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COMPREHENSIVE EVALUATION OF FOUR WARM ASPHALT MIXTURE REGARDING VISCOSITY, TENSILE STRENGTH, MOISTURE SENSITIVITY, DYNAMIC MODULUS AND FLOW NUMBER.

by

Anand Sampath

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Graduate College
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CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

Anand Sampath

has been approved by the Examining Committee
for the thesis requirement for the Master of Science
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James Stoner

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Paul Hanley

I dedicate this thesis to my parents, without whom I would not be where I am today

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ABSTRACT

Hot Mix Asphalt (HMA) has been used over the years for laying roads. It required the aggregate and the binder to be heated to temperatures above 160°C (320°F). Heating the aggregate and binder in large quantities consumed a lot of fuel. This called for alternative solutions in the technology of laying roads. This brought about a new technology called Warm Mix Asphalt (WMA). WMA is an emerging technology that can allow asphalt to be produced and compacted at a significantly lower temperature. In the past, a number of researchers evaluated various WMA mixtures using selected testing procedures in the laboratory. However, none of them evaluated all the major WMA products and compared them with WMA mixtures without an additive using a comprehensive set of testing protocols. This paper presents a comprehensive evaluation result of three major WMA additives (Sasobit®, Evotherm J1 and Rediset^{TM}) regarding their viscosity, tensile strength, moisture sensitivity, dynamic modulus and flow number. These three additives were chosen since all of them are prepared from a base wax product.

The asphalt showed a decreasing trend in viscosity with increase in the concentration of the additives. The WMA specimen with additives exhibits similar air voids as control WMA specimens which indicate these WMA additives are effective in compacting asphalt mixtures at low temperatures. The Indirect Tensile Strengths (ITS) and Tensile Strength Ratio (TSR) values of the WMA specimen with admixtures were found to be higher than the control WMA specimens. This result indicates that the admixtures play a significant role in enhancing the properties of WMA. WMA mixtures with additives exhibited higher dynamic modulus than the control WMA at all temperatures. All the specimens passed the requirement of 10,000 cycles of repeated loading. The WMA specimen with Sasobit® additive exhibited the lowest permanent deformation. Based on overall test results it can be concluded that Sasobit®, Evotherm J1 and Rediset^{TM} WMA additives are effective in producing WMA mixtures in the laboratory which have high strengths.

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CHAPTER 1 - INTRODUCTION

Warm mix asphalt (WMA) is an emerging technology that allows asphalt to flow at a lower temperature for mixing, placing and compaction. WMA technology not only reduces energy consumption, carbon dioxide emission, and asphalt oxidation but also increases paving season and hauling distance for a better working environment. In the past, a number of researchers evaluated various WMA mixtures using certain testing protocols in the laboratory. However, none of them evaluated all the major WMA products and compared them against control WMA (mixtures without an additive). A comprehensive evaluation of all three major WMA additives is presented in this thesis with regards to their fundamental characteristics such as viscosity, tensile strength, moisture sensitivity, dynamic modulus and flow number.

The additives which had a hydro-carbon base were selected for experimentation in the laboratory. The additives selected were: Sasobit®, Evotherm J1 and Rediset™. These three additives along with WMA as a control were tested for their fundamental engineering properties by performing the indirect tensile strength test and the moisture sensitivity test. To determine the flow of the asphalt, viscosity tests were done. To evaluate a long-term reliable WMA mixture performance over a wide range of traffic and climatic conditions, the dynamic modulus and the repeated load tests were conducted using the simple performance testing equipment.

Objective

To provide a safe and reliable highway, warm mix asphalt (WMA) pavement must meet requirements for strength, moisture sensitivity, stiffness and rutting. However, a major difficulty in evaluating WMA mixtures is that there is no national research done on the comparative analysis of a large number of WMA technologies using a comprehensive set of testing procedures. The main objectives of this thesis are to: 1) investigate the available technologies for producing WMA and 2) evaluate various WMA products with respect to their fundamental engineering properties and performance-related characteristics.

Literature review

At the Bitumen Forum of Germany in 1997, warm mix asphalt (WMA) technology was identified as one of means to lower emissions. The WMA technology was introduced in the United States in 2002 when the NAPA sponsored an industry scanning tour to Europe for asphalt paving contractors (1). In 2004, the World of Asphalt convention featured a demonstration project of WMA, and since then, WMA additive manufacturers have successfully performed many demonstration projects throughout the United States (2).

Hurley and Prowell (3, 4, 5) evaluated three different WMA additives: Aspha-Min®, Sasobit® and Evotherm™ and concluded that all three technologies improved the compactibility of the asphalt mixture and resulted in lower air voids compared to HMA. Hurley and Prowell (6) reported that, based on Hamburg wheel-tracking test, these three WMA additives did not increase the rutting potential. Prowell et al. (7) reported that the accelerated WMA test sections exhibited the excellent field performance in terms of rutting.

Biro et al. (8) reported that Sasobit® significantly reduced a permanent deformation based on the repeated creep recovery test. Lee et al. (9) reported that longer aging time in the rolling thin film oven (RTFO) test with the rubber modified asphalt resulted in an increase in the high temperature viscosity. Nazimuddin et al. (10) reported that Sasobit® decreased the rut depth which could justify the increase in high temperature binder grading. Kunnawee et al. (11) reported AC 60/70 binder modified with 3.0% Sasobit® not only improved the compactability but also exhibited a greater resistance to densification under simulated traffic. Gandhi and Amirkhanian (12) demonstrated that two of the three binders maintained the same PG grade with the addition of Sasobit®. Lee et al. (13) prepared three types of CIR-foam specimens: (a) CIR-foam with 1.5% of Sasobit®, (b) CIR-foam with 0.3% Aspha-min®, and (c) CIR-foam without any additive. They reported that WMA additives have improved the compactibility of CIR-foam mixtures resulting in a lower air void. The indirect tensile strength of CIR-foam mixtures with Sasobit® was the highest and the dynamic moduli of CIR-foam mixture with WMA additives were higher than ones without any additive. Flow number of CIR-foam mixtures with Sasobit® was the highest followed by ones with Aspha-min® and the specimens without any additive.

Kvasnak et al. (14) reported that the laboratory- produced WMA mixtures using Evotherm® DAT additive was more moisture susceptible than the plant-produced WMA mixtures with Tensile Strength Ratio (TSR) higher than 80% that is a ratio of the indirect tensile strength of the conditioned specimen over the dry specimen. Gonzalez-Leon et al.

(15) reported that WMA mixtures with Cecabase RT® additive achieved a minimum requirement of 75% that is a ratio of the fracture force of the wet specimen over the dry specimen. Xiao et al. (16) reported that TSR values of WMA mixtures with Sasobit® and Aspha-min® additives were lower than 85% but increased above 85% when 1.0% of hydrated lime was added. Hensley (17) recommended that asphalt compaction to occur on the field at a target viscosity of 0.28 ± 0.02Pa.s and a corresponding temperature of 160°C. However, Bahia et al. (18) recommended 3 Pa.s as the limiting low shear viscosity for estimating compaction temperature.

Lu and Redelius (19) studied the effect of asphalt that contains wax in them naturally. They concluded that using waxy bitumen, the asphalt mixtures showed higher fracture temperature. With regard to water sensitivity, they found that adding wax to asphalt does not affect the water sensitivity in any way. Another study conducted by Edwards et al. (20) says that bitumen containing natural waxes have higher modulus and lower phase angle.

Importance of using WMA

The importance of using WMA can be categorized into 3 categories: economic, operational and environmental (21). Table 1 represents the potential benefits of WMA.

Table 1: Potential benefits of WMA (21)

Potential Benefit	**Economic**	**Operational**	**Environmental**
Reduced fuel use	X		X
Late season (cool weather) paving		X	
Better workability and compaction	X	X	
Reduced plant emissions of greenhouse gases			X
Increased usage of RAP	X		
Improved working conditions for plant and paving crew		X	

Reduced Fuel Usage

Since the main advantage of warm mix is the reduction of mixing and compaction temperatures, compared to HMA there is significant reduction in the usage of fuels. Before mixing the asphalt with the aggregates it is necessary to heat the aggregates and get rid of the moisture. The additives reduce the viscosity at lower temperatures making it easy to mix asphalt with the aggregate at a lower temperature. Thus with the use of additives it is possible to lower the mixing and compaction temperature and therefore resulting in savings of up to 35%.

Late season paving

Research has shown that since WMA is compactable at lower temperatures than HMA, the mix can be produced at lower temperatures and can therefore remain compactable for a longer period of time than HMA. This means that it is possible to extend the paving season further into the year.

Better Workability and Compaction

WMA allows better workability at lower temperatures due to the addition of additives. Better workability would result in better compaction of the pavement since it would take fewer roller passes to obtain the desired air voids for the pavement. Many WMA users have reported similar densities to HMA.

