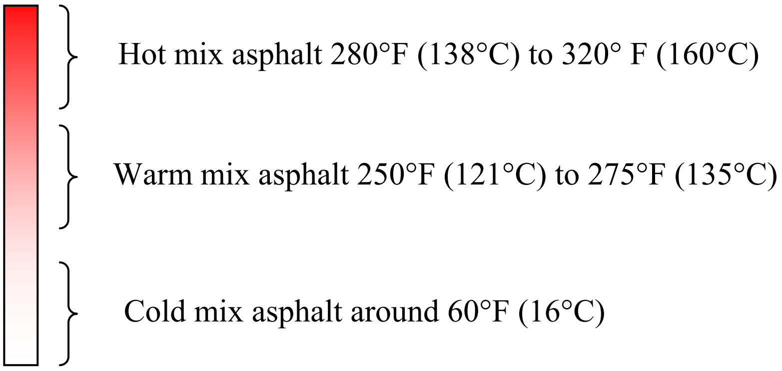


Figure 2.1 Typical mixing temperature range for asphalt mixes (Epps 2007).

At the time of this report, 14 WMA technologies identified by the WMA Technical Working Group (warmmixasphalt.com) have been widely used in the

United States and all over the world (Hurley and Prowell 2005a, Hurley and Prowell 2005b, Hurley and Prowell 2006, Diefenderfer et al. 2007, Prowell et al. 2007, Chowdhury and Button 2008, Tao et al. 2009, Kvasnak et al. 2009, Wielinski et al. 2009, Middleton and Forfylow 2009). These 14 technologies are listed below with the company name given first and followed by the product/technology name:

- Advanced Concepts Engineering Co.: Low Energy Asphalt
- Akzo Nobel: Rediset WMX
- Arkema Group: CECABASE RT
- Eurovia Services, GmbH: Aspha-min
- Astec Industries: Double Barrel Green System
- Gencor Industries: Ultrafoam GX^{TM}
- Maxam Equipment Inc.: Aquablack WMA
- McConnaughay Technologies: Low Emission Asphalt
- MeadWestvaco Asphalt Innovations: Evotherm
- Meeker Equipment Corp. Inc.: Aqua Foam WMA System
- PQ Corporation: Advera WMA
- Sasol Wax North America Corporation: Sasobit
- Stansteel: Accu-Shear Dual Warm-Mix Additive System
- Terex Roadbuilding: WMA System

These WMA technologies generally fall broadly into one of four categories based on the type of additive used (Vaitkus et al. 2009), and Table 2.1 provides a summary of these technologies.

- Water-based additives: foaming bitumen technology where foaming is caused by water (spraying water into hot bitumen or mixing the wet sand into asphalt mix).
- Water-bearing additives: foaming bitumen technology where foaming is

caused by natural or synthetic zeolite injection into asphalt mix during mixing process.

- Organic additives: additives are injected into asphalt mixer together with mineral materials for the reduction of bitumen viscosity.
- Chemical additives: additives are injected into the asphalt binder to make a "wetter" asphalt so as to more readily coat and lubricate aggregate before binder is placed in asphalt mixer.

Table 2.1 Summary of WMA technologies (Perkins 2009)

Technology	Category	Production Temperature (^oF)	Modifications to Plant Required
Aquablack WMA	Water-based	NA*	Yes
Double barrel Green	Water-based	255	Yes
Low Energy Asphalt	Water-based	255/220	Yes
Ultrafoam GX^{TM}	Water-based	NA*	Yes
WAM Foam	Water-based	145	Yes
WMA System	Water-based	NA*	Yes
Advera	Water-bearing	200	Some
Aspha-min	Water-bearing	215	Some
Evotherm	Chemical	195	Minor
Low Emission Asphalt	Chemical	275/215	Yes
Rediset WMX	Chemical	260	Minor
CECABASE RT	Organic	215	Not Known
Sasobit	Organic	235	Minor

*NA: Information not available.

A number of benefits have been identified with the use of WMA and fall into the categories of environmental, product and process improvements, and worker health (Kristjansdottir 2006, Button et al. 2007, D'Angelo et al. 2008, Perkins 2009, Hassan 2009). Benefits in the area of environmental aspects include the reduction of energy consumption and resulting reduction in CO_2 emissions. Burner fuel savings with WMA typically range from 20 to 35%, with 50% being possible for some technologies (D'Angelo et al. 2008, Mallick et al. 2009). Emissions such as CO_2 and dust are reduced when lower temperatures are used in the plant. Reductions of CO_2 can range from 15 ~ 40% and dust can be reduced by 25 ~ 50% (Perkins 2009). Product and process benefits include the ability to pave in cooler temperatures, haul the mix longer distance, compact with less effort, and the ability to incorporate higher percentages of recycled asphalt pavement (Kristjansdottir 2006, D'Angelo et al. 2008, Perkins 2009). Worker health benefits result from an improved worker environment with reduced worker exposure to fumes and aerosols, and temperature during placement and compaction, which may lead to greater productivity and worker retention (D'Angelo et al. 2008, Perkins 2009).

In Alaska asphalt mixes can be difficult to compact, particularly if the asphalt layers are thin and cool weather is present. Without adequate compaction, pavements are prone to distresses, including cracking, pavement raveling and potholing, which accelerate pavement aging leading to a reduced pavement life. The application of WMA technologies appears to have great promise to improve the overall mix workability which should lead to improved compaction, while being able to continue processing at lower air temperatures making the process ideal for cold regions where cooler temperatures are more prevalent. Among these WMA technologies, Sasobit product appears to be the most economic WMA technology for use in South East Alaska. Sasobit has the unique capability to be mixed into the binder at the refinery and can then be placed into sea going containers and barged to South East Alaska to the project site. All other WMA technologies require some type of plant modification, or special handling equipment to incorporate the WMA additive into the plant. To contractors producing and placing the WMA with Sasobit modified binder, there would be no plant modifications required and no change in field operations to produce WMA except that it can be produced at a lower temperature.

WMA USING SASOBIT

Sasobit is a Fischer-Tropsch wax, which is a synthetic aliphatic hydrocarbon wax by heating coal or natural gas with water to 180 to 280 °C (356 to 536 °F) in the presence of a catalyst (D’Angelo et al. 2008). Sasobit has a melting point of more than 98 °C (208 °F), high viscosity at lower temperatures, and low viscosity at higher temperatures. At temperatures below its melting point, Sasobit forms a lattice structure in the bitumen that is a basis for the structural stability of asphalts containing Sasobit. Sasobit can solidify in asphalt binder between 65 and 115ºC (149 and 239ºF) to regular distributed, microscopic small, stick-shape particles, hence resulting in an increase of asphalt binder stiffness. Figure 2.2 shows two forms of Sasobit, flakes and small prills or pellets. 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 (Hurley and Prowell 2005a).

Figure 2.2 Sasobit flakes and prills (Hurley and Prowell 2005a).

In 1997, Sasobit began to be marketed in Europe as an asphalt mixture compaction aid by Sasol Wax International (Sasol Wax 2005). Sasol Wax maintains a list of projects on its web site that utilize Sasobit in asphalt paving. As of October 2005, Sasol Wax listed 235 projects and trials in many countries, including Germany, Denmark, France, the Czech Republic, Hungary, Italy, the Netherlands, New Zealand, Norway, Russia, the United Kingdom, South Africa, Sweden, and Switzerland. A wide range of aggregate types and mix types were included (e.g., dense-graded mixes, stone mastic asphalt, and Gussaphalt) in these projects and trials. Sasobit addition rates ranged from 0.8 to 4 percent by mass of binder (Hurley and Prowell 2005a, Button et al. 2007).

Sasobit-Modified Binders

Sasobit is described as an “asphalt flow improver” to lower the viscosity of the asphalt binder and to reduce the mixing and compaction temperature (Damm et al. 2002, Hurley and Prowell 2005a, Wasiuddin et al. 2007). The study conducted by Hurley and Prowell (2005a) showed the compaction temperature for the Sasobit modified PG 64-22 is approximately 32^{o}F (18^{o}C) less than that for the PG 64-22 control base binder while producing the same viscosity at in-service temperature. For PG 64-22 and PG 70-28 binders evaluated in Wasiuddin et al.’s study (2007), 10-16ºC of reduction in mixing temperature was found for all three percentages of Sasobit (2%, 3% and 4%).

Aging characteristics of warm asphalt binders were investigated through simulating the aging of warm asphalt binders in the laboratory and results indicated that the binders extracted from the WMA had significantly lower aging index (ratio of the viscosity of extracted binders to original binders) compared to those extracted from control HMA (Gandhi and Amirkhanian 2008). The reduced aging of the binder with the addition of Sasobit was also found from Hurley and Prowell’s study (2005a).

The addition of Sasobit can significantly impact the PG and viscosity of the binders. Hurley and Prowell (2005a) reported that a PG 64-22 binder was produced by adding 2.5% Sasobit to the PG 58-28 binder, adding 4% Sasoflex to the PG 58-28 resulted in a PG 70-22, and adding 4% Sasoflex to the PG 64-22 resulted in a PG 76-22 binder. Wasiuddin et al. (2007) found that 3% Sasobit increased the high temperature end of the PG 64-22 binder from PG 64 (actual PG 65) to PG 68, while 4% Sasobit improved the PG 70 (actual PG 75) of PG 70-28 binder to PG 80. In Austerman et al.'s study (2009), the addition of 1.5% Sasobit changed the PG grade of the base binder from a PG 64-28 to a PG 70-22 and addition of 3.0% Sasobit changed the PG to a PG 70-16. The addition of Sasobit reduced the viscosity of the binder, with the largest viscosity reduction occurring with the dosage of 3.0% Sasobit. Reduction in binder viscosity and improvement in binder grading without increasing the viscosity indicates a two-way reductions (both direct and indirect) in production temperatures by Sasobit (Wasiuddin et al. 2007).

Biro et al. (2009) conducted rheological tests (DSR and viscosity) to evaluate the effect of Sasobit additive on properties of the binders. Their study found that Sasobit improved the stiffness and penetration resistance of the base binders, and binders with Sasobit had significantly lower permanent deformations after repeated creep-recovery tests compared to the base binders. Improvement in fundamental property of asphalt binders such as rutting resistance with the Sasobit modification was also found in other studies (Wasiuddin et al. 2007, Kanitpong et al. 2007). Kanitpong et al. (2007) also found Sasobit-modified binders have better fatigue resistance and higher complex shear modulus. However, stiffening effect of bitumens at low temperatures in terms of increased BBR creep stiffness by adding Sasobit indicated a possible lower resistance to cracking at these temperatures (Edwards et al. 2006).

Sasobit was also used to modify polymer modified asphalts (PMAs) (Kim et al. 2009). The rheological properties of PMAs containing two warm additives

(Asphalt-min and Sasobit) were investigated using a Bohlin DSR II. The use of Sasobit showed the enhanced rutting resistance properties of PMAs at high pavement temperature and more elastic properties at lower temperature.

Sasobit-Modified Mixtures

Laboratory Investigation

Performance of WMA using Sasobit has been widely evaluated in both the laboratory and the field. A laboratory study conducted at the national Center for Asphalt Technology (NCAT) (Hurley and Prowell 2005a) showed that Sasobit improved the compactability of asphalt mixtures in both the Superpave gyratory compactor (SGC) and vibratory compactor. The addition of Sasobit lowers the measure air voids in the SGC, which may indicate a reduction in the optimum asphalt content. The addition of Sasobit does not affect the resilient modulus of an asphalt mix compared to mixtures having the same PG binder (Hurley and Prowell 2005a).

The mixes containing Sasobit generally provided good rutting resistance (Hurley and Prowell 2005a, Kanitpong et al. 2007, Wasiuddin et al. 2007). Sasobit-modified mixes had a greater resistance to densification under traffic as well as a potential of greater resistance to permanent deformation under the traffic loads (Kanitpong et al. 2007). Sasobit was found to decrease the APA rut depths significantly, and these rut depths correlate well with the rutting factor $G^*/\sin\delta$ of binders. It was also observed that rutting potential decreases with decreasing mixing and compaction temperatures (Wasiuddin et al. 2007).

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 (Hurley and Prowell 2005a). Roque and Lopp (2006) used the Superpave IDT to evaluate Sasobit-modified mixtures' resistance to cracking. Sasobit-modified mixtures reduced the creep rate of the mixtures relative to the controls, which indicates that the Sasobit® modified mixtures would have a significantly reduced rate of microdamage development relative to the controls. It was also found that Sasobit-modified mixtures exhibited a slight reduction in failure strain, fracture energy and dissipated creep strain energy, with little or no change in stiffness or strength versus the controls. These results indicated that Sasobit-modified mixtures would exhibit better field cracking performance than the control mixtures. However, researchers also pointed out that lower creep response can result in higher thermal stresses. The effects of Sasobit on low temperature cracking would depend on the specific conditions to which the mixture is exposed. Additional tests at lower temperatures, along with a more complete thermal cracking analysis for specific environments of interest should be performed to get a more definitive answer regarding the effects of Sasobit on low temperature cracking.

The lower mixing and compaction temperatures can result in incomplete dying of aggregate. 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. Both tensile strength ratio (TSR) and Hamburg tests were conducted to assess moisture susceptibility, and mixtures containing Sasobit performed well in terms of moisture susceptibility (Hurley and Prowell 2005a). Kanitpong et al. (2007)'s study showed that there is no effect of Sasobit on the resistance of asphalt mixtures to moisture damage, but the reduction of mixing and compaction temperatures can cause detrimental effect on the moisture sensitivity. Xiao et al. (2009) used conventional testing procedures such as indirect tensile strength (ITS), TSR, deformation, and toughness to evaluate moisture damage in WMA mixtures containing moist aggregates. Their statistical analysis based on data of 180 specimens showed the Sasobit additive showed no significant influences on ITS values (dry or wet), deformation resistance, and toughness values under identical conditions, compared with control mixtures. Wasiuddin et al. (2008) investigated the moisture-induced damage mechanisms through evaluating the effect of Sasobit on the surface free energy components and related properties (wettability and adhesion) of selected binders. In their study, moisture susceptibility was defined as the amount of spontaneously released free energy due to the breaking of the binder-aggregate bond with water. Their study showed that Sasobit reduced the total surface free energy of asphalt binders. It greatly increased the wettability of asphalt binders over aggregates and reduced the adhesion between asphalt binders and aggregates.

In order to address challenges from increased demands for environmental friendly paving mixtures and increasing costs of raw materials, WMA additives and recycled asphalt pavement (RAP) have been incorporated into new HMA mixtures. Penny (2006) carried out a study to evaluate the use of heated RAP materials with emulsion and the use of HMA with Sasobit as base course materials. The use of Sasobit helped to achieve almost similar workabilities and compactabilities at lower temperatures, as compared to those of HMA with neat asphalt binder. No significant difference was found between the modulus of the Sasobit and hot mix asphalt samples in her study. In another study of using 100% RAP HMA as a base course (Tao and Mallick 2009), the workability of RAP was improved at temperatures as low as 110^{o}C with the addition of Sasobit H8. This was also consistent with the conclusion obtained from the study conducted by Austerman et al. (2009).

The effects of Sasobit on asphalt concrete mixture performance when used as a compaction aid in high RAP (35% RAP at that time) surface mixtures were evaluated in the laboratory of Advanced Asphalt Technologies, LLC (AAT

2005). When used at 1.5% by weight of total binder, Sasobit marginally increases the high temperature stiffness of the mixture, but has limited effect on intermediate and low temperature stiffness. At this concentration, aging characteristics and the rutting, fatigue cracking, and thermal cracking resistance of the mixture are not significantly affected by the addition of Sasobit. It appears that Sasobit may have a beneficial effect of slightly improve the resistance of mixtures to moisture damage. However, Austerman et al. (2009)'s work showed that the addition of Sasobit increased the moisture susceptibility of the mixture.