Reduced Plant Emissions of Greenhouse Gases

Before laying the roads the aggregates are heated to a dry condition. This requires the use of fossil fuels. Also once the aggregates are heated, it is mixed with asphalt and the mixture is stored at an elevated temperature in order to facilitate the construction. This also requires the use of fossil fuel. Burning fossil fuel contributes to the production of several pollutants like carbon dioxide (CO_2), nitrogen oxide (NO_x), and sulphur dioxide ($S0_2$). Thus by using WMA it is possible to cut down on the gaseous emissions since the amount of fuel used in WMA is significantly less. Table 2 represents the reduction of emissions due to using WMA.

Table 2: Reduction in emission of greenhouse gases (1).

Emission	**Reduction in Measured Emission – WMA (compared to HMA)**
CO_2	15-40%
SO_2	18-35%
NO_x	18-70%
CO	10-30%
Dust	25-55%

Increased Usage of RAP

Reclaimed Asphalt Pavement (RAP) is the term given for the asphalt material that has been removed and/or reprocessed and can be used as aggregates for laying roads. The usage of RAP in HMA has been limited by many highway agencies due to the concern that the materials might get aged at high temperatures and would potentially lead to early cracking of the roads. The mixing temperature in WMA is significantly lower and can thus facilitate the use of RAP for construction.

Improved Working Conditions

From the work completed in Europe (1) it is seen that the worker exposure to fumes is lesser in WMA when compared to HMA. The reduction in the mixing temperature causes a visible reduction in the smoke and odor and may thus result in improved working conditions.

CHAPTER 2 - WARM MIX ASPHALT ADDITIVES EVALUATED

To produce WMA mixtures in the laboratory, as shown in Figure 1, three WMA additives were obtained: Sasobit®; Evotherm J1; and Rediset^{TM} WMX. Rediset and Sasobit were organic additives whereas Evotherm was a chemical additive.

Figure 1: Additives (from left to right) a) Sasobit® b) Rediset^{TM} c) Evotherm J1

Sasobit®

Organic additives, that have melting points below a normal asphalt production temperature, can be added to asphalt to reduce its viscosity. With organic additives, the viscosity of asphalt is reduced at the temperature above the melting point in order to produce asphalt mixtures at lower temperatures. Below the melting point, organic additives tend to increase the stiffness of asphalt (22).

Sasobit® has been used in three different sizes for WMA pavements. They are pellets, flakes and powder. Sasobit® is a Fischer-Tropsch (FT) wax produced from the coal gasification process and is typically added at the rate of 1.5% by weight of asphalt. Recently it has started production from natural gas using the FT process. In Fischer-Tropsch process, the carbon-monoxide atoms get converted into a mixture of hydrocarbons having molecular chain lengths from 1 to 100 carbon atoms or greater. In this process, white hot coal is treated with a blast of steam. Iron or cobalt act as a catalyst in the reaction. The reaction can be represented as follows: -

$(2n+1)H_2 + nCO \rightarrow C_nH_{(2n+2)} + nH_2O$

The makers of Sasobit® claim that there exists a difference between the generic paraffin wax and the FT wax. They say that Sasobit® has a much longer chain length - 40 to 115 carbon atoms and thus has a melting point around 99°C compared to 20 to 45 carbon atoms and a melting point of 50°C to 80°C for generic paraffin wax. The makers also claim that Sasobit® forms a lattice structure in the asphalt binder which is the basis for the stability of asphalt that contains Sasobit®. Sasobit® can be added to the asphalt (wet process) or the asphalt mixture (dry process). Sasobit® helps in increasing the compactibility of the mixture and thus creates lower air voids in the specimen when compared to the mixture without any additives. Since Sasobit® can dissolve with the binder at lower temperatures; a high shear mixer is not required at the construction site for mixing the additive with asphalt. Sasobit® forms a homogeneous solution with the base binder after stirring and lowers the viscosity of asphalt. Sasobit® manufacturer claims that a mixing temperature can be lowered by up to 32°C (23).

Rediset^{TM} WMX

Rediset^{TM} WMX is a combination of organic additives and surfactants that is developed to enhance the adhesion between asphalt and aggregates. The manufacturer of Rediset^{TM}, Azko Nobel claims that the surfactants improve the wetting ability of the asphalt binder for better coating with the aggregates, and the organic additives provide a reduction of the viscosity of the binder and a lubricating effect for easier coating and compaction (24). It is supplied in a pellet form that can be added at a dosage rate of 1.5% to 2.5% by weight of asphalt that can be added to the asphalt or the mixture (25). According to the recommendation of the manufacturer, a dosage of 2% by weight of asphalt is used for preparing the specimens. Rediset^{TM} is said to improve the cohesive strength of the asphalt and reduces the rutting and moisture sensitivity of the final pavement (25). Researchers have done underwater Hamburg wheel tracking test and the result shows that Rediset^{TM} improves the cohesive strength on par with or better than lime or cement. Rediset^{TM} reduces the production temperature of asphalt by 60°F and can reduce the fuel consumption by at least 20% and will cause lower CO_2 emissions.

Evotherm J1

Various chemical additives are emerging for WMA that help asphalt coat the aggregates at lower temperatures. Most of them are proprietary and the manufacturers do not disclose detailed information about their chemical compositions.

Initially, MeadWestvaco developed Evotherm™ that is composed of 70% asphalt and 30% water by weight along with a small amount of surfactant. Then, Evotherm ET was developed which was a water based emulsion which replaces the liquid asphalt in the HMA design. Later, a new Evotherm® DAT (Dispersed Additive Technology) was developed with a lesser amount of water that can be directly injected as a solution to the asphalt line at the plant. Recently, Evotherm J1, also known as REVIX, was developed with no water that would reduce an internal friction between binder and aggregate and between coated aggregate particles during mixing and compaction (14, 21). According to the manufacturer of EvothermJ1, an emulsion is created when Evotherm is mixed with the asphalt. When this emulsion is used for mixing aggregates, it creates better workability, aggregate coating, adhesion, and increased compaction. The liquid Evotherm J1 can be added to asphalt at a dosage rate of 0.5% by weight of asphalt. The effectiveness of the Evotherm J1 was demonstrated in a field test, where a production temperature was reduced by up to 56°C (26). MeadWestvaco also report that due to the reduction in the production temperature at the plant, there can be energy savings of up to 55%, which results in 45% reduction in CO_2 and SO_2 emissions, 50% reduction in NO_x, 41% reduction in the total organic material and benzene soluble fractions were found to be below detectable limits.

CHAPTER 3 - BINDER TESTING

A wide range of tests were done on the samples to analyze their properties. The testing was divided into binder testing and mixture testing. In binder testing viscosity tests were done and the properties of the various additives on asphalt were recorded. For mixture testing, a variety of tests were conducted to analyze the performance of the various additives. The Indirect Tensile Strength (ITS) tests were done to evaluate the strength of the sample. Then moisture sensitivity test using the AASHTO T-283 method was performed to analyze the effect of moisture on the mixture. The flow number and the dynamic modulus tests were done to analyze the effect of repeated loadings on the sample. The specific gravity and the air void of the samples were measured. The air voids gave a good measure about the effect of compaction under different additive. The following flowchart summarizes the list of experiments done using different additives.