Mallick et al. (2008) successfully used Sasobit H8 in recycling HMA with 75% RAP at a lower temperature. The results of voids, tensile strength, rutting potential and moduli at different temperatures showed that it is possible to produce mixes with 75% RAP with similar air voids as virgin mixes at lower than conventional temperatures using 1.5% Sasobit. In general, most of the mixtures with high percentage of RAP could be designed to meet specification requirements for gradation and volumetrics with the addition of Sasobit. However, the dose of Sasobit additive may need to be increased (Mogawer et al. 2009).

Field Practices

Significant work has been conducted to demonstrate construction practices and to develop mix design procedures for WMA technologies. Some of examples are summarized as follows.

Three trial sections using two WMA technologies (two with Sasobit and one with Evotherm) were constructed in various locations in Virginia in 2006 (Diefenderfer et al. 2007). The trial sections with Sasobit-modified WMA were a 1.5-in overlay placed on a new base mixture on the eastbound lane of US 211 (as part of a larger pavement rehabilitation project) in Rappahannock County, Virginia, and a 1.5-in overlay on the southbound lane of US 220 in Highland County, Virginia. The sections were evaluated over a 2-year period to assess the initial performance of the WMA and compare it with that of HMA control sections constructed at the same time. For the two Sasobit trial sites, coring and visual inspections were performed regularly along with historic data and ground-penetrating radar scans. The HMA and WMA sites performed similarly through the first two years of service and should be expected to perform equally (Diefenderfer and Hearon 2010). No significant distresses were indicated by visual surveys in WMA sections. There were not significant differences of air-void contents and permeability between the HMA and WMA in each trial, though the WMA produced using Sasobit aged at a slightly reduced rate than the HMA, as indicated by decreased stiffening.

Goh and You (2008) reported results from a field demonstration consisting WMA (using Sasobit) and HMA at M-95, north of US-2 at Iron Mountain, Michigan. Observation from the field visit indicated significantly reduced emission during WMA construction compared to HMA construction. The rutting test of field cores using the APA showed that WMA with a reduction of 25°C (45°F) in compacting temperature has a similar rutting performance with HMA. The moisture susceptibility of WMA was comparable to HMA and the fatigue potential of WMA was slightly higher than HMA (Goh and You 2009).

A field project located in Kimbolton, Ohio was conducted to evaluate three WMA technologies (i.e. Evotherm, Aspha-min, and Sasobit) with a control section (Hurley et al. 2009). Field performance was evaluated through tests of mixture volumetric properties, rutting susceptibility, moisture resistance, dynamic modulus, and emissions. Different WMA technologies all performed equal to or better than the control mixtures. A decrease in emissions was also determined for the Sasobit and Aspha-min. Another newly completed project using same types of warm mixes sponsored by Ohio DOT (Sargand et al. 2009) confirmed the results obtained by Hurley et al. (2009). This project included a test site consisting of an overlay on Ohio State Route 541 in Guernsey County, and a test pavement constructed in the Accelerated Pavement Load Facility in Lancaster.

Two projects were constructed in Yellowstone National Park, one on the East Entrance Road west of Cody, WY and one south of Gardiner, MT (Perkins 2009). Two WMA technologies (Advera and Sasobit) were used in the East Entrance Road project in August of 2007. The contractor saved 20% on fuel costs at the asphalt plant, and WMA construction was handled similarly to HMA. The slab made with loose mixtures of Sasobit WMA showed slightly higher rutting depth than that of HMA in the Hamburg Wheel Test, though both passed Montana DOT specifications of 13 mm or less of rut in the specified number of passes. The inflection point in the rutting curve indicated stripping of Sasobit slab.

In addition, test sections containing moderate and high levels of RAP (20% and 45% RAP) with Sasobit addition were established at the NCAT test track (West et al. 2009). All sections performed well for rutting and raveling. The 45% RAP section with PG 76-22 plus Sasobit had moderate cracking, which appears to reflect cracking from the underlying pavement.

Experiences with these trial sections were used in the development of state DOTs' special provision to allow the use of WMA. An informal survey of state DOTs produced 12 states having specifications for WMA use (Perkins 2009). These states include Alabama, California, Florida, Idaho, Indiana, Iowa, Maine, Ohio, Pennsylvania, Texas, Virginia, and Washington.

CHAPTER III

EXPERIMENTAL DETAILS

A detailed laboratory testing plan is described in this chapter to assess the material properties of WMA including binder characterization and mixes performance. Materials and mix designs are presented as well.

MATERIALS

Materials used for both binder and mixes including aggregates, control binder (PG 58-28), and Sasobit were consistent with those used in the field trial in the Petersburg-Mitkof Highway Upgrade Project, Phase II. PG 58-28 asphalt binder and Sasobit were provided by U.S. Oil & Refining Co., and Figure 3.1 shows the Sasobit used in this study, which is a type of high melting point Fischer-Tropsch paraffin wax. Three Sasobit contents (i.e. 0.8%, 1.5% and 3% of weight of binder) were selected based on both previous studies and field trial experience. Aggregates, loose mixtures, and cores were collected and delivered from the field to the university laboratory for laboratory testing.

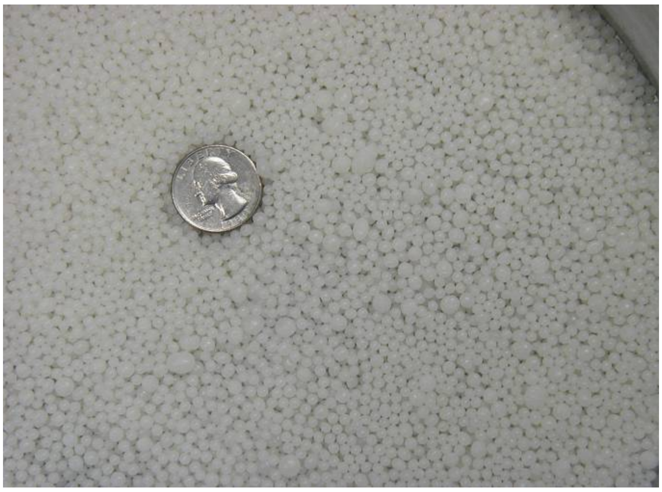


Figure 3.1 Sasobit used in the study.

BINDER TESTS

Binder tests were conducted for control PG 58-28 asphalt binder and Sasobit modified binders according to Superpave criteria. Table 3.1 gives a list of testing equipment to conduct various physical tests for PG grading, the related purpose for testing, and the related performance parameter being partly influenced by the asphalt binder. Table 3.2 summarizes the tests conducted in the laboratory. For each test, at least three replicates were provided for each temperature measured. The testing data were then analyzed according to the ASTM C670-03, which is the standard practice for preparing precision and bias statements for test methods for construction materials. The detailed results for determining PGs according to the AASHTO M320-05 are presented in the Appendix.

Table 3.1 Superpave asphalt binder testing equipment and purpose (Brown et al. 2009)

Equipment	Purpose	Performance Parameter
Rolling Thin Film Oven (RTFO)	Simulate binder aging (hardening) during HMA production and construction	Resistance to aging (durability) during construction
Pressure Aging Vessel (PAV)	Simulate binder aging(hardening) during HMA service life	Resistance to aging(durability) during service life
Rotational Viscometer (RV)	Measure binder properties at high construction temperature	Handling and pumping
Dynamic Shear Rheometer (DSR)	Measure binder properties at high and intermediate service temperatures	Resistance to permanent deformation (rutting) and fatigue cracking
Bending Beam Rheometer (BBR)	Measure binder properties at low service temperature	Resistance to thermal cracking
Direct Tension Tester (DTT)	Measure binder properties at low service temperature	Resistance to thermal cracking

Table 3.2 Summary of binder tests conducted in the lab

Binder Aging	Tests	Specification	Test equipment /Model
Original Binder	Rotational viscosity	ASTM D4402-06	Brookfield DV-III
	DSR test	AASHTO T315-08	Rheometric Scientific/ARES-RAA
Short-term aging (RTFO)	DSR test	AASHTO T240-08 AASHTO T315-08	Rheometric Scientific/ARES-RAA
	Mass loss	AASHTO T240-08	Mettler Toledo Balance
Long-term aging (PAV)	DSR test	AASHTO R28-06 AASHTO T315-08	Rheometric Scientific/ARES-RAA
	BBR test	AASHTO R28-06 AASHTO T313-08	Cannon Instrument/TE-BBR

Testing of Original Binder

Testing of original binder includes flash point test (AASHTO T48), RV test (ASTM D4402), and DSR test (AASHTO T315). The flash point test was not conducted in the lab. The RV test utilizes a Brookfield viscometer (including a temperature controller, a digital data controller and a rotational viscometer as shown in Figure 3.2) to ensure ease of pumping and handling of the binder at the hot mix production plant. This is attained by specifying a maximum viscosity of 3 Pas (≈3000mm^2/s) at 135°C. In addition, the RV tests were performed for all binders at temperatures from 105ºC to 165ºC to determine mixing and compaction temperatures at which the viscosities of binders range between 0.15 and 0.2 Pa.s, and between 0.25 and 0.3 Pa.s, respectively.

The DSR is conducted on both the original and aged binder. A controlled-strain DSR (Figure 3.3) was used to measure the viscoelastic behavior at different temperatures of the binder in terms of complex modulus (G*) and phase angle (δ). The DSR applies a torque to a thin film of binder specimen placed between two plates at a frequency of 10 radians per second. The applied torque and resulting shear strain are used in the computation of G* and δ. The specification requires determining the temperature that corresponds to a minimum value of 1.0 kPa for G*/sinδ.

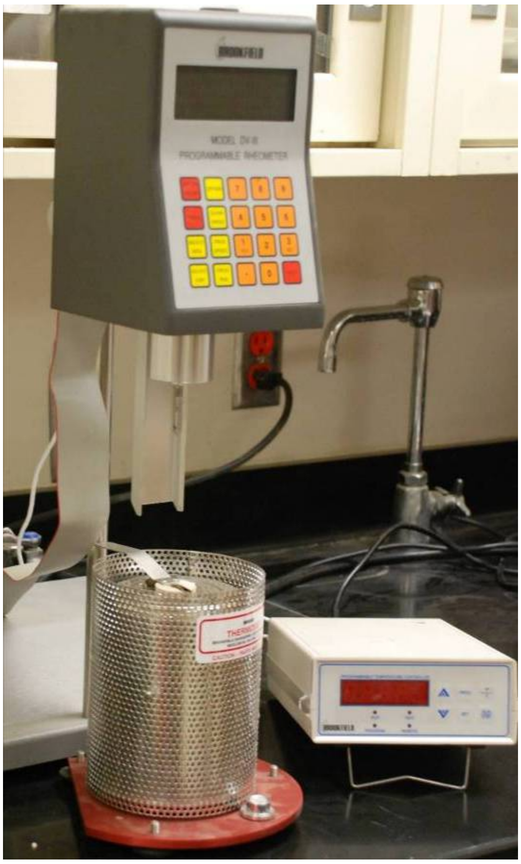


Figure 3.2 Brookfield rotational viscometer.

Figure 3.3 Dynamic Shear Rheometer.

Testing of RTFO Aged Residue

According to AASHTO T240-08, the RTFO (Figure 3.4) exposes fresh thin films of binder to heat (163°C) and air for 85 minutes by rotating coated bottles (15 revolutions/minute) and blowing air into the bottles (4000 ml/minute). The average percent mass loss is calculated after testing. The specification of 1% maximum mass loss guards against binders that age excessively. The RTFO residue is tested again using the DSR. In this case the limit on $G^*/\sin\delta$ required is 2.2 kPa for a loading rate of 10 radians/second. DSR tests on the original and RTFO aged binders are supposed to evaluate the binder's resistance to rutting.

Figure 3.4 Rolling Thin-Film Oven (RTFO).

Testing of PAV Aged Residue

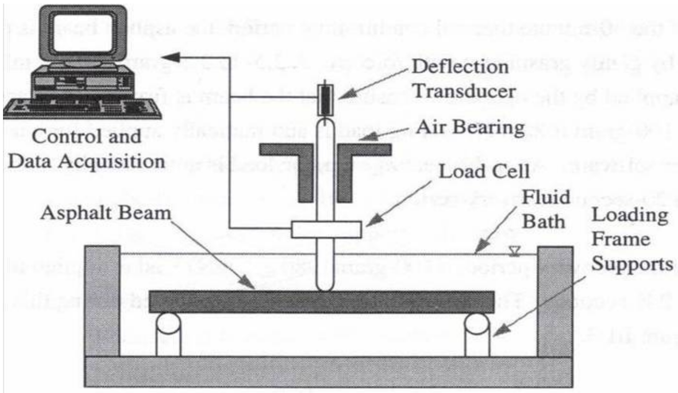
The RTFO residue is aged again in a PAV (Figure 3.5 (a)) to simulate long term aging. In this case, the binder is subjected to high temperature (90°C, 100°C, or 110°C) and pressure of 2070 kPa for 20 hours according to AASHTO R28-06. The sample pans are then placed in the degassing oven (Figure 3.5 (b)) maintained at 163°C for 30 minutes to remove entrapped air from the samples.

(a) (b)

Figure 3.5 a) Pressuring aging vessel; b) degassing oven.

The PAV residue is then tested using the DSR to evaluate the fatigue resistance of the binder. The specification in this case requires determining the temperature associated with a maximum G*sinδ of 5000 kPa for a loading rate of 10 radians/second. The BBR Test (Figure 3.6 (a)) is used to evaluate the stiffness of the PAV aged binder at low temperatures. As illustrated in Figure 3.6 (b), The BBR subjects a small beam of binder to a constant creep load and measures the resulting deflection at a temperature related to the anticipated lowest pavement service temperature. By using simple beam theory, the creep stiffness (S) and the creep rate (m-value) which is defined as the rate of change of stiffness with time are calculated. The S at 60 seconds must be less than 300 MPa, and the m-value at this time of loading must be at least 0.30 in order to meet the binder specification (AASHTO M320). If the stiffness is between 300 MPa and 600 MPa, then the direct tension test (DTT) (AASHTO TP3) should be used. In this test, a dog-bone shaped sample of binder is pulled at a slow rate of 1 mm/minute at low temperatures to determine the failure strain (defined at the maximum recorded load during the test). The specification requires that the failure strain be at least 1%. The m-value requirement must be satisfied in both cases.

(a)



(b)

Figure 3.6 a) BBR equipment; b) components of BBR.

MIXTURE DESIGN

As shown in Table 3.3, Superpave mix design was used to prepared mixtures in the lab with same binder content (5%) and binder grade (PG 58-28) consistent with the field design. The job mix formula (Marshall mix design) used for field mixtures was re-produced in the lab as well. Gradations of aggregates used in the field and the laboratory designs are illustrated in Figure 3.7.

MIXTURE TESTS

A detailed laboratory testing plan of WMA mixtures (Table 3.4) was developed to assess the performance of WMA mixtures, including 1) volumetric properties (i.e. voids filled with asphalt (VFA), voids in mineral aggregate (VMA) and VTM); 2) material characterization (dynamic modulus |E*| and flow number F_N) by the SPT; 3) rutting performance by the APA; 4) low temperature performance by the IDT; and 5) moisture sensitivity. Specimens for all tests were fabricated by the SGC specified in AASHTO T312-08.