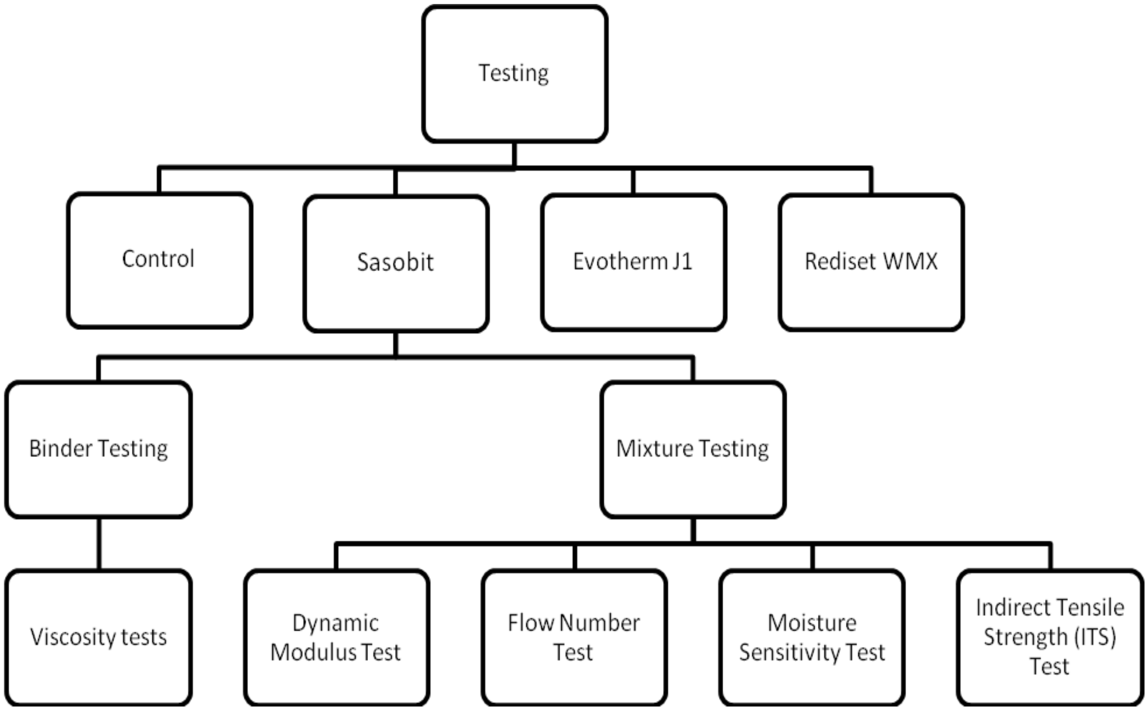

Figure 2: Flow chart of the list of experiments performed

Viscosity Test

The concept of warm mix technologies is to reduce the asphalt binder viscosity, which allows the asphalt to attain a suitable viscosity to coat the aggregates and thus compact the mixes at lower temperatures. Therefore the viscosity of the binder is very essential for the proper coating of asphalt on the aggregates. Studies have shown the benefits of using warm mix asphalt but limited research has been done on a comparative study of the effect of viscosity of the asphalt with addition of different additives. This study aims to determine the effect of the additives on the viscosity of the binder and the effectiveness of each additive. The additives used for the study are Sasobit®, Evotherm

J1 and Rediset^{TM} WMA. The viscosity of asphalt with these additives was then compared with the viscosity of virgin asphalt. In addition, viscosity test was conducted using the generic paraffin wax to determine if it contributed towards reduction in viscosity of the binder. Paraffin wax is a non-polar substance and hence will not cause any hindrance to coating of asphalt on the aggregates.

It is important to note that asphalt binders behave differently at different temperatures. In the field it is very difficult to regulate the temperature and it is often found that at different sites the aggregates are mixed at different temperatures. It is therefore very important to comprehensively study the effect of temperature on the viscosity of the binder so that we can determine down to what temperature it is possible to mix the asphalt with the aggregates. For this purpose the study was conducted from 120°C to 135°C with increments of 5°C.

It is also very important to analyze the effect of the concentration of additives added to the binder so that we can determine the optimum amount of additives to be added to asphalt. Determination of the optimum amount of additive to be added to asphalt will cause significant savings to the user of these products. For the purpose of this study and considering the economical benefits, the study was done using 5 different concentrations of the additives, which are 0.5%, 1.0%, 1.5%, 2.0% and 3.0% per unit weight of asphalt.

Once the equilibrium temperature was attained, the testing started. About 15ml of binder was added to the sample chamber just before the testing could be done in order to minimize the effect of aging due to the high temperature. A total of 3 readings was taken for each specimen at an interval of one minute in order for the test result to be consistant.

It was essential that the three readings taken would not vary from each other significantly. Therefore the viscometer was allowed to run for a period of 10 minutes prior to observing the reading and only when the difference between the maximum and the minimum reading was lesser than 0.01 Pa.s, the readings were taken. Figures 3 to Figure 6 demonstrates the trend in the viscosity of the specimens at different concentration at the same temperature. Tables 3 to 6 show the numerical values of viscosity at different temperature and concentration. It can be observed that the addition of 0.5% of paraffin wax had the same effect as 3.0% of the commercial additives. This test result could potentially pave way for future research on the effect of paraffin wax on asphalt binders. As expected, the viscosity of asphalt increased from 1.245 Pa.s to 3.010 Pa.s. At 120°C, the asphalt viscosity exceeded the limit of 3 Pa.s which is the maximum viscosity at which the asphalt can be pumped at the field. However, with the addition of 0.5% of additives the viscosity reduced below 2.4 Pa.s making the asphalt passable to pump at lower temperature. It should be noted that at higher temperatures the additives did not play a significant part in lowering the viscosity of the binder.

Table 3: Viscosity of binder with EvothermJ1

Evotherm J1	Viscosity at 135°C (Pa.s)	Viscosity at 130°C (Pa.s)	Viscosity at 125°C (Pa.s)	Viscosity at 120°C (Pa.s)
Virgin Asphalt	1.25	2.37	2.85	3.01
0.5%	1.11	1.46	1.92	2.25
1.0%	1.07	1.33	1.79	2.10
1.5%	1.05	1.23	1.72	1.95
2.0%	0.95	1.16	1.65	2.04
3.0%	0.84	1.08	1.45	1.84

Table 4: Viscosity of binder with Rediset

Rediset™	Viscosity at 135°C (Pa.s)	Viscosity at 130°C (Pa.s)	Viscosity at 125°C (Pa.s)	Viscosity at 120°C (Pa.s)
0.5%	1.20	1.54	2.02	2.49
1.0%	1.13	1.44	1.93	2.14
1.5%	1.12	1.40	1.84	2.09
2.0%	1.11	1.39	1.86	1.99
3.0%	0.94	1.15	1.66	2.07

Table 5: Viscosity of binder with Sasobit

Sasobit®	Viscosity at 135°C (Pa.s)	Viscosity at 130°C (Pa.s)	Viscosity at 125°C (Pa.s)	Viscosity at 120°C (Pa.s)
0.5%	1.22	1.54	1.99	2.40
1.0%	1.22	1.46	1.94	2.32
1.5%	1.12	1.38	1.89	2.14
2.0%	0.96	1.32	1.72	2.06
3.0%	0.96	1.23	1.72	2.00

Table 6: Viscosity of binder with generic Paraffin Wax

Generic Paraffin Wax	Viscosity at 135°C (Pa.s)	Viscosity at 130°C (Pa.s)	Viscosity at 125°C (Pa.s)	Viscosity at 120°C (Pa.s)
0.5%	0.88	1.09	1.37	1.76
1.0%	0.82	1.01	1.29	1.65
1.5%	0.79	0.97	1.22	1.55
2.0%	0.73	0.90	1.13	1.43
3.0%	0.65	0.80	1.01	1.28

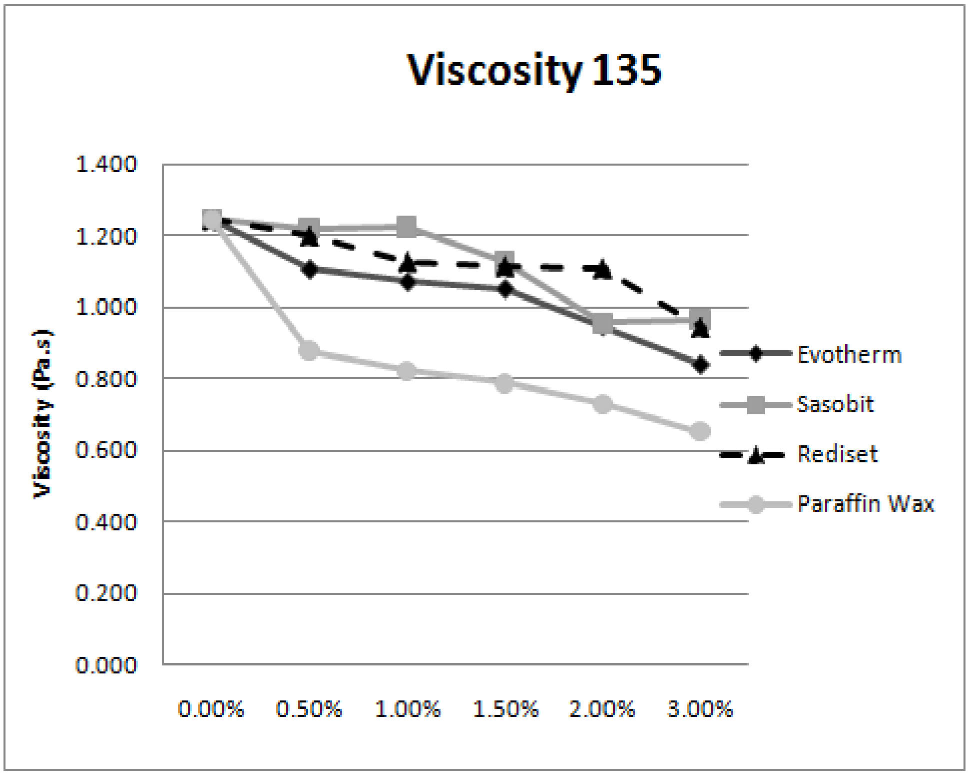

Figure 3: Viscosity of the binder at 135°C

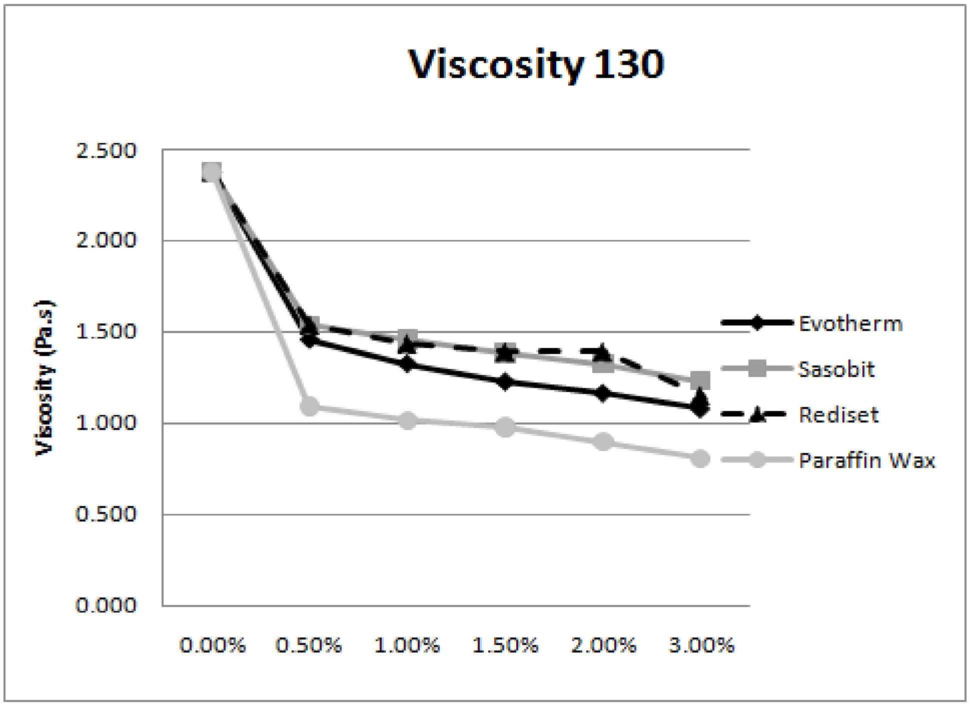

Figure 4: Viscosity of the binder at 130°C

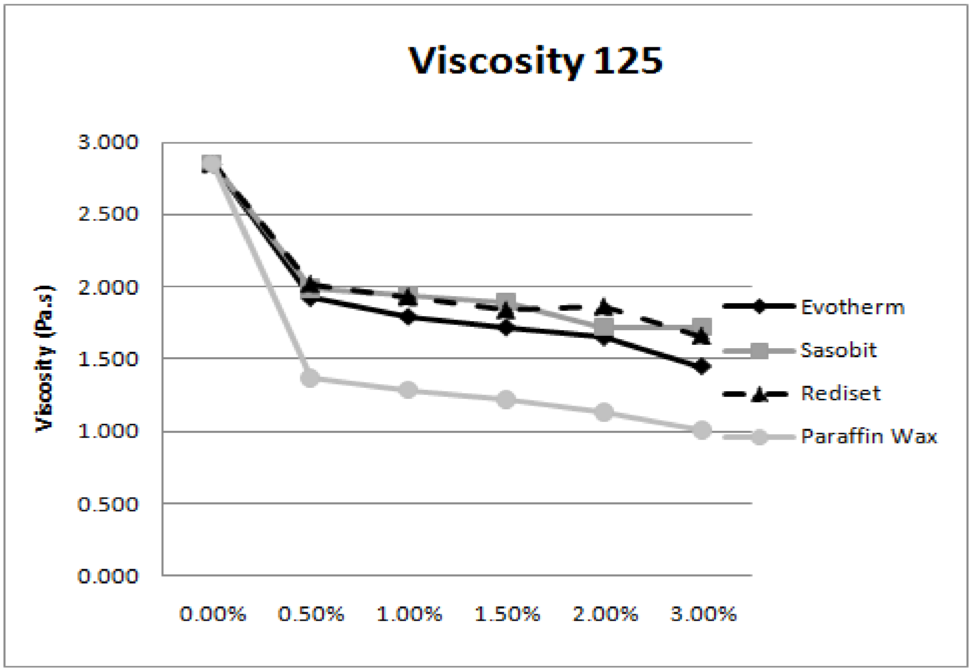

Figure 5: Viscosity of the binder at 125°C

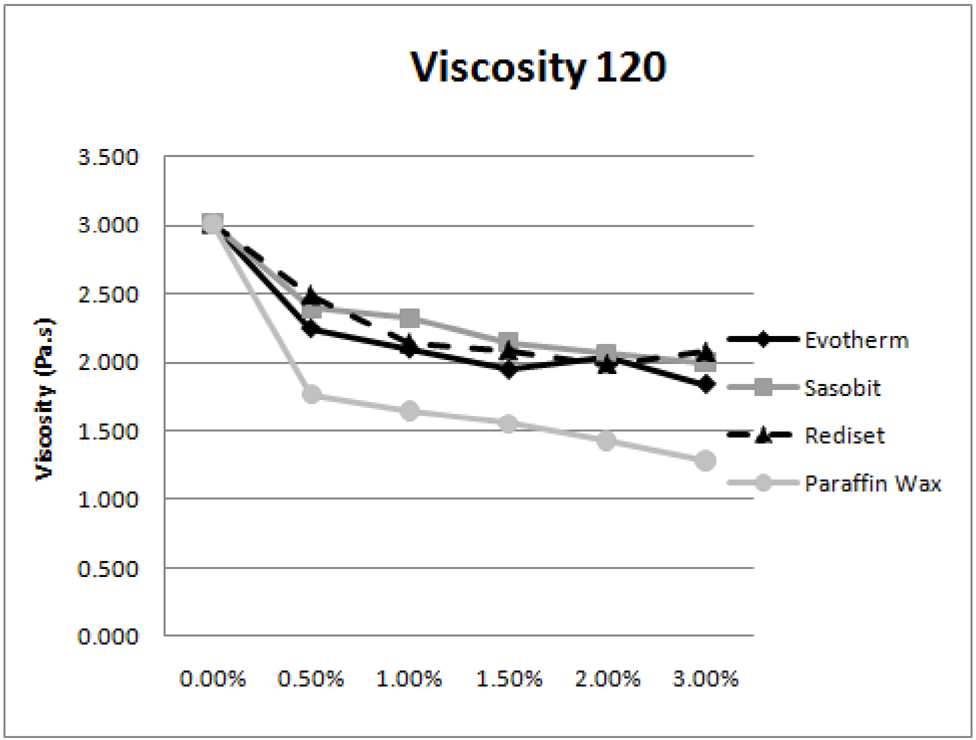

Figure 6: Viscosity of binder at 120°C

CHAPTER 4 - MIXTURE TESTING

In order to produce consistent specimens for laboratory testing, the same mix design parameters and testing conditions were selected for all WMA additives. As shown in Figure 7, five stockpiles of aggregates (3/4" crushed, 3/8" chip, crushed limestone, manufactured sand, and natural sand) were blended to produce the SuperPave design gradation. Table 7 outlines the number of gyrations to be done in order to obtain a desired traffic volume and the design ESAL of 0.3 to <3 million was used for this study.

Table 7: AASHTO guideline relating the number of gyrations to the Traffic volume

Design ESALs	Compaction Parameters			Typical Roadway Application[a]
(millions)	$N_{initial}$	N_{design}	N_{max}	
< 0.3	10	50	75	Applications include roadways with very light traffic volumes such as local roads, country roads, and city streets where truck traffic is prohibited or at a very minimal level. Traffic on these roadways would be considered local in nature, not regional, intrastate, or interstate. Special purpose roadways serving recreational sites or areas may also be applicable to this level.
0.3 to < 3	10	75	115	Applications include many collector roads or access streets. Medium trafficked city streets and the majority of country roadways may be applicable to this level.
3 to < 30	10	100	160	Applications include many two-lane, multilane, divided, and partially or completely controlled access roadways. Among these are medium to highly trafficked city streets, many state routes, U.S. highways, and some rural Interstates.
> 30	10	125	205	Applications include the vast majority of the U.S. Interstate System, both rural and urban in nature. Special applications such as truck-weighing stations or truck-climbing lanes on two-lane roadways may also be applicable to this level.

[a] As defined by A Policy on Geometric Design of Highways and Stress, 1994, AASHTO.