Table 3.3 Details of mix designs

Mixture Name	Control Mixture	Sasobit Mixture 1	Sasobit Mixture 2	Sasobit Mixture 3	Field Mixture
Mix Design Type	Superpave				Marshall
G_{mm}	2.6784	2.6763	2.6626	2.6517	2.6237
G_{mb}	2.575	2.5553	2.5545	2.5421	2.5702
Design Binder Content	5%				
Design Binder Type	PG 58-28				
Design Sasobit content	0	0.8%	1.5%	3.0%	1.5%
Design air void	4%				2.5%
Metric (U.S.) Sieve	Gradation (%passing)				
19mm (3/4 in.)	100				100
12.5mm (1/2 in.)	96				87
9.5mm (3/8 in.)	84.3				75
4.75mm (No.4)	51.3				53
2.36mm (No.8)	28.9				39
1.18mm (No.16)	18.5				29
0.6mm (No.30)	11.5				22
0.3mm (No.50)	7.5				16
0.075mm (No.200)	5				6.3

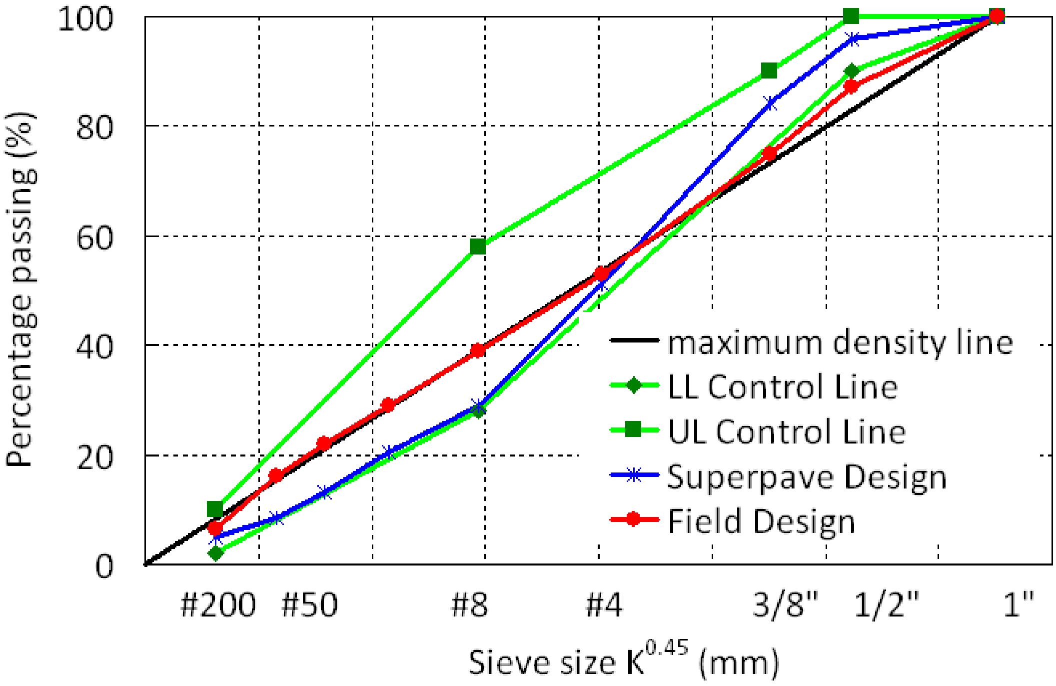


Figure 3.7 Aggregate gradations for mix designs.

Table 3.4 Summary of laboratory testing plan

Tests	Parameters	Specimen Size (mm)	Target air void (%)	Test Temp. (°C)
Volumetric Properties	Maximum specific gravity (G_{mm}); bulk specific gravity (G_{mb}); VMA; VFA; VTM;	115(H) 150(D)	4.0	25
Simple Performance Tests	Dynamic modulus |E*|; Flow number F_N	150(H) 100D)	4.0	4.4, 21.1, 37.8, 54
Rutting Test	Rut depth measurement	75(H) 150(D)	7.0	58
Indirect Tensile Test (IDT)	Tensile creep compliance and creep stiffness, D_t and S; tensile strength (σ_t)	38-50(H) 150(D)	7.0	-20, -10, 0
Moisture Induced Sensitivity Test (MIST)	TSR	90(H) 150(D)	7.0	25

Simple Performance Tests

Purely elastic materials exhibit their strain response to applied stress in phase, that is to say they perfectly correspond with no time lag. A purely viscous material exhibits a 90º lag in strain to applied stress, which is known as phase angle (δ) and characterizes the extent to which a material is elastic or viscous. Asphalt mixtures exhibit viscoelastic material behavior and therefore there is a phase angle falling between the two extremes, as graphically presented in Figure 3.8. Because of this viscoelastic behavior, asphalt mixtures demonstrate both storage and loss (dissipation) of energy.

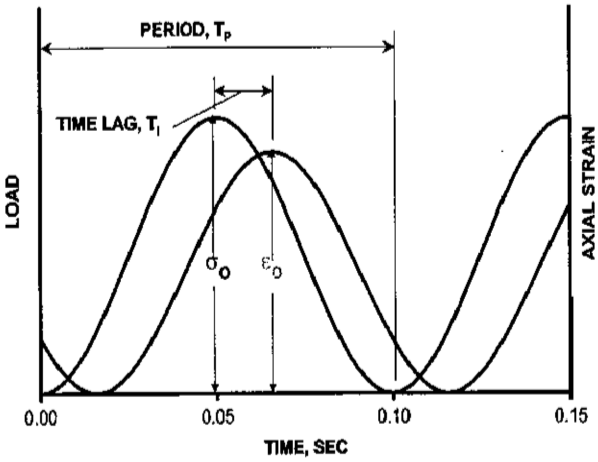


Figure 3.8 Typical dynamic modulus loading and response (Bonaquist et al. 2003).

The stress-strain relationship for asphalt mixes under continuous sinusoidal loading can be defined by a complex number, E*, which is defined as the ratio of the amplitude of the sinusoidal stress of pulsation ω applied to the material $\sigma = \sigma_0\sin(\omega t)$ and the amplitude of the sinusoidal stain $\varepsilon = \varepsilon_0\sin(\omega t-\delta)$ that results in a steady state:

$$E^* = \frac{\sigma}{\varepsilon} = \frac{\sigma_o e^{i\omega t}}{\varepsilon_o e^{i(\omega t-\delta)}} \tag{3.1}$$

The modulus of this complex number E* is the dynamic modulus |E*|, where σ_o is the stress amplitude and ε_o is the recoverable strain amplitude:

$$|E^*| = \frac{\sigma_o}{\varepsilon_o} \tag{3.2}$$

The dynamic modulus test is a strain controlled test performed as a 100 mm (4 inch) diameter, 150 mm (6 inch) tall cored cylindrical specimen is subjected to a continuous haversine axial compressive load. The test is performed over a range of loading frequencies (25, 20, 10, 5, 2, 1, 0.5, and 0.1 Hz) and four temperatures (4.4, 21.1, 37.8, and 54°C) according to the proposed standard practice in NCHRP report 614 for NCHRP Project 9-29 (Bonaquist 2008). The SPT manufacture by IPC Global of Australia was used to perform the test, which is a digital servo hydraulic control testing machine equipped with a continuous electronic control and data acquisition system (CDAS). The cored cylindrical samples are placed within the machine and affixed with three radially mounted linear variable displacement transducers (LVDT). The LVDTs measure displacements across a 70 mm gauge length. Figure 3.9 shows the setup of the SPT.

Figure 3.9 Setup of the SPT.

The F_N test is a repeated-load permanent deformation test used to evaluate the creep characteristics of HMA as related to permanent deformation. Tests are performed by applying a uniaxial compressive load to a 100 mm (4 inch) diameter, 150 mm (6 inch) tall cored cylindrical specimen. The compressive load is applied in haversine form with a loading time of 0.1 seconds and a rest duration of 0.9 seconds for a maximum of 10,000 cycles or until a deformation of 50,000 microstrain is reached. In this study, the specimens were tested at temperature of 54°C.

Permanent strain of samples used in F_N evaluation demonstrates itself in three distinct stages. The primary zone is a period of rapid strain accumulation at the beginning of the test, followed by the secondary zone which is identifiable by a constant accumulated strain rate. As the secondary zone continues and the pavement structure breaks down there is eventually a jump to the tertiary zone, marked by an increase in strain rate. The point at which the permanent strain rate is at its minimum and tertiary flow begins is noted as the flow number for that mixture. Figures 3.10 and 3.11 graphically demonstrate this progression of permanent strain.

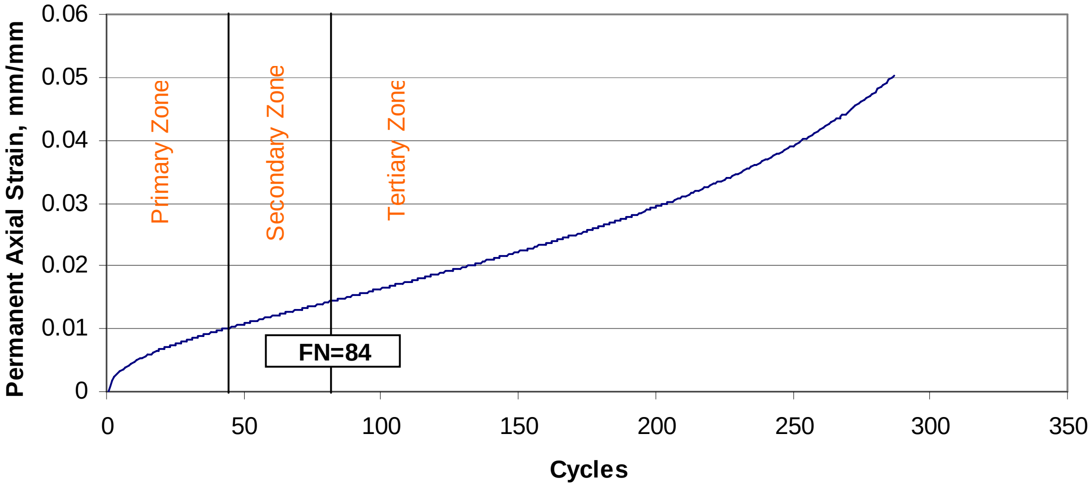


Figure 3.10 Typical accumulation of permanent strain in F_N test.

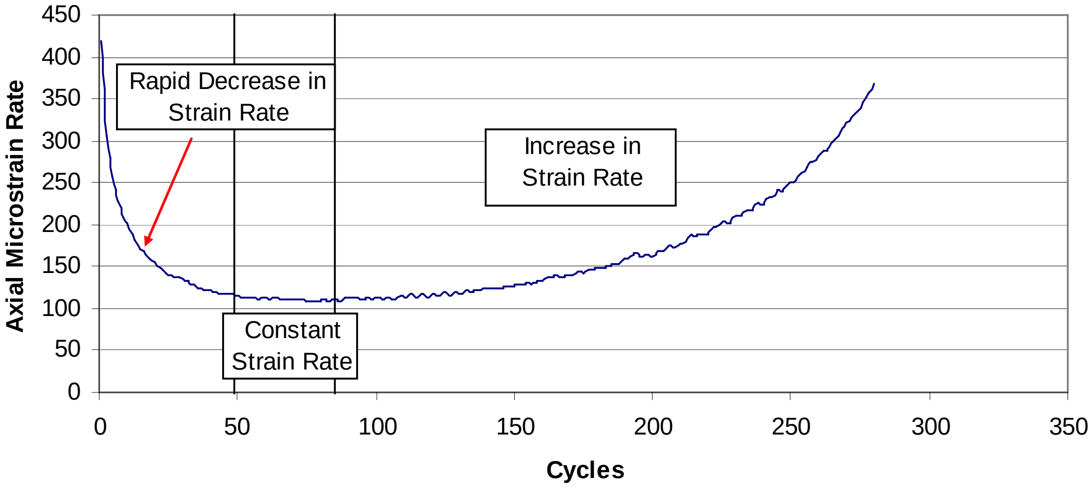


Figure 3.11 Typical accumulation of permanent strain rate in F_N test.

The same SPT used for the |E*| testing is used for F_N testing with exclusion of the previously mentioned LVDTs. Permanent deformations are measured internally by the displacement of the load frame. The CDAS processes accumulated strain to a strain rate by the following formula:

$$\frac{d\delta i}{dt} \cong \left(\delta_{i+\Delta n} - \delta_{i-\Delta n}\right) / 2\Delta n \tag{3.3}$$

where,

dδi/dt = strain rate at logged datum "i" (cycle or second),

$\delta_{i+\Delta n}$ = strain at i+Δn samples,

$\delta_{i-\Delta n}$ = strain at i-Δn samples, and

Δn = sampling interval.

The derivatives are smoothed to ensure proper calculation of the minimum strain rate by determining a running average at each point. This eliminates the effects of jumps in the data which may cause anomalies. Two points before and after and also the point in question are summed and then divided by 5.

$$\frac{d\delta i}{dt} \cong \left(\delta_{i-2\Delta n} / dt + \delta_{i-\Delta n} / dt + \delta_i / dt + \delta_{i+\Delta n} / dt + \delta_{i+2\Delta n}\right) / 5 \tag{3.4}$$

Data is then analyzed on a comparative basis. Mixtures with higher flow numbers are more stable mixes which should exhibit less permanent deformation in field conditions than mixes with lower flow numbers which are deemed as poorer quality mixes.

For simple performance tests, three scenarios of specimens were prepared: 1) lab-mixed lab-compacted specimens using raw materials with 4% of air voids content (Superpave mix design); 2) field-mixed lab-compacted specimens using loose mixtures collected from the field with 4% of air voids content (Superpave mix design); and 3) field-mixed lab-compacted specimens using loose mixtures collected from the field with 2.5% of air voids content (job mix formula in the field).

Rutting Performance Test

The rutting performance of WMA was determined by using the APA according to AASHTO TP63-07. The APA allows for an accelerated evaluation of rutting potential after volumetric design (Skok et al. 2002). Permanent deformation (rutting) susceptibility of mixes is assessed by placing a beam or cylindrical samples under repetitive wheel loads and measuring the permanent deformation. The APA features an automated data acquisition system, which obtains rutting measurements and displays these measurements in a numeric and/or graphical format.

Specimens of 75±2 mm in height and 150 mm in diameter were fabricated with VTM of 7±0.5% and volumetric properties were verified before tests. Field cored samples with diameters of 150 mm were also cut to the required heights before testing. For each mix, four specimens (in left and right tracks shown in Figure 3.12) were used for the tests. A test temperature of 58 ºC was selected to conform to the climate condition in Alaska area. The APA hose pressure was set at 100 psi with a wheel load of 100 lbs and frequency of 60 Hz. A total stroke time of 8000 was applied to evaluate rutting susceptibility.

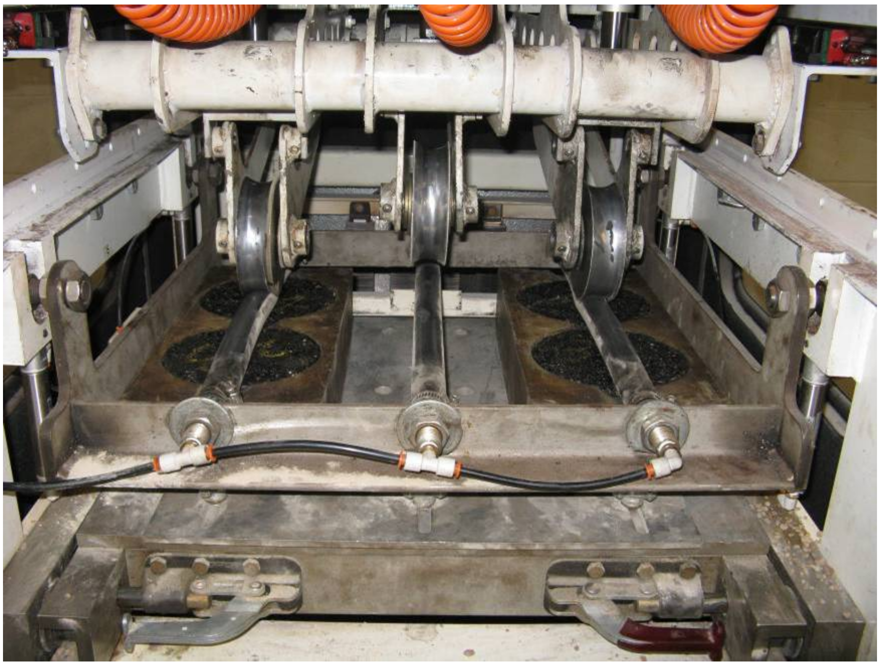


Figure 3.12 APA for rutting test.