Following the Iowa DOT specification I.M. 510, 86 gyrations were selected for the surface mix under a traffic volume of 3 Million ESAL. The optimum asphalt (PG 70-34) content of 5.5% was selected for aggregates with a nominal maximum aggregate size of 19.0mm (28)

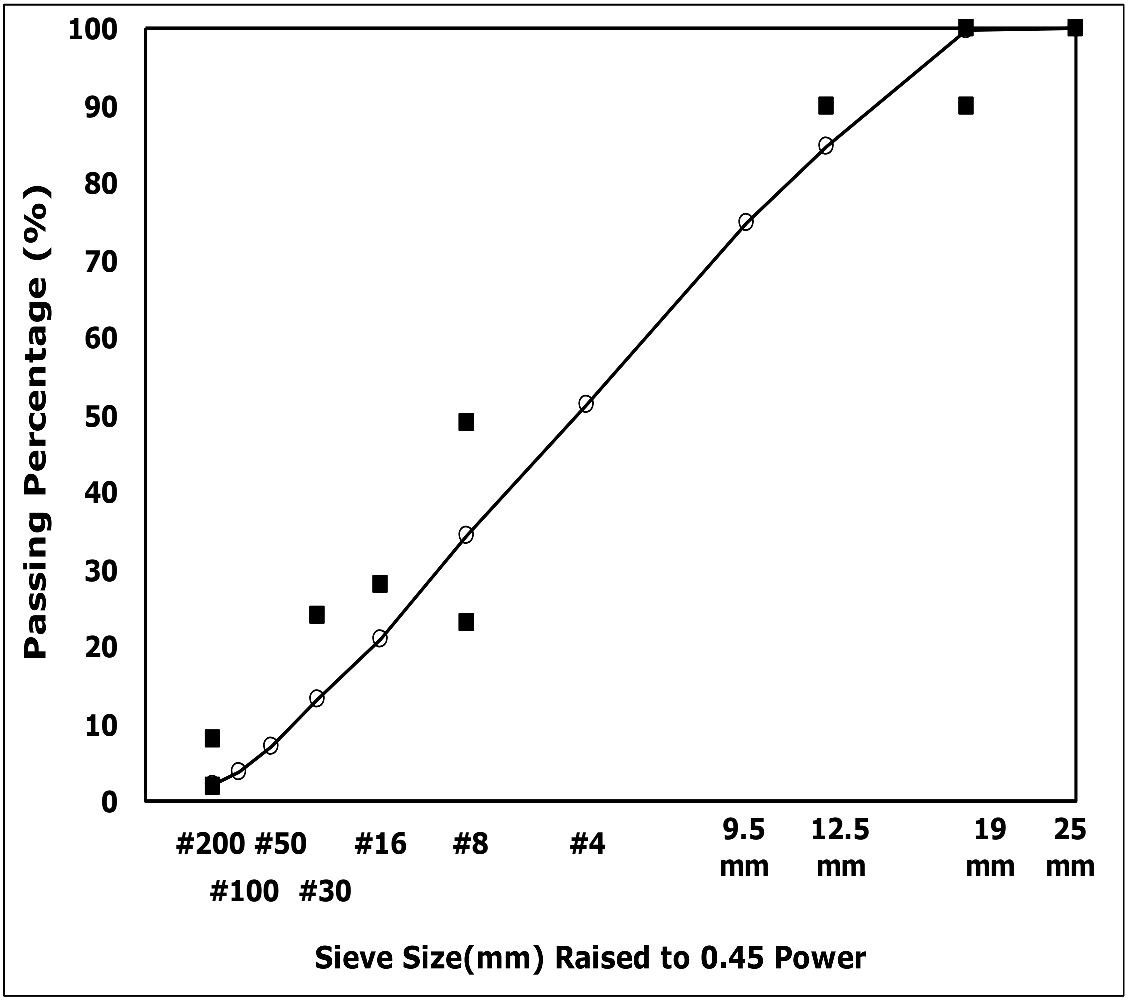

Figure 7: Gradation of aggregates used

Dosage Rate of Warm Mix Asphalt Additives

Following the manufacturers' recommendations, as summarized in Table 8, WMA specimens were produced. The specimens were prepared by a wet process for Sasobit®, Evotherm J1 and Rediset^{TM} WMX and by a dry process for Sasobit®.

Table 8: The dosage of the additive added to the binder

Additive	**Process**	**Quantity**
Sasobit®	Dry Process	1.50% of binder weight
	Wet Process	
Evotherm J1	Wet Process	0.50% of binder weight
Rediset^{TM} WMX	Wet Process	2.00% of binder weight

Sample Preparation

The aggregate was heated at temperature of 125°C for 6 hours and the PG 70-34 asphalt was heated at 149°C for 1.5 hours in the oven. To produce WMA mixtures by the dry process, WMA additive was added to the heated aggregate and manually stirred in the bucket mixer and then asphalt was added. To produce WMA mixtures by the wet process, WMA additive was added to the heated asphalt and then added to the heated aggregate. Aggregate, asphalt and WMA additive were mixed for 60 seconds and the WMA mixtures were then heated at 125°C for 20 minutes in the oven. The heated WMA mixtures at 125°C were added in a preheated gyratory mold at 125°C and compacted for 86 gyrations.

Laboratory test results

Basic characteristics of laboratory WMA specimens were measured that include mixing and compaction temperature; theoretical maximum specific gravity; bulk specific gravity; and air void. To evaluate fundamental engineering properties and performance-related characteristics of laboratory WMA specimens, four laboratory tests were conducted: 1) indirect tensile strength test; 2) moisture sensitivity test; 3) dynamic modulus test; and 4) repeated load test.

Mixing and Compaction Temperatures

The binder temperature was kept constant at 149˚C. The temperatures of aggregate, mixture, and compacted specimen were measured throughout the sample preparation process of each specimen. As shown in Figure 8, WMA mixtures were produced at temperatures between 117˚C and 122˚C. The WMA mixtures were compacted at temperatures between 117˚C and 121˚C.

Table 9: Temperature of different mixtures

Products	Average Aggregate Temperature (˚C)		Average Mixing Temperature (˚C)		Average Temperature Before Compaction (˚C)		Average Temperature After Compaction (˚C)	
	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
EvothermJ1	122.5	3.53	119.5	0.70	118.16	3.54	99.67	5.78
Rediset	125	1	121	1	119.9	1.91	104.5	7.81
Sasobit (Dry)	122.5	3.53	121.5	2.12	121.67	2.16	105.83	0.75
Sasobit (Wet)	125	0	120	0	116.9	2.12	103.36	7.95
Control WMA	124.5	0.7	122.5	2.12	118.71	3.59	93	4.51

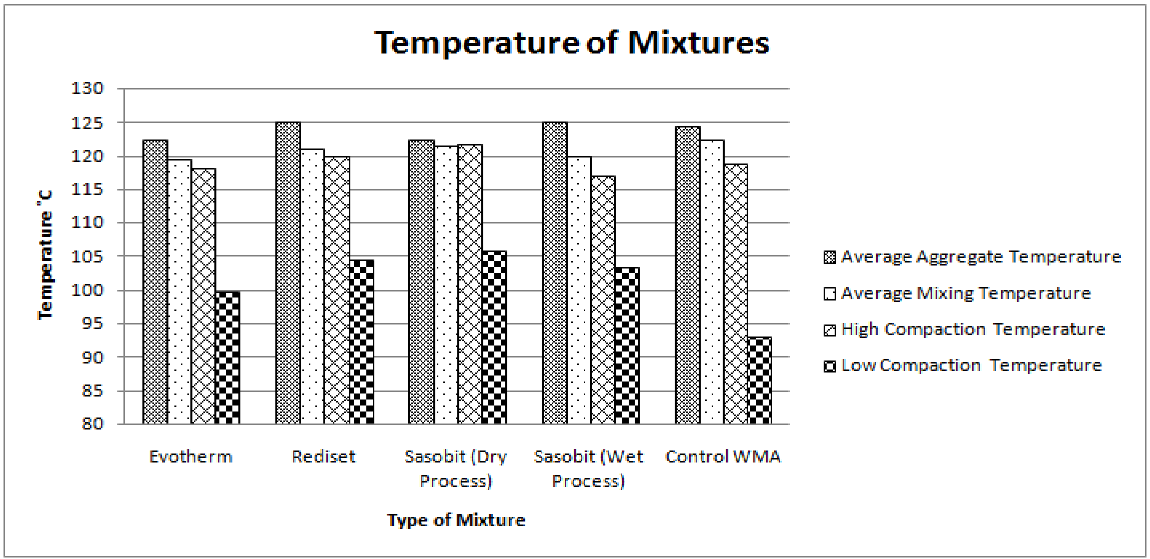

Figure 8: Comparison of the different temperatures of samples

Theoretical Maximum Specific Gravity, Bulk Specific Gravity, Air Void and Height of specimen

The theoretical maximum specific gravity was measured twice for each mixture using a CoreLok device ranging between 2.420 and 2.449. The bulk specific gravities of each specimen were determined following the AASHTO T 166 (29). Figure 9 shows the average of bulk specific gravities of three specimens prepared for the indirect tensile strength test, two specimens for dynamic modulus test, and two specimens for repeated load test. Given the same compaction level of 86 gyrations, the bulk specific gravities of WMA specimens ranged between 2.362 and 2.428. Figure 10 and Figure 11 shows the average air voids for each set specimens. The air voids of WMA specimens ranged between 2.5% to 4%. As shown in Figure 11, average air void of WMA specimens with Sasobit® was the lowest followed by Evotherm J1 and Rediset^{TM} WMX and they were all lower than the average air void of the control WMA specimens for the repeated load test and the dynamic modulus test. However, for the ITS test (Figure 10) Sasobit had the highest air voids followed by control WMA. This result indicates these WMA additives are effective in the compaction of the asphalt mixture at a low temperature.