Indirect Tensile Test (IDT)

The IDT device (Figure 3.13) along with an environmental chamber and a programmed data acquisition system was used to determine the tensile creep stiffness *S(t)*, and tensile strength S_t according to AASHTO specification T322-07. The IDT is performed by loading a cylindrical specimen under a uniform compressive load, which develops a relatively uniform tensile stress ultimately causing the specimen to fail by splitting along the vertical diameters. Specimens of 38-50 mm in height and 150 mm in diameter were fabricated with VTM of 7±0.5% and volumetric properties were verified before tests. Field-cored samples with diameters of 150 mm were also cut to the required heights before testing. Tensile creep compliance *D(t)* of each mixture was monitored at three different temperatures at 10°C intervals, i.e. -20, -10 and 0°C, respectively. At each tested temperature, normalized horizontal and vertical deformations from 6 specimen faces (3 specimens, two faces per specimen) were measured with LVDTs shown in Figure 3.13.

Creep compliance *D(t)* of each mixtures were tested and calculated according to the test specification as the formula:

$$D(t) = \frac{\Delta X \times D_{avg} \times b_{avg}}{P_{avg} \times GL} \times C_{cmpl} \qquad (3.5)$$

where,

$D(t)$ = creep compliance (kPa),

ΔX = trimmed mean of the horizontal deformations (meter),

D_{avg} = average specimen diameters (meter),

b_{avg} = average specimen thickness (meter),

P_{avg} = average force during the test (kN),

GL = gage length (38mm), and

C_{cmpl} = creep compliance parameter at any given time, computed as

$$C_{cmpl} = 0.6354 \times (\frac{X}{Y})^{-1} - 0.332 \tag{3.6}$$

where,

X = horizontal deformation, and

Y = vertical deformation.

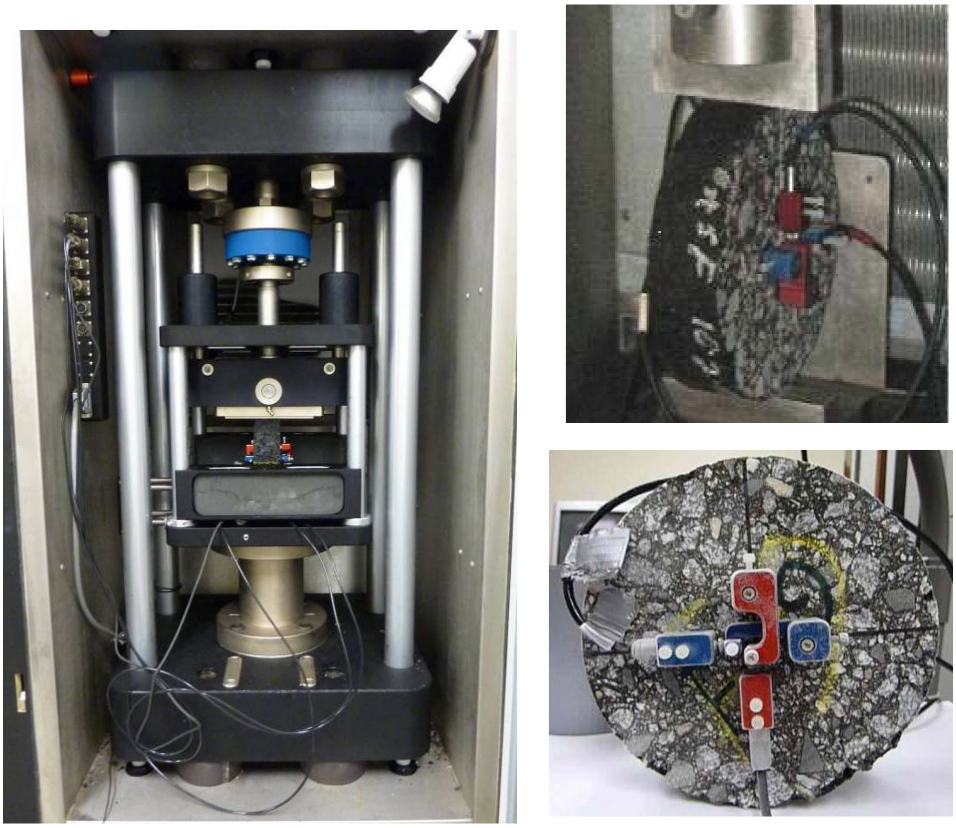


Figure 3.13 IDT setup.

Creep stiffness $S(t)$ at the time t was calculated as the inverse of the creep compliance $D(t)$, i.e.

$$S(t) = \frac{1}{D(t)} \tag{3.7}$$

Since creep test is a non-destructive test, further testing was conducted on the same set of test specimens to determine the indirect tensile strength by applying a load to the specimen at a rate of 12.5mm/min of vertical movement. The indirect tensile strength S was calculated by Equation 3.8.

$$S = \frac{2 \times P_{fail}}{\pi \times b \times D} \tag{3.8}$$

where,

P_{fail} = failure (peak) load,

b = specimen thickness, and

D = specimen diameter.

Moisture Induced Sensitivity Test (MIST)

The MIST, also called retained tensile strength test or TSR test, is conducted to measure the change of indirect tensile strength resulting from the effects of water saturation and accelerated water conditioning of a freeze-thaw cycle for WMA specimens according to AASHTO T283-07. It is intended to evaluate the susceptibility of WMA mixtures to the long term stripping.

Specimens of 90±5 mm in height and 150 mm in diameter were fabricated with VTM of 7±0.5% and volumetric properties were verified before tests. Field-cored samples with diameters of 150 mm were also cut to the height of 55±5 mm before testing. At least six specimens were prepared for each mix: three as the control set (dry) and the other three as the conditioned set. Specimens for dry subset wrapped in plastic bags were placed in a water bath (with a temperature of 25±0.5°C) for 2h±10 min with a minimum 25mm of water above their surface before measurement of indirect tensile strength. Specimens of the conditioned set were first placed in a vacuum container with a vacuum absolute pressure of 25 in. Hg partial pressure for approximately 5 minutes before submerged in water for another 5 minutes. If the degree of saturation was between 70-80 percent, water saturated specimens were covered with a plastic film and wrapped in a plastic bag. The wrapped conditioned specimens were then placed in a freezer at a temperature of -18°C for 16 hours, followed by soaking in a water bath water at 60°C for 24 hours. After a complete freeze-thaw cycle, specimens for conditioned set were tested for their indirect tensile strength as that of dry set.

The TSR was then calculated as:

$$TSR = \frac{S_2}{S_1} \tag{3.9}$$

where,

S_1 = average tensile strength of the dry subset, kPa, and

S_2 = average tensile strength of the conditioned subset, kPa.

CHAPTER IV

RESULTS AND ANALYSIS

This chapter summarizes data results and analysis for both binder and mixture tests. The constructability of WMAs used in field trials was assessed and the correlation between the content of Sasobit additive and Superpave PG and stiffness of modified binders were evaluated. Engineering properties of Sasobit modified mixtures including dynamic modulus, low-temperature performance, rutting susceptibility, and moisture sensitivity were presented as well.

PERFORMANCE OF SASOBIT-MODIFIED BINDERS

Constructability of Sasobit-Modified Binders

The RV was used to evaluate high temperature workability of un-aged asphalt binders. High temperature binder viscosity was measured to ensure that the asphalt is fluid enough during pumping and mixing. Figure 4.1 illustrates the viscosity of Sasobit-modified binders at temperatures ranging from 105ºC to 165ºC. All binders exhibited the decrease of viscosity with the increase of temperature. In addition, viscosity decreased with the increase of Sasobit content from 0% to 3% at each test temperature. The mixing and compaction temperatures of binders were determined based on Figure 4.1, and summarized in Table 4.1, with corresponding viscosities between 0.15 and 0.2 Pa.s, and between 0.25 and 0.3 Pa.s, respectively. It can be seen from Table 4.1 that the addition of Sasobit decreased both mixing and compaction temperatures. Compared with the control binder without Sasobit addition, the addition of 3% Sasobit contributed to a decrease of more than 15ºC in mixing temperature and a decrease of 13ºC in compaction temperature. It was consistent with a well-accepted statement that Sasobit is 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 (Damm et al. 2002, Hurley and Prowell 2005a, Wasiuddin et al. 2007).

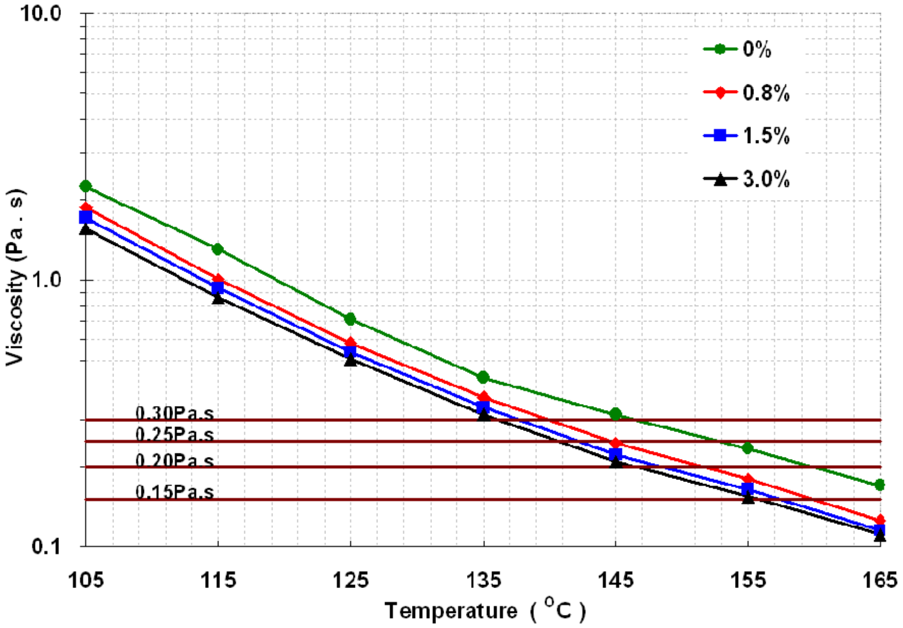


Figure 4.1 Viscosity of Sasobit-modified binders.

Table 4.1 Mixing and compaction temperatures of Sasobit-modified binders

Sasobit (%)	Mixing Temp (ºC) (Viscosity 0.15~0.20 Pa.S)	Compaction Temp (ºC) (Viscosity 0.25~0.30 Pa.S)
0	160~170	146~153
0.8	151~160	139~144
1.5	148~158	137~142
3.0	146~155	135~139

PG of Sasobit-Modified Binders

Results of Superpave binder tests are summarized in Table 4.2. Detailed testing results are presented in the Appendix. The direct tension strain data were not available, because based on the specification, the direct tension strain is only necessary when m-value requirement is satisfied but the creep stiffness requirement is not. The direct tension test is not required if the creep stiffness is less than 300 MPa. As shown in Table 4.2, for different Sasobit contents, the

PG high temperature ranged from 58ºC to 76ºC, while low temperature ranged from -28ºC to -16ºC. With the increase of Sasobit content from 0% to 3%, the high temperature end of asphalt PG increased from 58 to 76, however, the low temperature end also increased from -28ºC to -16ºC. Similar impacts of Sasobit addition on binder PG can be found from other researchers' studies (Hurley and Prowell 2005a, Wasiuddin et al. 2007, Austerman et al. 2009).

Table 4.2 Summary of Superpave binder test results

Sasobit (%)	Mass Loss (%)	Viscosity @135ºC	Grade Temp (ºC) for DSR			Grade Temp (ºC) for BBR		PG Grade	
			Origin	RTFO	PAV	BBR-S	BBR-m	High	Low
0	0.47	0.433	58	64	19	-18	-18	58	-28
0.8	0.41	0.491	70	64	22	-12	-12	64	-22
1.5	0.26	0.445	70	70	22	-12	-12	70	-22
3.0	0.17	0.392	76	76	25	-6	-6	76	-16

Figure 4.2 illustrates PGs of Sasobit-modified binders. According to Superpave specification, a PG 58-28 binder (control binder) is intended for use in an environment where an average seven-day maximum pavement temperature of 58ºC and a minimum pavement design temperature of -28ºC, are likely to be experienced. A PG 76-16 binder (modified with 3% Sasobit) is intended for use in an environment where an average seven-day maximum pavement temperature of 76°C and a minimum pavement design temperature of -16°C, are likely to be experienced, etc. Since the Superpave asphalt binder specification is meant to be performance based, it addresses three primary performance parameters of asphalt pavements: permanent deformation (rutting), fatigue cracking, and low temperature (thermal) cracking.

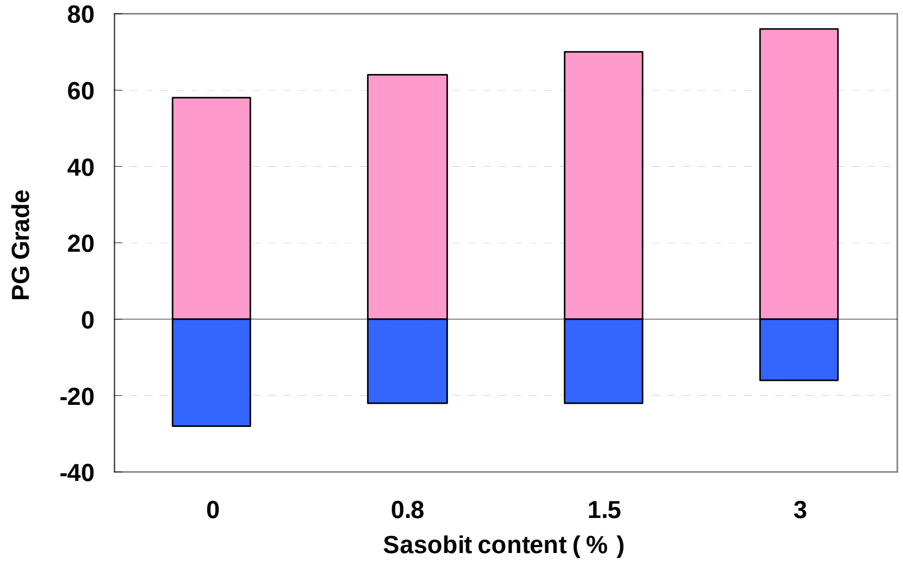


Figure 4.2 PGs of Sasobit-modified binders.

Effects of Sasobit on Rutting Performance of Binders

The Superpave binder specification uses a rutting factor, G*/sinδ, as a measure of asphalt binder's stiffness or rutting resistance at high pavement service temperature. The testing results of G*/sinδ for both original and RTFO aged binders are illustrated in Figures 4.3 and 4.4, respectively. For both conditions, the rutting factor increased with the increase of Sasobit addition, and the increment became more significant at higher percentage of Sasobit content. The high temperature of PG is determined based on that the G*/sinδ must be at least 1.00 kPa for the original asphalt binder and a minimum of 2.20 kPa for the RTFO aged asphalt binder when tested by DSR. With the increase of Sasobit content from 0%, 0.8%, 1.5% to 3%, accordingly, high temperature of PG increased from 58ºC, 64ºC, 70ºC to 76ºC, indicating improved rutting resistance of binders with the addition of Sasobit. This conformed to other researchers' findings (Wasiuddin et al. 2007, Kanitpong et al. 2007, Biro et al. 2009).

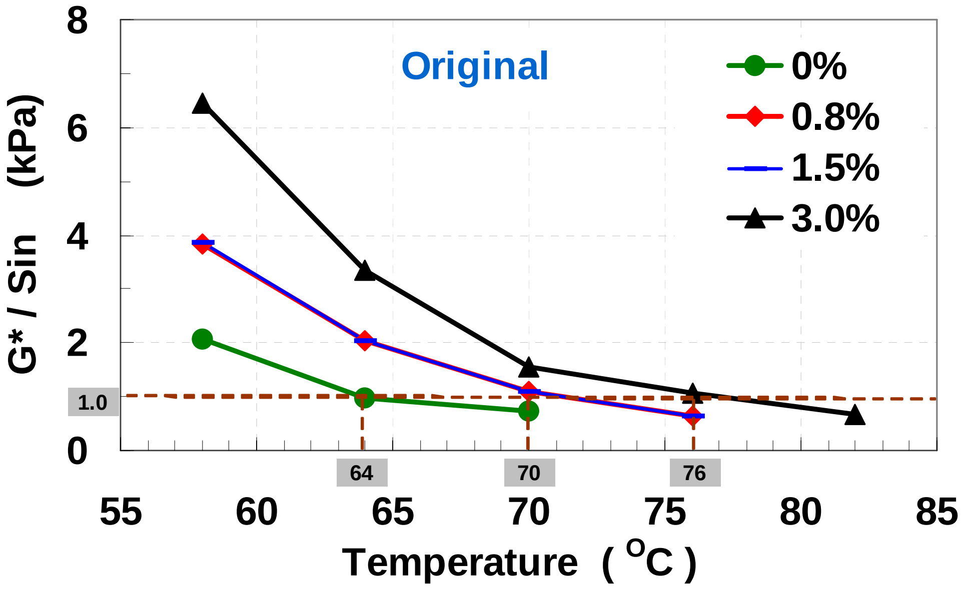


Figure 4.3 Rutting factor of original Sasobit-modified binders.