The height of the specimen (Figure 12) plays an important role in the entire procedure as it gives a sense of how much the specimen can be compacted. The height of the specimen plays a direct role with the air voids and the strength of the specimen. If the specimen can be compacted well, the height will be less, resulting in lesser air voids and higher strength. While comparing the height of different samples, it was found that height of the sample and air voids were inversely proportional.

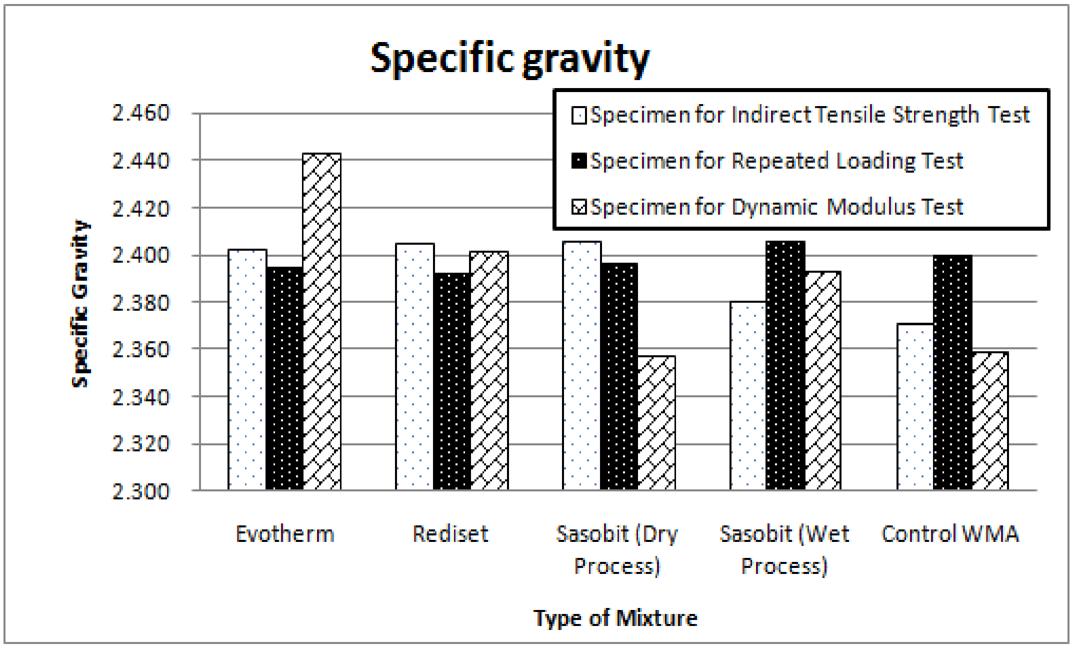

Figure 9: Comparison of the specific gravity results of the samples produced.

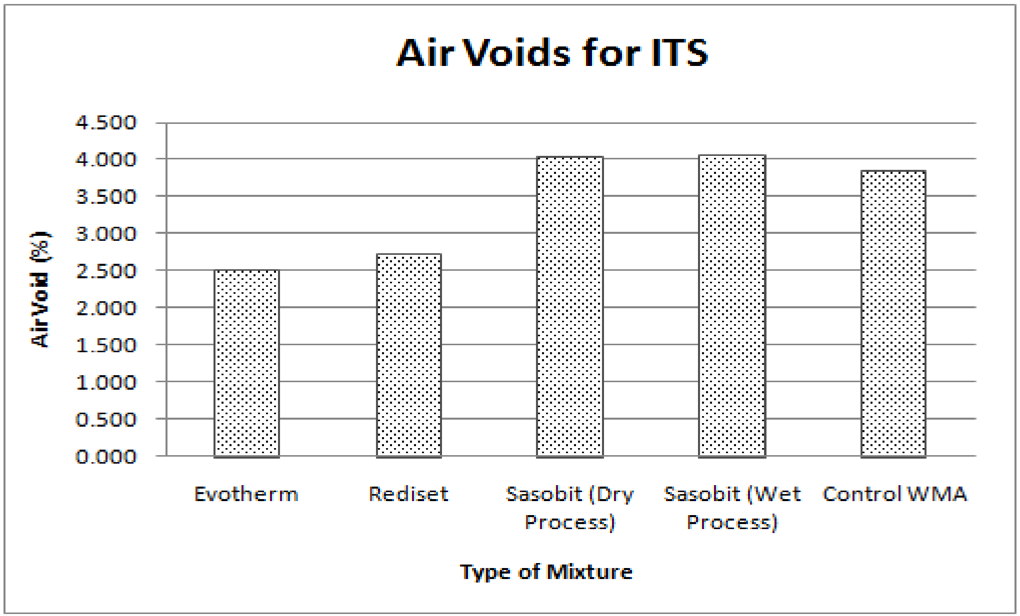

Figure 10: Comparison of the airvoids of different samples.

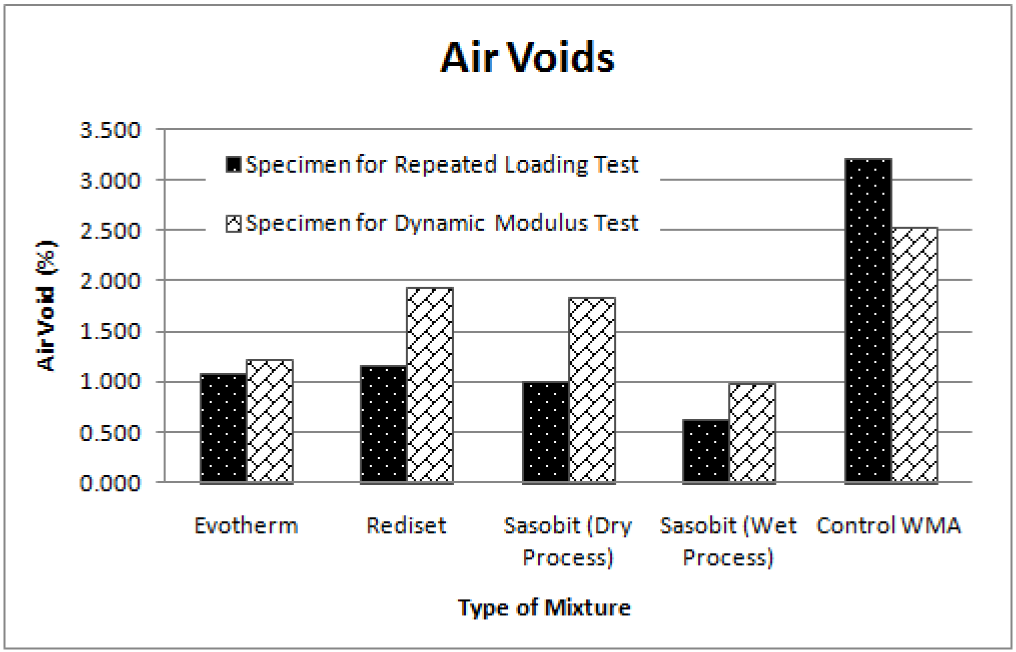

Figure 11: Air voids of Flow number test and Dynamic Modulus Test

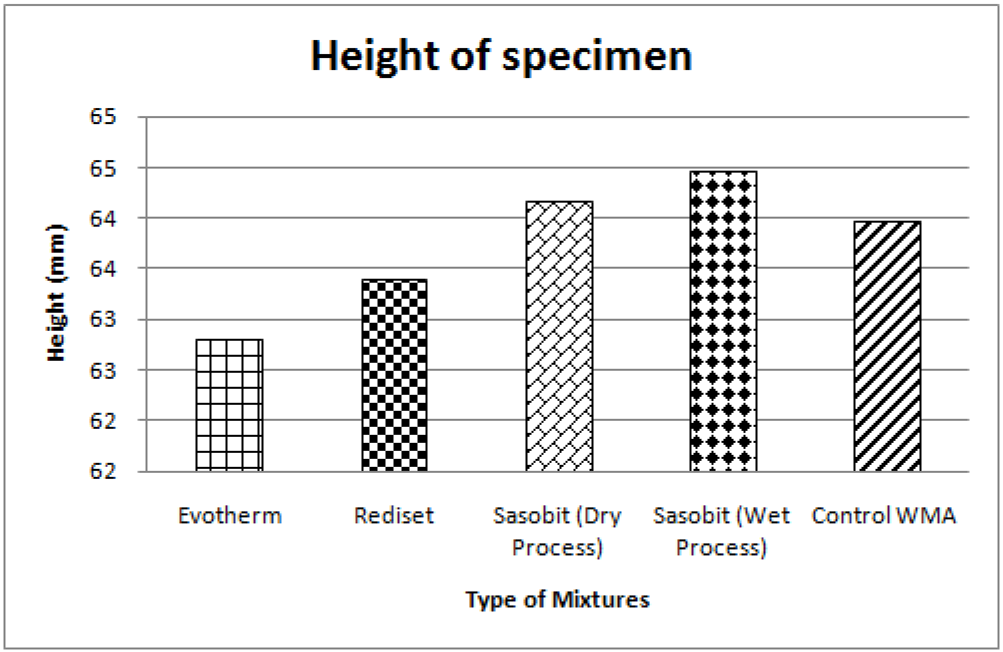

Figure 12: Average height attained by different specimens

Indirect Tensile Strength Test

To determine the indirect tensile strength of different types of warm mix asphalt (WMA) mixtures, four WMA mixtures and a control WMA mixture were produced in the laboratory. Three test specimens for each mixture were prepared by gyratory compactor at 86 gyrations. After one-day of curing at room temperature, the bulk specific gravity of the compacted specimens was measured using a CoreLok device. Next day, the indirect tensile strength of specimens was measured using the Master Loader 3000 after having them cured in the oven at 25˚C for 2 hours. Only when the temperature of the specimen stabilized at 25°C, the samples were loaded onto the master loader 3000.

It must be noted that the indirect tensile strength tests were performed four times in order to get a consistent result. Figure 11 shows the average indirect tensile strengths of WMA mixtures and the control WMA. Care was taken while placing the samples on the master loader 3000 such that the surface with the least amount of cracking was placed longitudinally. As shown in Figure 13, the average indirect tensile strengths of WMA specimens ranged between 740kg.f and 930kg.f. All the values of the strengths were greater than the indirect tensile strength value of the control WMA specimen (743kg.f).

It can be clearly seen that the addition of the additives seems to have a positive effect on the strength of the samples. Evotherm J1 had the highest strength followed by Rediset^{TM} and Sasobit®. The control WMA had the lowest strength. It can be said that the strength is inversely proportional to air voids and height of the sample.

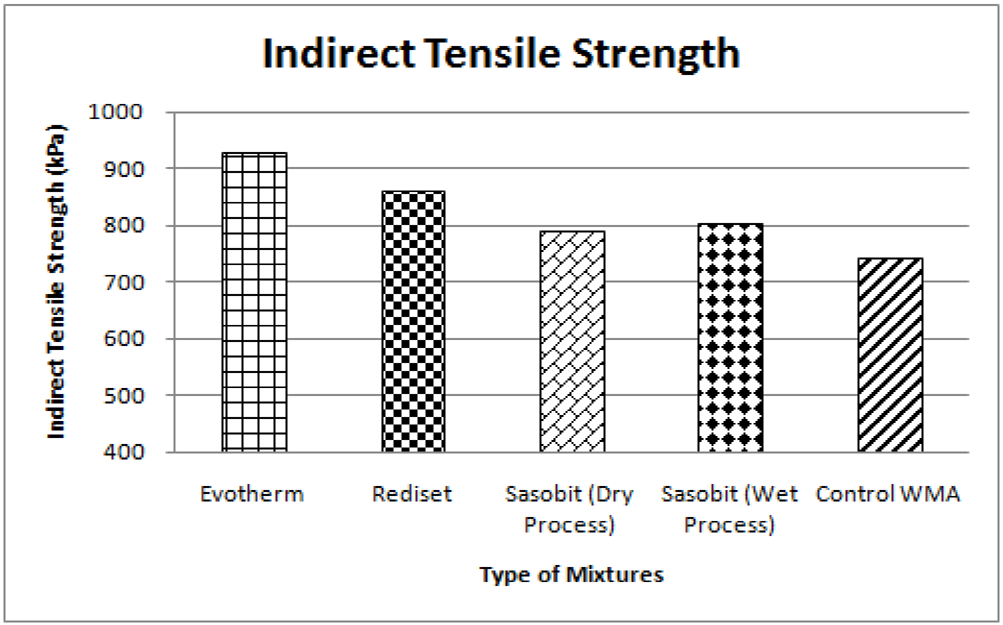

Figure 13: Comparison of the indirect tensile strength between the additives

To determine if there is a correlation between air voids, height of specimen and indirect tensile strengths, as shown in Table 10, specimens were ranked in an increasing order of air voids and in a decreasing order of indirect tensile strength. Overall, WMA mixtures with the lower air voids (Evotherm J1 and Rediset^{TM}) exhibited higher indirect tensile strength.

Table 10: Ranking of the additives according to air voids and ITS

Type of Mix	Ranking					
	Air Void (%)	Ranking of Air Void	Height (mm)	Ranking of Height	Indirect Tensile Strength (kg.f)	Ranking of ITS
Evotherm J1	2.503	1	62.8	1	930.32	1
Rediset^{TM} WMX	2.734	2	63.4	2	861.15	2
Sasobit® (dry process)	4.043	4	64.2	4	789.40	4
Sasobit®(wet process)	4.060	5	64.5	5	804.23	3
Control WMA	3.853	3	64	3	743.44	5

Moisture Sensitivity Test

To evaluate the moisture sensitivity of WMA mixtures, the modified Lottman test following AASHTO T 283 (30) was performed. Six specimens (three for dry condition and three for wet condition) for each of four WMA mixtures and the control WMA mixture were prepared. To prepare the test specimens with 7 ± 0.5% air void, all specimens were compacted at between 6 and 20 gyrations. For dry conditioning, three specimens in a sealed pack were placed in the water bath at 25˚C for 2 hours and, for wet conditioning, three specimens saturated at between 70% and 80% were placed in a freezer at -18˚C for 16 hours and in water bath at 60˚C for 24 hours followed by conditioning in water bath at 25˚C for 2 hours.

The moisture damage in asphalt mixtures is determined as a loss of strength due to the presence of moisture in terms of a tensile strength ratio (TSR) that is defined as a ratio of the indirect tensile strength of a wet specimen over that of a dry specimen. Figure 14 shows average indirect tensile strengths at dry and wet conditions, TSR values of 4 WMA mixtures and the control WMA. As seen in Figure 14, the average TSR values of WMA specimens ranged between 58.6% and 69.1%, all below the Superpave specification of 80%. This result indicates that the WMA mixtures are susceptible to moisture damage. Rediset$^{\text{TM}}$ and EvothermJ1 exhibited higher tensile strength ratios than Sasobit. All the tensile strength ratios of the samples with additives were lesser than that of control WMA (69.1%)

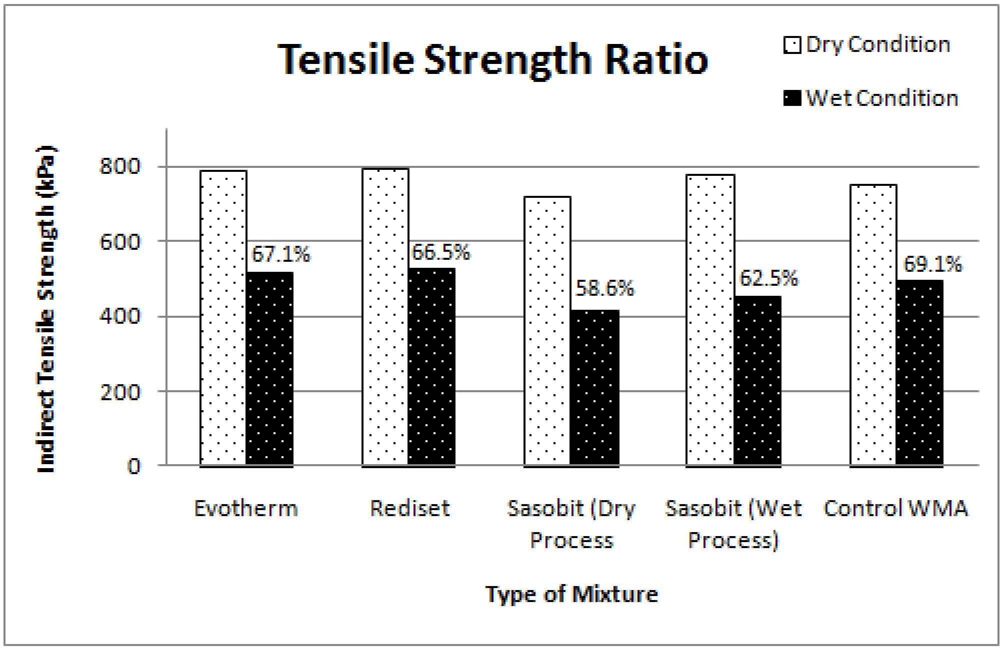

Figure 14: Tensile Strength Ratio (TSR)

Table 11: Ranking of the products based on their Tensile Strength Ratio

Type of Mix	Ranking			
	Average Indirect Tensile Strength		Tensile Strength Ratio (TSR) (%)	Ranking of ITS
	Dry (kPa)	Wet (kPa)		
Evotherm J1	804	541	67.1	2
Rediset™ WMX	808	536	66.5	3
Sasobit® (Dry Process)	743	422	58.6	5
Sasobit® (Wet Process)	774	484	62.5	4
Control WMA	768	531	69.1	1

Dynamic Modulus Test

To determine the dynamic modulus, four WMA mixtures and control WMA were produced in the laboratory. Two test specimens with 100-mm diameter and 150-mm height were prepared for each type by gyratory compactor at 86 gyrations. After one-day curing at room temperature, the bulk specific gravity of the compacted specimens were measured. Next day, the dynamic modulus test was performed at three temperatures of 4.4°C, 21.1°C, and 37.8°C and six frequencies of 25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz, and 0.1Hz (31). To minimize a potential damage to the specimens, testing began at the lowest temperature and proceeded to a higher temperature. For a given temperature, the testing began with the highest frequency of loading and proceeded to a lower frequency. A minimum contact load equal to 5.0% of the dynamic load was applied to the specimen. A sinusoidal axial compressive load was applied to the testing specimen while maintaining the axial strain at 100 microstrain. The test results during the last ten cycles were recorded for each frequency.