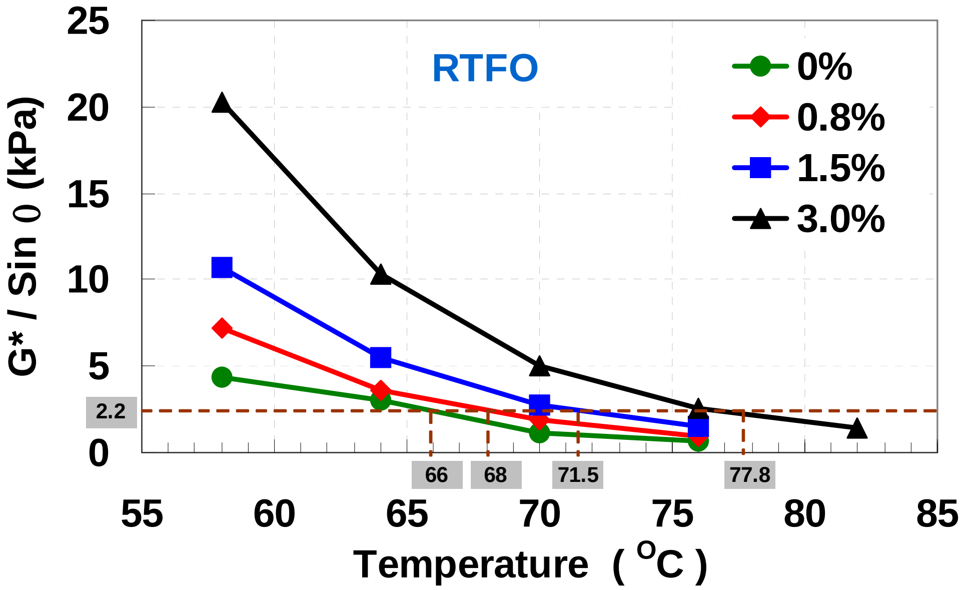


Figure 4.4 Rutting factor of RTFO aged Sasobit-modified binders.

Effect of Sasobit on Fatigue Resistance of Binders

The specification uses a fatigue factor, G*sinδ, which represents asphalt binder's resistance to fatigue cracking. The specification has a maximum limit of 5000 kPa for G*sinδ for the binder subjected to PAV aging, and tested at intermediate pavement service temperature. Figure 4.5 illustrates the results of G*sinδ as a function of temperature for PAV aged binders. It can be seen that the G*sinδ increased with the increase of Sasobit addition. The additions of 0.8% and 1.5% Sasobit showed very close increment compared with the control binder without Sasobit addition. The binder with 3% Sasobit provided highest increment of G*sinδ. In addition, the intermediate pavement service temperature increased with the increase of Sasobit addition. Kanitpong et al. (2007) found that Sasobit-modified binders have better fatigue resistance. However, our results shown in Figure 4.5 implied higher fatigue factor at same intermediate temperature, and associated reduced resistance to fatigue cracking.

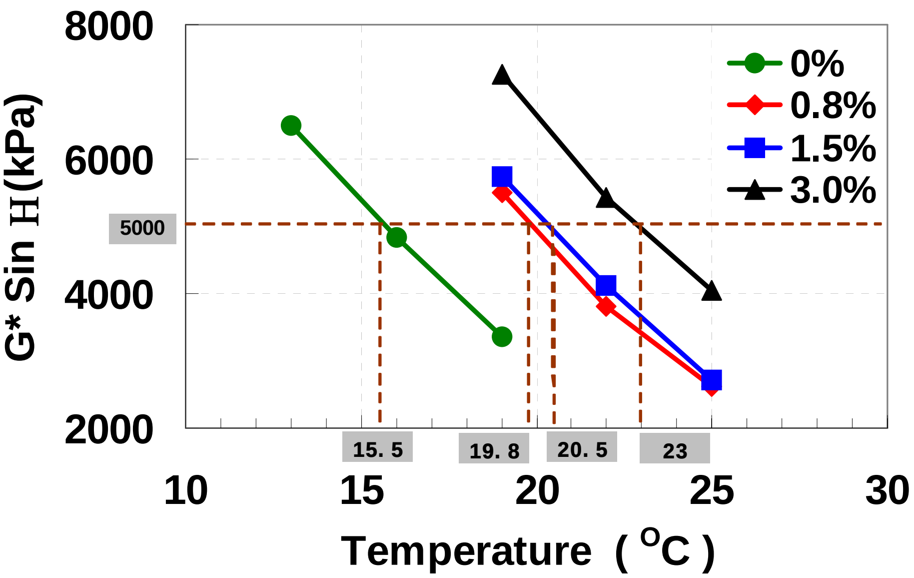


Figure 4.5 Fatigue factor of PAV aged Sasobit-modified binders.

Effect of Sasobit on Low Temperature Performance of Binders

A lower creep stiffness and a higher m-value of PAV aged binder at a low temperature usually mean a higher resistance to low temperature cracking of pavement materials. Figures 4.6 and 4.7 illustrate creep stiffness and m-value of PAV aged binders by BBR tests. With the increase of Sasobit content, creep stiffness increased while m-value decreased, indicating that Sasobit addition increases the tendency for low temperature cracking of the base asphalts. This result was not consistent with Gandhi and Amirkhanian (2008)’s results which showed the Sasobit additive did not have any significant effect on the fatigue cracking parameter (G*sinδ) or the creep stiffness of the binders.

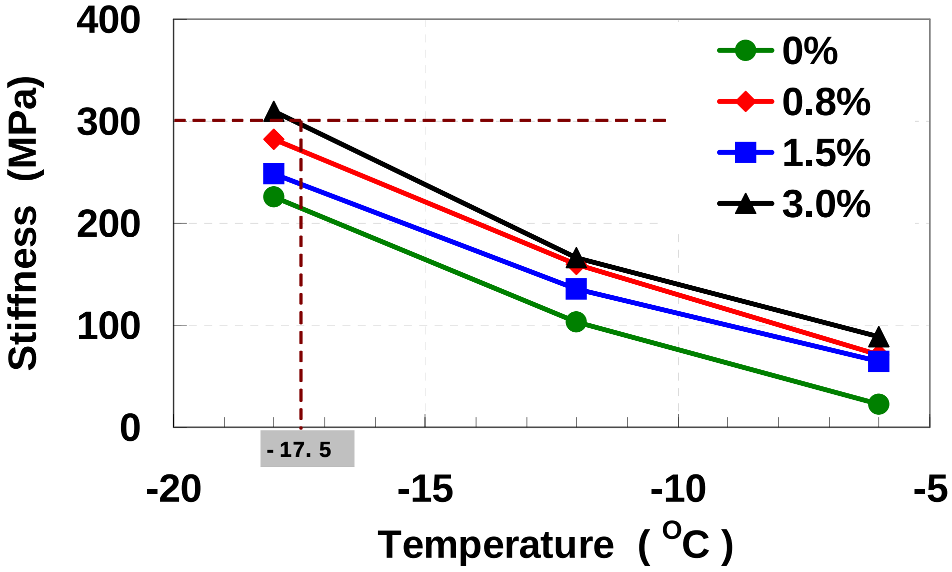


Figure 4.6 Creep stiffness of PAV aged Sasobit-modified binders.

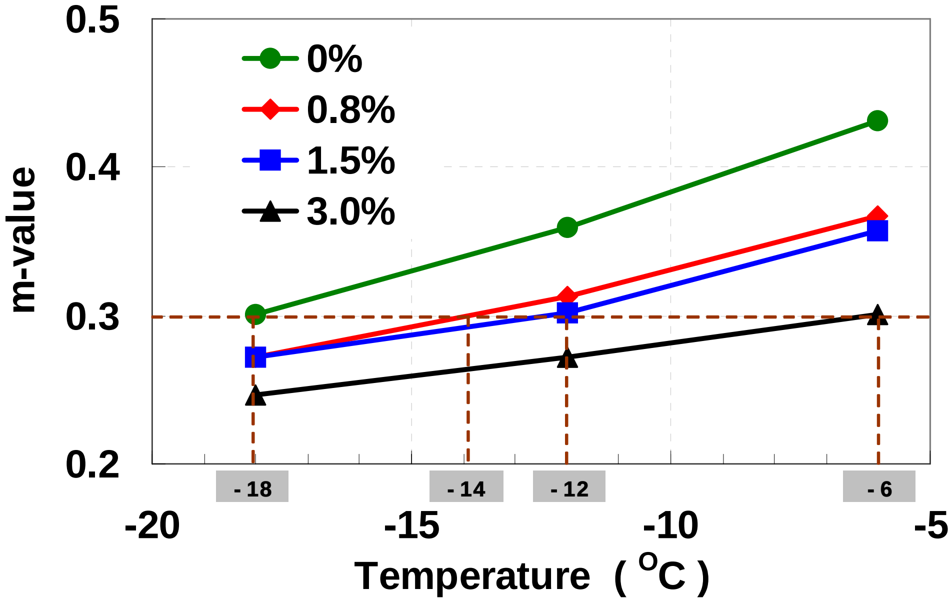


Figure 4.7 m-value of PAV aged Sasobit-modified binders.

PERFORMANCE OF SASOBIT-MODIFIED MIXTURES

Simple Performance Tests

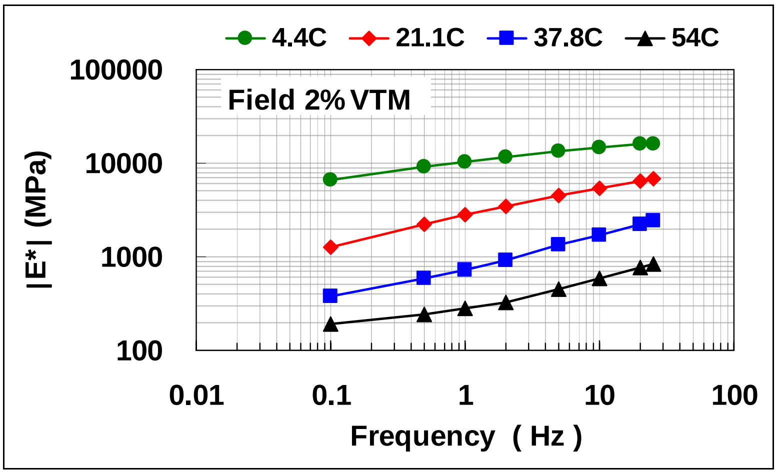
Volumetric properties of Sasobit-modified mixtures were verified before tests and the results are summarized in Table 4.3. The VTM (%) of laboratory mixtures met the design criteria, i.e. 4±0.5% air voids for SPT specimens. Specimens were also compacted using loose mixtures collected from the field with two different VTMs: 1) 4% to be consistent with that those lab-mixed lab-compacted specimens; and 2) 2.5% to be consistent with that in the job mix formula for the field mix.

Table 4.3 Volumetric properties for SPT specimens

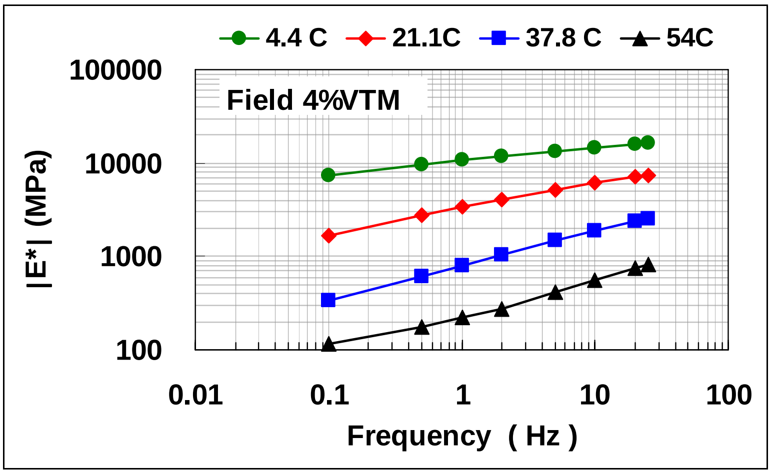
Mix Name	***Control Mix***	***Sasobit Mix 1 (0.8%)***	***Sasobit Mix 2 (0.8%)***	***Sasobit Mix 3 (0.8%)***	***Field 2%***	***Field 4%***
G_{mm}	2.6792	2.6763	2.6626	2.6517	2.6237	2.6237
Sasobit content	0	0.80%	1.50%	3.00%	1.50%	1.50%
SPT Specimens						
G_{mb}	2.5557	2.5553	2.5545	2.5421	2.5702	2.5237
VTM(%)	4.61	4.52	4.06	4.13	2.05	3.82
VMA(%)	13.53	13.55	13.57	13.99	11.87	13.46
VFA(%)	65.94	66.62	70.09	70.46	82.72	71.61
STD(s)	0.43%	0.35%	0.23%	0.11%	1.80%	0.07%

Dynamic Modulus (|E|)*

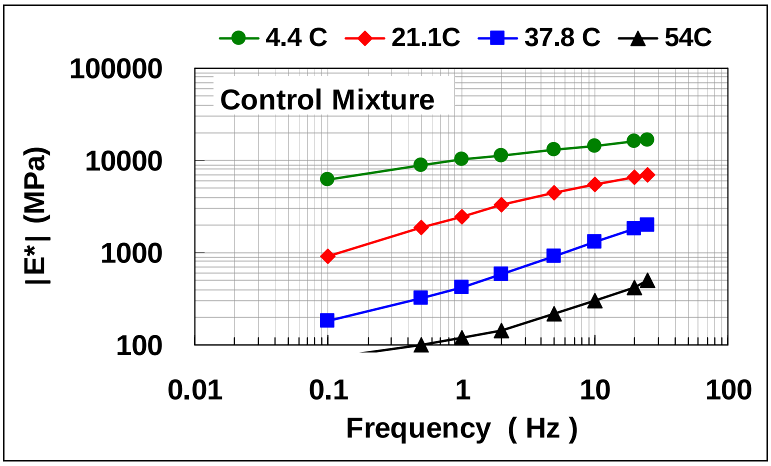
Figure 4.8 illustrates the curves of |E*| versus loading frequency in logarithm at four test temperatures for all mixes. Results showed that ay any loading frequency, the |E*| decreased with an increase in temperature for any mix. Under constant temperature, the |E*| increased with the increase of loading frequency. It is clear that the |E*| is dependent of both temperature and loading frequency.



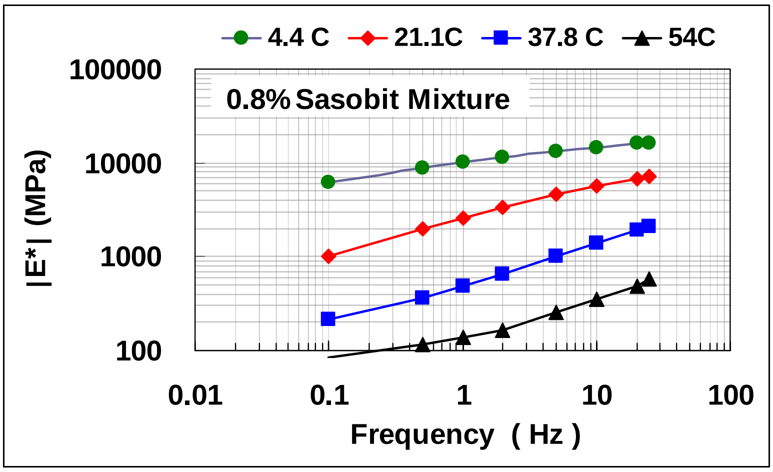
(a) Field mix (2% VTM)



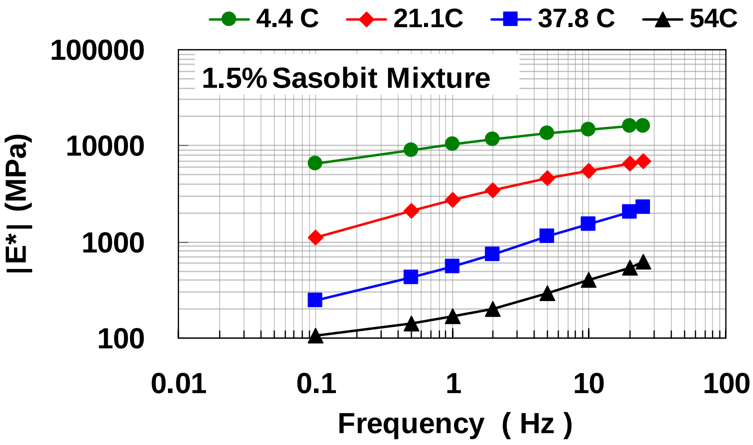
(b) Field mix (4% VTM)



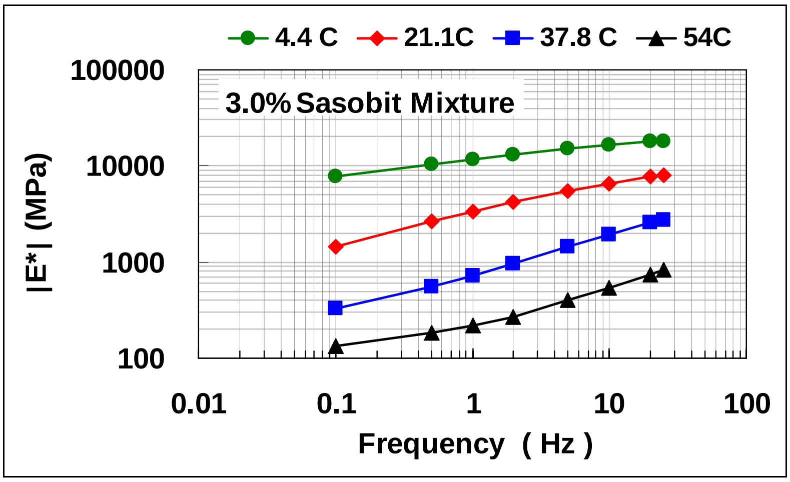
(c) Control mix



(d) 0.8% Sasobit mix



(e) 1.5% Sasobit mix

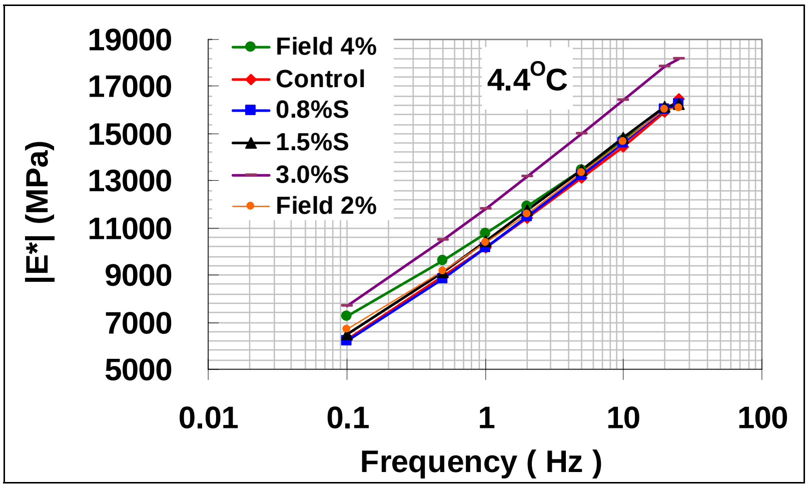


(f) 3.0% Sasobit mix

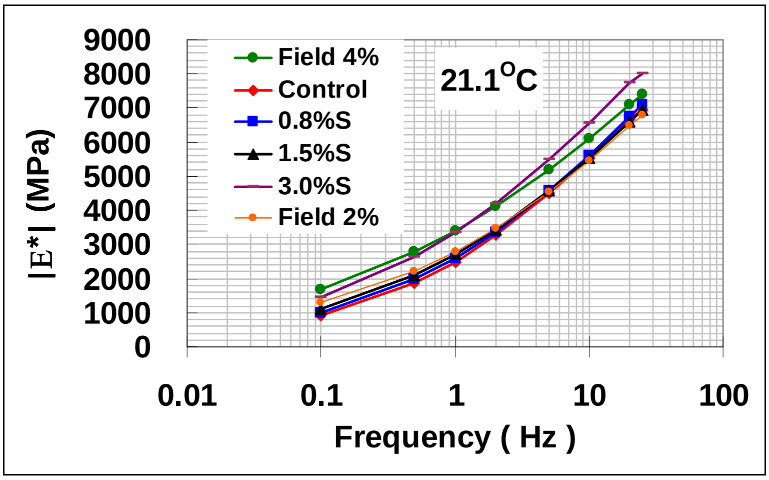
Figure 4.8 |E*| of SPT mixtures.

Figure 4.9 illustrates the measured |E*| of all mixtures at different temperatures. In general, higher Sasobit content contributed to higher |E*| value. In addition, this trend (or the effect of Sasobit addition on the |E*|) was more significant at higher temperatures for lab-mixed lab-compacted mixtures. At lower test temperatures (i.e. 4.4°C and 21.1°C) as shown in Figures 4.9 (a) and (b), lower Sasobit addition (i.e. 0.8% and 1.5%) did not change |E*| value compared with the control mixture, while 3% Sasobit addition significantly increased the |E*| value. At higher temperatures (i.e. 37.8°C and 54°C) as shown in Figures 4.9 (c) and (d), the |E*| increased with the increase of Sasobit content from 0% to 3%. Therefore, the |E*| value was more sensitive to Sasobit addition at higher temperatures.

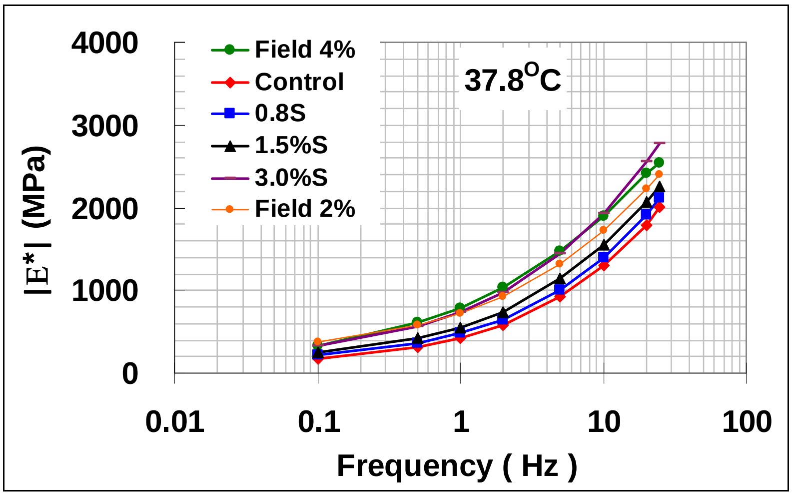
It is generally accepted that low |E*| values at low and intermediate temperatures are beneficial for an asphalt mixture to resist low temperature and fatigue cracking, whereas high |E*| values at high temperatures are desirable for rutting resistance. According to the |E*| results, it appears that the addition of Sasobit was beneficial to the rutting resistance of the mixtures with an increase of |E*| value at higher temperatures (i.e. 37.8°C and 54°C) and was not to resistances to low temperature and fatigue cracking because of higher |E*| values at low and intermediate temperatures (i.e. 4.4°C and 21.1°C). More performance tests are needed to evaluate the contribution of Sasobit addition, as presented later.



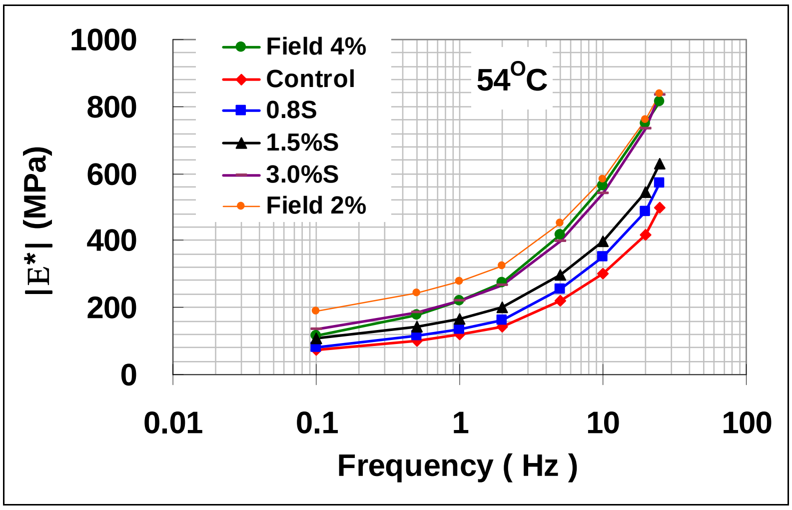
(a) 4.4°C



(b) 21.1°C



(c) 37.8°C



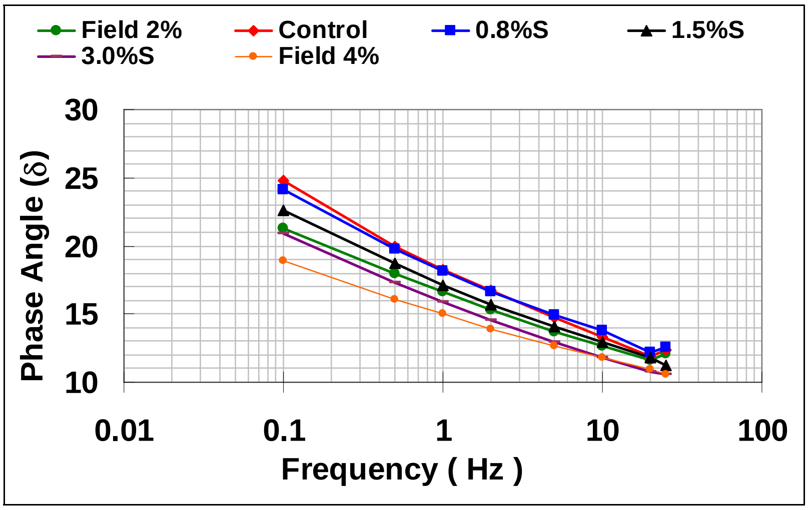
(d) 54°C

Figure 4.9 |E*| of mixes at different temperatures.

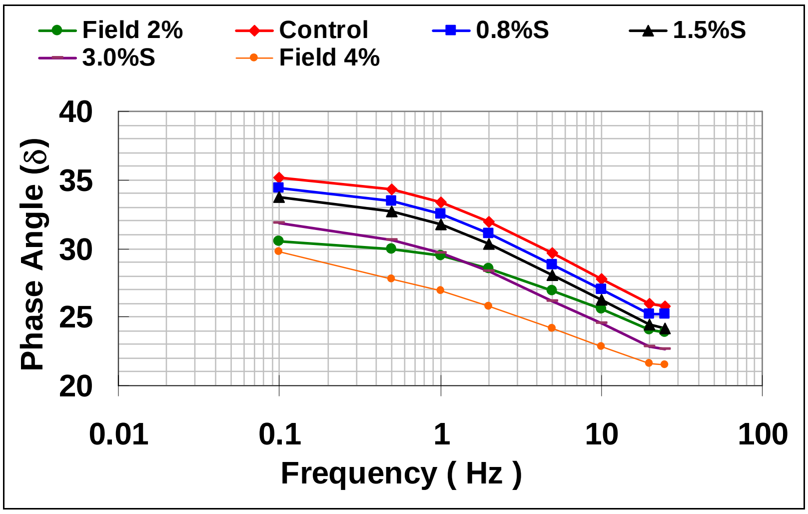
The field mixtures (field-mixed lab-compacted specimens) with both 2% and 4% of VTMs showed very close |E*| values. In addition, their |E*| values were the highest at higher temperatures (i.e. 37.8°C and 54°C). At the lowest temperature (i.e. 4.4°C), the |E*| values of field-mixed lab-compacted mix modified with 1.5% Sasobit were very close to those of lab-mixed lab-compacted mix modified with same Sasobit addition. However, with the increase of temperature, field-mixed lab-compacted mix presented higher |E*| values at all loading frequencies. The difference between their |E*| values became most significant at the highest temperature (i.e. 54°C).

Phase angle (δ)

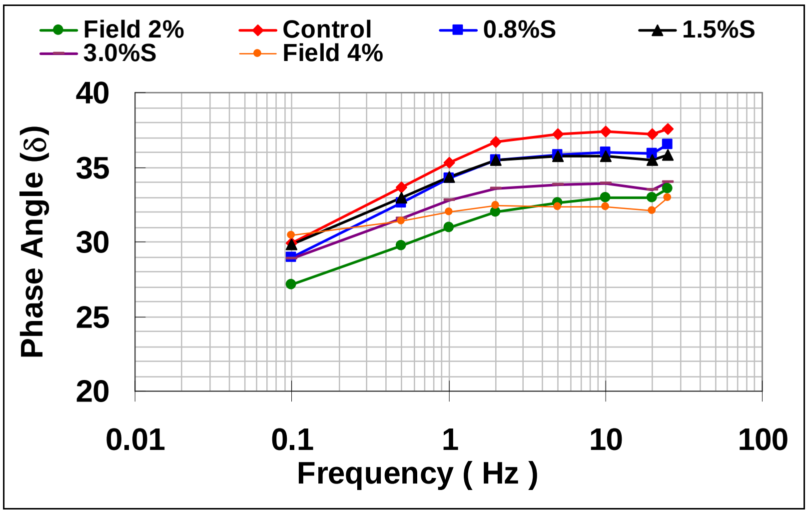
Figure 4.10 illustrates the measured phase angle (δ) of mixtures with the change of loading frequency at different temperatures. Phase angle (δ) is an angle in degrees between a sinusoidal applied stress and the resulting strain in a controlled stress |E*| test. δ is primarily employed to estimate viscoelastic property of mixtures. It exhibits purely elastic behavior for δ value of 0°, purely viscous behavior for δ value of 90° and viscoelastic behavior in between for most asphalt mixtures in practice. Results showed that for all mixtures, at lower and intermediate temperatures of 4.4°C and 21.1°C (Figures 4.10 (a) and (b)), δ decreased with an increase in loading frequency, but increased at higher temperatures of 37.8°C and 54°C (Figures 4.10 (c) and (d)). In addition, at any temperature and loading frequency, δ value of lab-mixed lab-compacted mixtures (Superpave mix design with 4% of air voids content) decreased with the increase of Sasobit content.



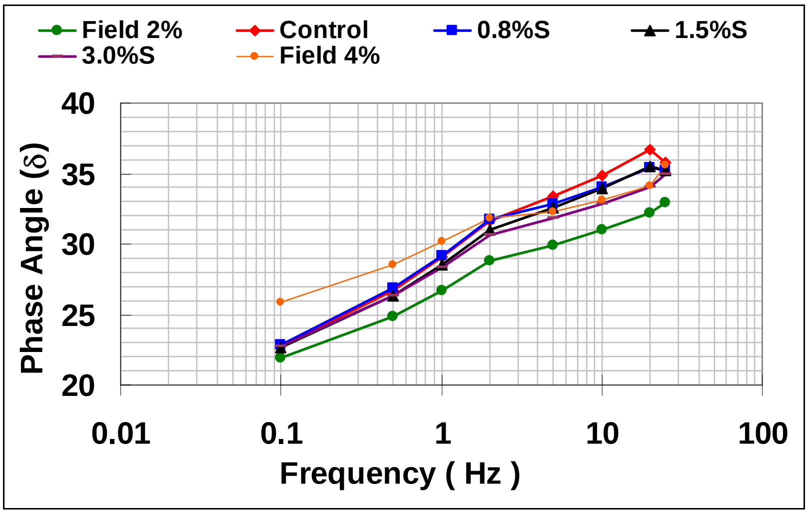
(a) 4.4°C



(b) 21.1°C



(c) 37.8°C



(d) 54°C

Figure 4.10 Phase Angel (δ) at different temperatures.

As for the field mixtures (field-mixed lab-compacted specimens), at lower temperatures, the mix with 4% VTM showed lower δ values than that with 2% VTM. However, with the increase of the temperature, the former presented higher δ values, indicating its more viscous behavior than the latter. At any temperature, the δ value of field-mixed lab-compacted mix modified with 1.5% Sasobit (4% VTM) was lower than that of lab-mixed lab-compacted mix modified with same Sasobit addition (4% VTM). This was also consistent with the comparison of their |E*| values.

Flow Number (F_N)

Flow number (F_N) test is a laboratory approach to determine the permanent deformation characteristics (rutting performance) of paving materials by applying a repeated dynamic load. As introduced in Chapter III, the F_N of the mixture is defined as the starting point (or the minimum strain rate) in cycle number, at which tertiary flow occurs on a cumulative permanent strain curve during the test. Figure 4.11 illustrates F_N and associated microstrain values of mixtures at test temperature of 54°C, where “Field VTM 2%” stands for field-mixed lab-compacted specimens with 2.5% of air voids content (job mix formula in the field), and “Field VTM 4%” stands for field-mixed lab-compacted specimens with 4% of air voids content (Superpave mix design). For all lab-mixed lab-compacted specimens using raw materials with 4% of air voids content (Superpave mix design), F_N increased with the increase of Sasobit content. Mixtures with higher F_Ns are more stable mixes which should exhibit less permanent deformation in field conditions. Therefore Sasobit addition provided better rutting performance of mixes, which was consistent with the result for Sasobit-modified binders. Field mixture with 2.5% of VTM showed the highest F_N value of 2104 among all mixtures. Field mixture with 4% of VTM also had higher F_N value (906) compared with that of lab-mixed lab–compacted mixture with raw materials (390) with same design air voids and Sasobit addition (1.5%). It may be because of stiffer mixes prepared with loose mixtures, which was correlated with their higher |E*| values shown in Figure 4.9 (d).

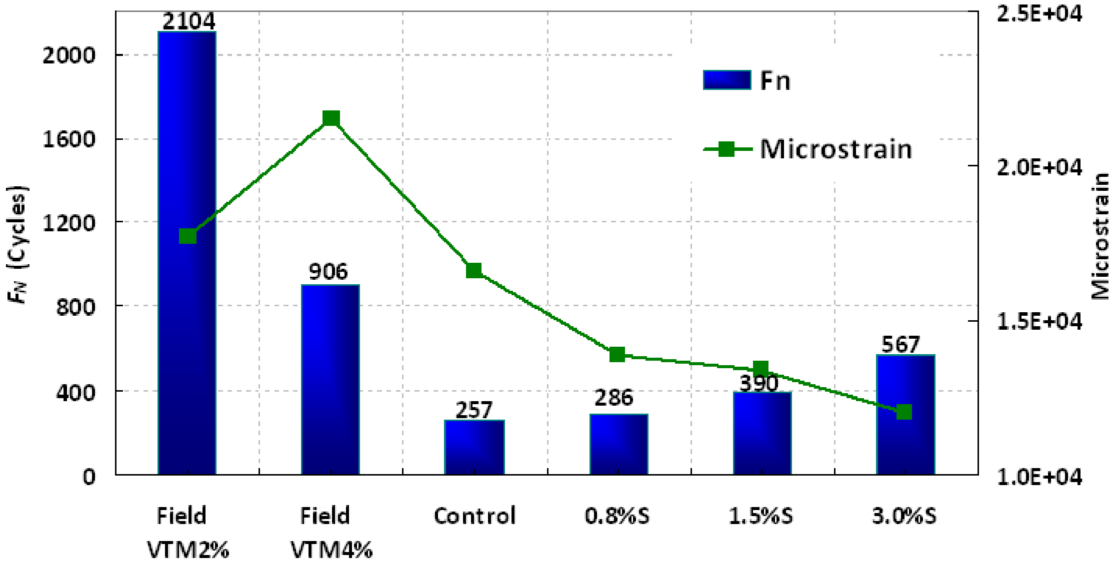


Figure 4.11 F_Ns and associated microstrains of mixtures.

Rutting Performance

Rutting performance of laboratory prepared specimens using raw materials and field core samples was evaluated by the APA according to AASHTO TP63-07 at the temperature of 58°C. Volumetric properties of Sasobit-modified mixtures were verified before tests and the results are summarized in Table 4.4. Results show that VTM (%) of laboratory mixtures meets the design criteria, i.e. 7±0.5% air voids for APAspecimens.

Table 4.4 Volumetric properties for APA specimens

Mix Name	Control Mix	Sasobit Mix 1 (0.8%)	Sasobit Mix 2 (1.5%)	Sasobit Mix 3 (3.0%)	Field Mix
G_{mm}	2.6784	2.6763	2.6626	2.6517	2.6237
Sasobit content	0	0.8%	1.5%	3.0%	1.5%
APA Test Specimens					
G_{mb}	2.4868	2.4825	2.4727	2.4621	2.476
VTM (%)	7.18	7.24	7.13	7.15	5.62
VMA (%)	15.86	16.10	16.34	16.70	15.17
VFA (%)	54.73	54.77	56.36	57.18	62.31
STD (σ)	0.4%	0.3%	0.1%	0.1%	1.3%

Results from APA test are illustrated in Figure 4.12. It can be seen that with the increase of Sasobit content from 0% to 3%, rutting depth of lab-mixed lab-compacted specimens decreased from 4.222mm to 2.643mm accordingly, indicating improved rutting resistance of mixtures with the addition of Sasobit. It conformed to F_N results presented above. It was also consistent with Kanitpong et al. (2007)'s APA test result. In addition, the rutting depth of the field-cored samples (3.788 mm) was higher than that of lab-mixed lab-compacted specimens with same 1.5% of Sasobit content (2.849 mm).

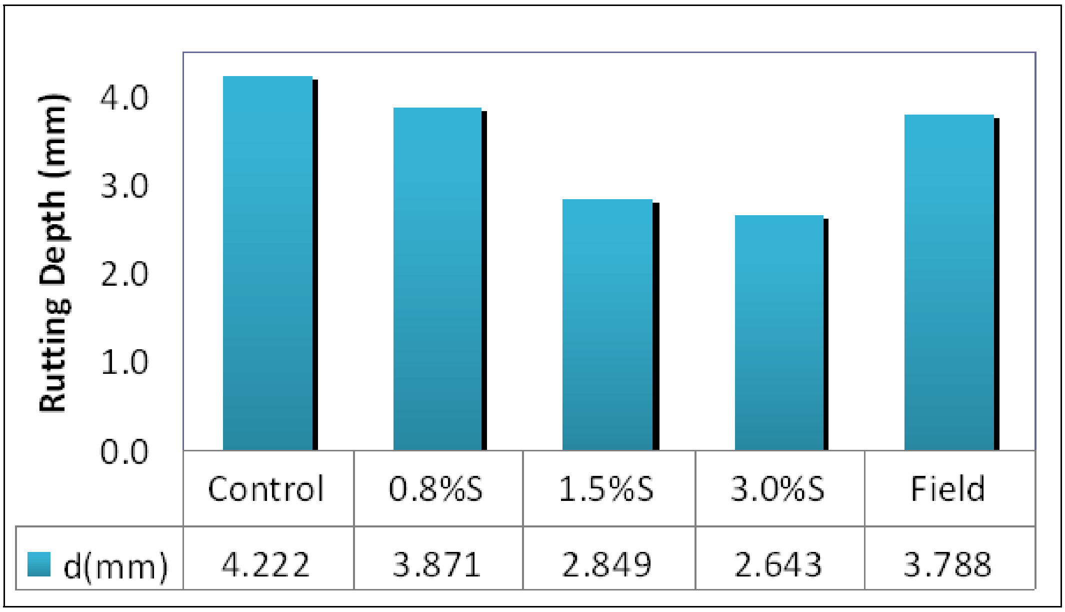


Figure 4.12 APA rutting depths for all mixtures.

Low Temperature Performance

Low temperature performance of mixtures including their tensile creep stiffness *S(t)*, and tensile strength *S* was evaluated according to AASHTO specification T322-07 by the IDT. Volumetric properties of IDT specimens were verified before test and results are summarized in Table 4.5. Results show that VTM (%) of lab-mixed lab-compacted mixtures using raw materials meets the design criteria, i.e. 7±0.5% air voids for IDT specimens. Field-cored samples showed lower VTM.

Table 4.5 Volumetric properties for IDT specimens

Mix Name	Control Mix	Sasobit Mix 1 (0.8%)	Sasobit Mix 2 (1.5%)	Sasobit Mix 3 (3.0%)	Field Mix
G_{mm}	2.6784	2.6763	2.6626	2.6517	2.6237
Sasobit content	0	0.8%	1.5%	3.0%	1.5%
IDT Test Specimens					
G_{mb}	2.4899	2.4855	2.4737	2.4601	2.5147
VTM (%)	7.07	7.13	7.09	7.23	4.17
VMA (%)	15.76	15.91	16.31	16.77	13.77
VFA (%)	55.16	55.17	56.49	56.90	69.75
STD (σ)	0.33%	0.25%	0.33%	0.31%	1.0%

Tensile strength is a general accepted measuring factor for asphalt mix for their low temperature cracking resistance. Higher tensile strength at low temperatures indicates higher resistance to thermal cracking. As show in Figure 4.13, tensile strength of all mixes increased with the decrease of temperature because of its corresponding higher elastic property under lower temperature. For all laboratory prepared specimens, tensile strength decreased with the increase of Sasobit content at all testing temperatures, which indicated degraded resistance to low temperature cracking. This observation was consistent with that of Sasobit-modified binders as discussed previously. Field-cored samples presented highest tensile strengths probably due to the contribution of lower VTM to the tensile strength of mixtures.

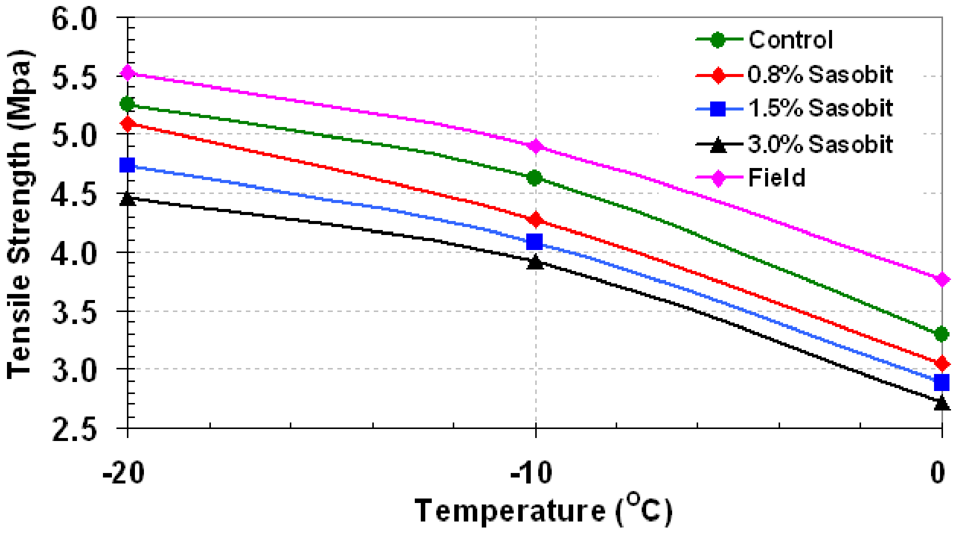
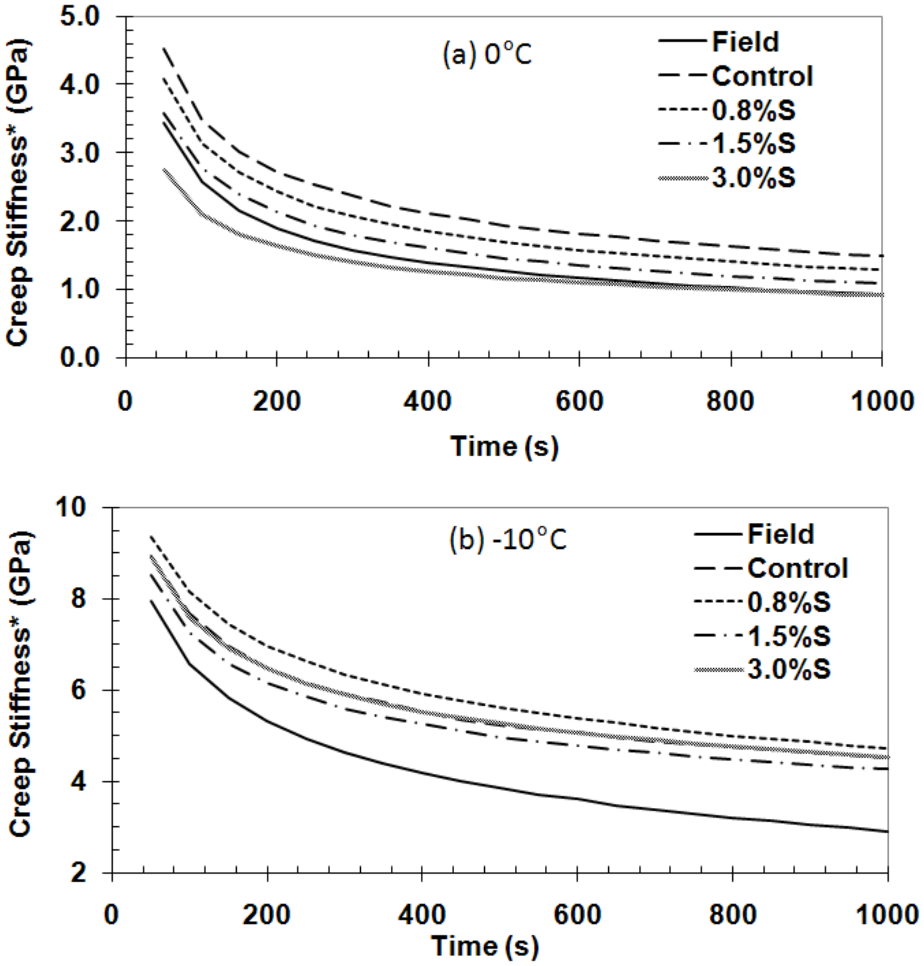


Figure 4.13 Tensile strengths of mixes at different temperatures.

Figure 4.14 compares creep stiffness *S(t)* of all mixes as a function of loading time under three temperatures, i.e. 0°C, -10°C and -20°C. In general, creep stiffness increased with the decrease of temperature, which was correlated to the trend of tensile strength over temperature. At testing temperature of 0°C, creep stiffness increased with the decrease of Sasobit content. However, large variability of creep stiffness was observed with the change of Sasobit content at lower temperatures. When test temperature dropped to -10°C, 0.8% Sasobit addition provided highest creep stiffness; while at temperature of -20°C, mix with 1.5% Sasobit content had the highest creep stiffness. Field mixture presented the lowest creep stiffness at all testing temperatures, which was different from its performance in tensile strength.



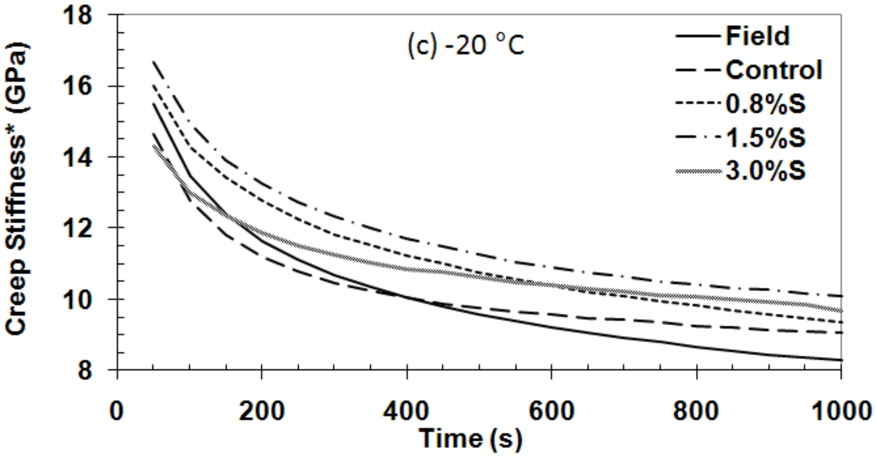


Figure 4.14 Creep stiffness of mixes at different temperatures.

Moisture Sensitivity

The effect of Sasobit on moisture susceptibility of mixes was evaluated by the MIST according to AASHTO T283-07. The volumetric properties were verified and summarized for MIST specimens in Table 4.6. Results showed that VTM (%) of laboratory prepared mixtures meets the design criteria, i.e. 7±0.5% air voids content. Field-cored samples showed 5.9% of VTM.

Table 4.6 Volumetric properties for MIST specimens

Mix Name	Control Mix	Sasobit Mix 1 (0.8%)	Sasobit Mix 2 (1.5%)	Sasobit Mix 3 (3.0%)	Field Mix
G_{mm}	2.6784	2.6763	2.6626	2.6517	2.6237
Sasobit	0	0.8%	1.5%	3.0%	1.5%
MIST Test Specimens					
G_{mb}	2.4788	2.4697	2.4618	2.4555	2.4692
VTM (%)	7.48	7.72	7.54	7.40	5.90
VMA (%)	16.13	16.44	16.71	16.92	15.33
VFA (%)	53.64	53.05	54.86	56.28	61.52
STD (σ)	0.61%	0.34%	0.23%	0.28%	4.0%

Table 4.7 summarizes the detailed results of MIST and Figure 4.15 illustrates the TSR results. The test results exhibited almost no difference in their tensile strength for all laboratory mixes in dry condition. However, TSR value slightly increased with the increase of Sasobit content from 0% to 3%, indicating

slightly better resistance to moisture susceptibility with the addition of Sasobit content. The TSR values of field mix and laboratory mix with the same Sasobit content of 1.5% were very close. Although there was a concern of increased susceptibility to moisture damage due to Sasobit addition from previous studies (Wasiuddin et al. 2008), the results from this study indicated at least the addition of Sasobit did not contribute to moisture damage of WMA compared with the control mix. Other studies also showed Sasobit performed well or had no significant influences in terms of moisture susceptibility (Hurley and Prowell 2005a, Kanitpong et al. 2007, Xiao et al. 2009).

Table 4.7 Tensile strength and TSR (%) of MIST specimens.

Mixture	Dry Subset (kPa)	Conditioned Subset (kPa)	TSR (%)
Control Mix	1452	996	68.61%
Sasobit Mix 1-0.8%	1464	1002	68.46%
Sasobit Mix 2-1.5%	1444	1051	72.79%
Sasobit Mix 3-3.0%	1431	1112	77.69%
Field Mix	1240	927	74.74%

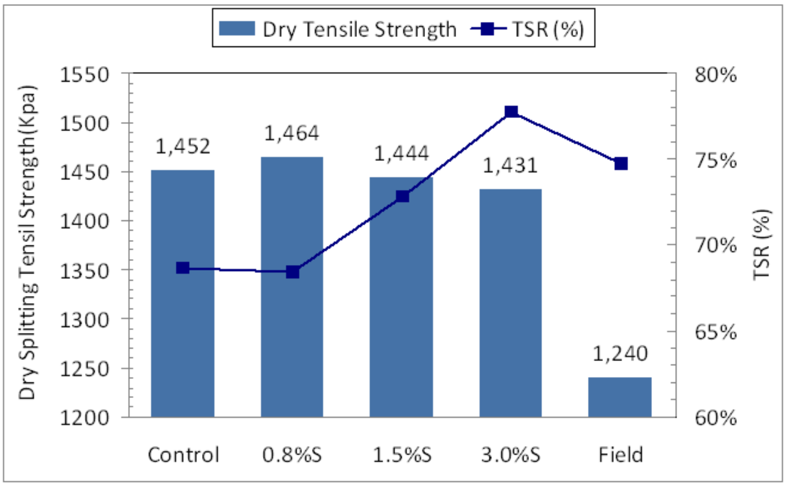


Figure 4.15 Moisture sensitivity of mixes.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

In line with the Sasobit WMA demonstration project conducted in Southeast Alaska, this study focused on evaluating performance of WMA binders and mixes in the laboratory. This chapter presents the summary of research findings as well as recommendations regarding the feasibility of using WMA for Alaska conditions and future work.

CONCLUSIONS

The following conclusions could be made from this study:

- The addition of Sasobit reduced both mixing and compaction temperatures of mixes. Compared with control binder without Sasobit addition, the addition of 3% Sasobit contributed to a decrease of more than 15ºC in mixing temperature and a decrease of 13ºC in the compaction temperature.
- The Sasobit addition significantly impacted the PG of binders. With the increase of Sasobit content from 0% to 3%, the high temperature end of asphalt PG increased from 58 to 76, however, the low temperature end also increased from -28ºC to -16ºC as well. Results from binder tests implied that Sasobit improved rutting resistance but deteriorated resistances to both fatigue and low temperature cracking.
- The SPT results showed that for lab-mixed lab-compacted mixtures, |E*| value increased with the increase of Sasobit content. This trend (or the effect of Sasobit addition on the |E*|) was more significant at higher temperatures. The field-mixed lab-compacted mixtures with both 2% and 4% of VTMs showed very close |E*| values. At the lowest temperature (i.e. 4.4°C), the |E*| values of field-mixed lab-compacted mix modified with

1.5% Sasobit were very close to those of lab-mixed lab-compacted mix modified with same Sasobit addition. However, with the increase of temperature, field-mixed lab-compacted mix presented higher |E*| values at all loading frequencies. The difference between their |E*| values became most significant at the highest temperature (i.e. 54°C).

- The results of δ values of mixtures were consistent with the comparison of their |E*| values. At any temperature and loading frequency, δ value of lab-mixed lab-compacted mixtures (Superpave mix design with 4% of air voids content) decreased with the increase of Sasobit content. As for the field-mixed lab-compacted specimens, at lower temperatures, the mix with 4% VTM showed lower δ values than that with 2% VTM. However, with the increase of the temperature, the former presented higher δ values, indicating its more viscous behavior than the latter. At any temperature, the δ value of field-mixed lab-compacted mix modified with 1.5% Sasobit (4% VTM) was lower than that of lab-mixed lab-compacted mix modified with same Sasobit addition (4% VTM).
- Mixtures with higher F_Ns are more stable mixes which should exhibit less permanent deformation in field conditions. For all lab-mixed lab-compacted specimens with 4% of air voids content (Superpave mix design), F_N increased with the increase of Sasobit content. Therefore Sasobit addition provided better rutting performance of mixes, which was also consistent with the result for Sasobit-modified binders. Field-mixed lab-compacted mixture had higher F_N value compared with that of lab-mixed lab–compacted mixture with same design air voids (4% of VTM) and same Sasobit addition (1.5%).
- For all lab-mixed lab-compacted specimens, the increase of Sasobit content from 0% to 3% produced reduced rutting depth from 4.222 mm to 2.643 mm accordingly, indicating improved rutting resistance of mixtures with the addition of Sasobit. It conformed to |E*| and F_N results from the SPT, and it was also consistent with other researchers' findings. In addition, the

rutting depth of the field-cored samples was higher than that of laboratory prepared specimens with same 1.5% of Sasobit content.

- For all laboratory prepared specimens, tensile strength decreased with the increase of Sasobit content at all testing temperatures, which indicated degraded resistance to low temperature cracking. This observation was consistent with that of Sasobit-modified binders. Field cored samples presented highest tensile strengths probably due to the contribution of lower VTM to the tensile strength.
- The MIST results exhibited slightly increased TSR values of lab prepared mixes with the increase of Sasobit content from 0% to 3%. The TSR values of field mix and laboratory mix with the same Sasobit content of 1.5% were very close. The results from this study indicated at least the addition of Sasobit did not contribute to moisture damage of WMA compared with the control mix.

RECOMMENDATIONS

Laboratory investigation of Sasobit-modified binders and WMAs in this study identified a lot of engineering benefits of WMAs using Sasobit over traditional HMA. WMAs using Sasobit with reduced mixing and compaction temperatures, improved workability and rutting resistance, and insignificant effect on moisture susceptibility favorably indicated the suitability of this WMA technology for Alaska conditions. The IDT results showed degraded resistance to low temperature cracking of WMA using Sasobit in this study. However, the effects of Sasobit on low temperature cracking would depend on the specific conditions to which the mixture is exposed. Additional tests at lower temperatures, along with a more complete thermal cracking analysis for specific environments of interest should be performed to get a more definitive answer regarding the effects of Sasobit on low temperature cracking.

The limited tests of field specimens in this study generally displayed higher variance/ inconsistency in results than those of lab-mixed lab-compacted specimens. Therefore, closer correlation between lab results and field performance data should be sought in the future study. Studies should include long-term performance and associated life cycle cost analyses.

Since the field demonstration project of WMA using Sasobit was constructed in 2008 in Southeast of Alaska, another two field trials in both central and northern regions of Alaska used WMA technologies (Double Barrel Green and Evotherm) in the 2009 paving season. It is expected that WMA use will increase in future Alaskan paving projects. In addition, in order to address challenges from increased demands for environmental friendly paving mixtures and increasing costs of raw materials, other WMA applications in Alaska such as incorporating WMA additives to RAP and crumb rubber asphalt mixture are needed to be investigated.

WMA technologies are new, and most are proprietary. The NCHRP has currently several major completed/on-going research projects (projects 09-43, 09-47, and 09-47A) that are evaluating different aspects of WMA technologies including mixture design, performance testing, field construction, emission measurement, etc. The National Asphalt Paving Association (NAPA) and NCAT in cooperation with FHWA have spent a lot of research efforts as well. There are also a lot of completed/on-going research projects funded by different state highway agencies and private industries to evaluate these new technologies. However, nationally coordinated studies are still needed to answer lots of questions regarding the implementation of WMA technologies, especially long-term performance, cost analysis, specifications and quality control.

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APPENDIX – PG Tests of Binders

Table 1 Data summary of control binder

Binder	Parameters	Specification	Temperature Measured	Measured Parameters	Pass/Fail
Original	Viscosity at 135ºC	3 Pa·s, Max	135 ºC	0.433	Pass
	DSR G*/Sinδ	1.0 kPa, Min.	58 ºC	2.0723KPa	Pass
			64 ºC	0.9871 KPa	Fail
			70 ºC	0.7228 KPa	Fail
RTFO aged	Mass Loss	1%, Max	163 ºC	0.47%	Pass
	DSR G*/Sinδ	2.2 kPa, Min	58 ºC	4.3172 KPa	Pass
			64 ºC	3.0646 KPa	Pass
			70 ºC	1.1682 KPa	Fail
PAV aged	DSR G*Sinδ	5000 kPa, Max	13 ºC	6502KPa	Fail
			16 ºC	4835KPa	Pass
			19 ºC	3355KPa	Pass
	BBR-Creep stiffness (S)	300 MPa, Max	-6 ºC	22.14 MPa	Pass
			-12 ºC	103.5 MPa	Pass
			-18 ºC	226.5 MPa	Pass
			-24 ºC	558 MPa	Fail
	BBR-m-value	0.300, Min	-6 ºC	0.4315	Pass
			-12 ºC	0.3595	Pass
			-18 ºC	0.3005	Pass
			-24 ºC	0.21	Fail

Table 2 Data summary of binder modified with 0.8% Sasobit

Binder	**Parameters**	**Specification**	**Temperature Measured**	**Measured Parameters**	**Pass/Fail**
Original	Viscosity at 135ºC	3 Pa·S, Max	135 ºC	0.491	Pass
	DSR G*/Sinδ	1.0 kPa, Min.	58 ºC	3.8278KPa	Pass
			64 ºC	2.0337KPa	Pass
			70 ºC	1.0850KPa	Pass
			76 ºC	0.6298KPa	Fail
RTFO aged	Mass Loss	1%, Max	163 ºC	0.41%	Pass
	DSR G*/Sinδ	2.2 kPa, Min	58 ºC	7.2419 KPa	Pass
			64 ºC	3.6027KPa	Pass
			70 ºC	1.8473KPa	Fail
			76 ºC	0.9900KPa	Fail
PAV aged	DSR G*Sinδ	5000 kPa, Max	19 ºC	5510KPa	Fail
			22 ºC	3814KPa	Pass
			25 ºC	2628KPa	Pass
	BBR-Creep stiffness (S)	300 MPa, Max	-6 ºC	71.65MPa	Pass
			-12 ºC	160 MPa	Pass
			-18 ºC	282.5 MPa	Pass
	BBR-m-value	0.300, Min	-6 ºC	0.3670	Pass
			-12 ºC	0.3125	Pass
			-18 ºC	0.272	Fail

Table 3 Data summary of binder modified with 1.5% Sasobit

Binder	**Parameters**	**Specification**	**Temperature Measured**	**Measured Parameters**	**Pass/Fail**
Original	Viscosity at 135ºC	3 Pa·S, Max	135 ºC	0.445	Pass
	DSR G*/Sinδ	1.0 kPa, Min.	58 ºC	3.8523KPa	Pass
			64 ºC	2.0344KPa	Pass
			70 ºC	1.0888KPa	Pass
			76 ºC	0.6287KPa	Fail
RTFO aged	Mass Loss	1%, Max	163 ºC	0.26%	Pass
	DSR G*/Sinδ	2.2 kPa, Min	58 ºC	10.7444 KPa	Pass
			64 ºC	5.4831KPa	Pass
			70 ºC	2.7777KPa	Pass
			76 ºC	1.4787KPa	Fail
PAV aged	DSR G*Sinδ	5000 kPa, Max	19 ºC	5730KPa	Fail
			22 ºC	4121KPa	Pass
			25 ºC	2708KPa	Pass
	BBR-Creep stiffness (S)	300 MPa, Max	-6 ºC	63.90MPa	Pass
			-12 ºC	135.50 MPa	Pass
			-18 ºC	249 MPa	Pass
	BBR-m-value	0.300, Min	-6 ºC	0.3570	Pass
			-12 ºC	0.3020	Pass
			-18 ºC	0.2720	Fail

Table 4 Data summary of binder modified with 3.0% Sasobit

Binder	**Parameters**	**Specification**	**Temperature Measured**	**Measured Parameters**	**Pass/Fail**
Original	Viscosity at 135ºC	3Pa·S, Max	135 ºC	0.392	Pass
	DSR G*/Sinδ	1.0 kPa, Min.	58 ºC	6.4579KPa	Pass
			64 ºC	3.3371KPa	Pass
			70 ºC	1.5516KPa	Pass
			76 ºC	1.0790KPa	Pass
			82 ºC	0.6600KPa	Fail
RTFO aged	Mass Loss	1%, Max	163 ºC	0.17%	Pass
	DSR G*/Sinδ	2.2 kPa, Min	58 ºC	20.2569KPa	Pass
			64 ºC	10.3197KPa	Pass
			70 ºC	5.0488KPa	Pass
			76 ºC	2.6025KPa	Pass
			82 ºC	1.3918KPa	Fail
PAV aged	DSR G*Sinδ	5000 kPa, Max	19 ºC	7256KPa	Fail
			22 ºC	5438KPa	Fail
			25 ºC	4043KPa	Pass
	BBR-Creep stiffness (S)	300 MPa, Max	-6 ºC	88.33MPa	Pass
			-12 ºC	166 MPa	Pass
			-18 ºC	310MPa	Fail
	BBR-m-value	0.300, Min	-6 ºC	0.3010	Pass
			-12 ºC	0.2715	Fail
			-18 ºC	0.2470	Fail