The average dynamic moduli of two specimens are plotted against the loading frequency at 4.4°C, 21.1°C, and 37.8°C in Figures 8 (a), (b) and (c), respectively. All the specimens with additives had a higher dynamic modulus when compared with the control WMA specimens. Sasobit® (Wet Process) specimens particularly exhibited the highest dynamic modulus followed by Rediset^{TM} WMA.

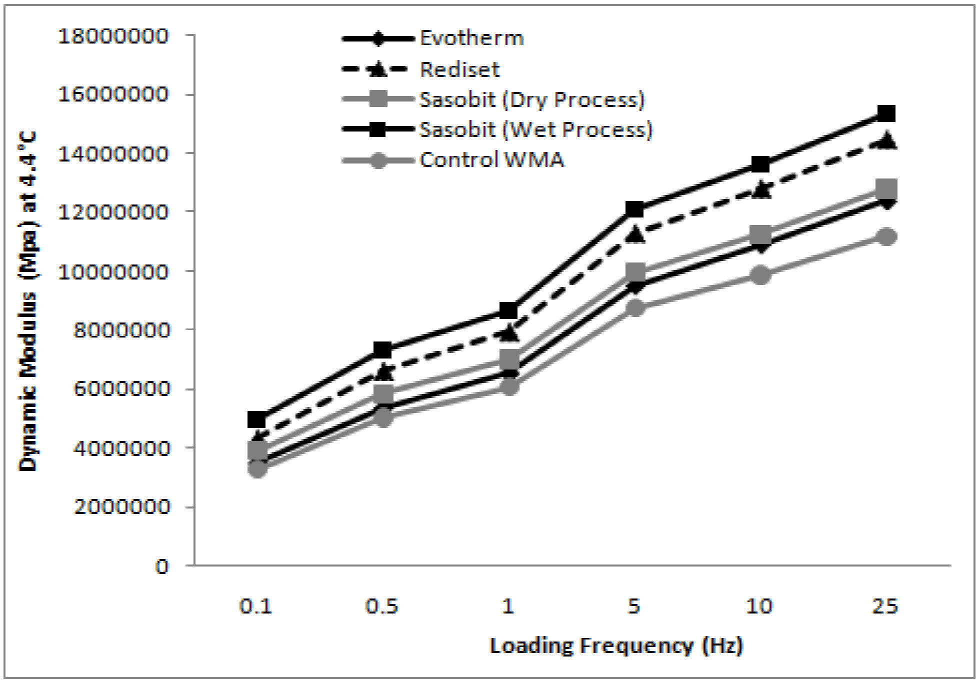

Figure 15: Dynamic modulus of the additives at 4.4°C

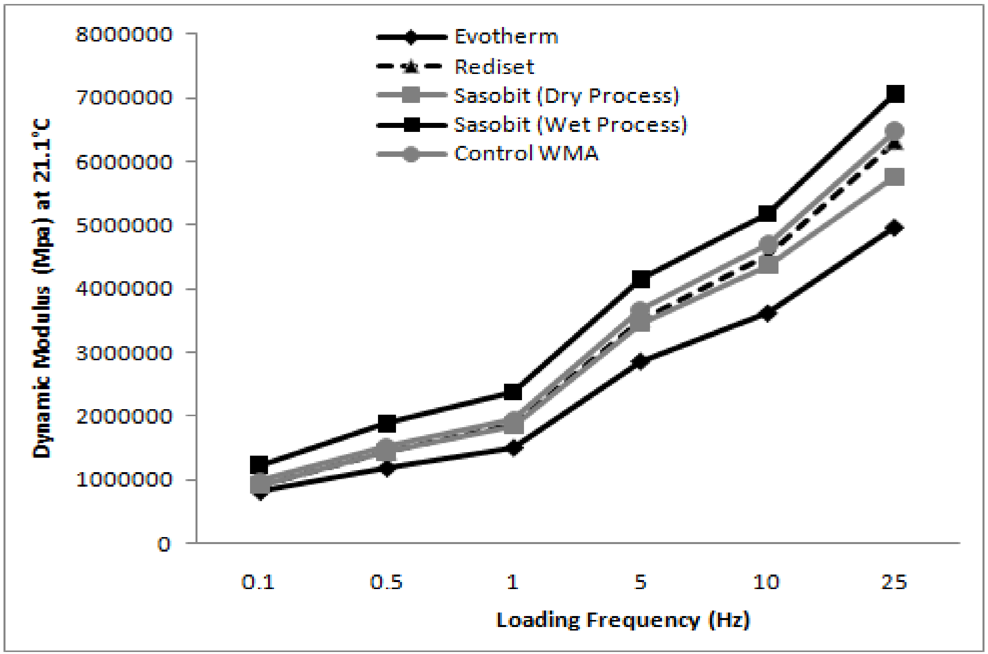

Figure 16: Dynamic modulus of the specimens at 21.1°C

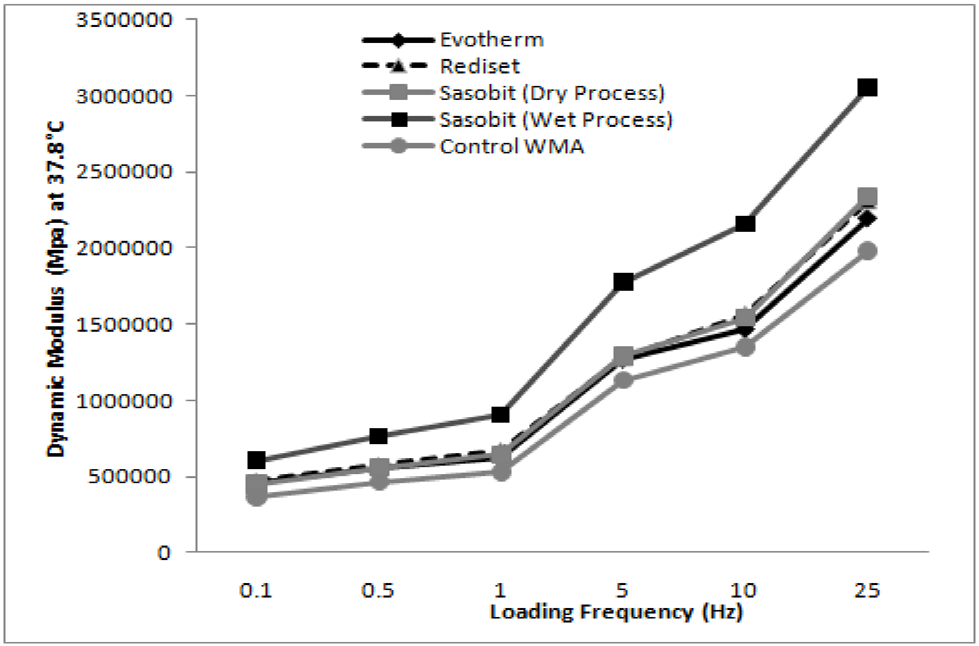

Figure 17: Dynamic modulus of the specimen at 37.8°C

Repeated Load Test

The repeated load test was performed on four WMA mixtures and the control WMA mixture. Two specimens with 100-mm diameter and 150-mm height for each were prepared by gyratory compactor at 86 gyrations. The uniaxial compression load without confinement was applied to obtain a loading stress level of 600kPa at 45˚C. The loading stress was applied in the form of a haversine curve with a loading time of 0.1 second with a rest period of 0.9 second in one cycle. The test was conducted up to 10,000 cycles or until achieving 5.0% of cumulative permanent deformation stain.

Figure 18 shows plots of the cumulative permanent strains against the number of loading cycles for the four WMA mixtures and the control WMA mixture (two specimens for each). It should be noted that the control WMA specimen and all WMA specimens, passed the requirement of 10,000 cycles. None of the specimen failed under the loading which indicates that WMA is resistant to rutting. Evotherm J1 had the maximum cumulative strain followed by Rediset and then the control WMA.

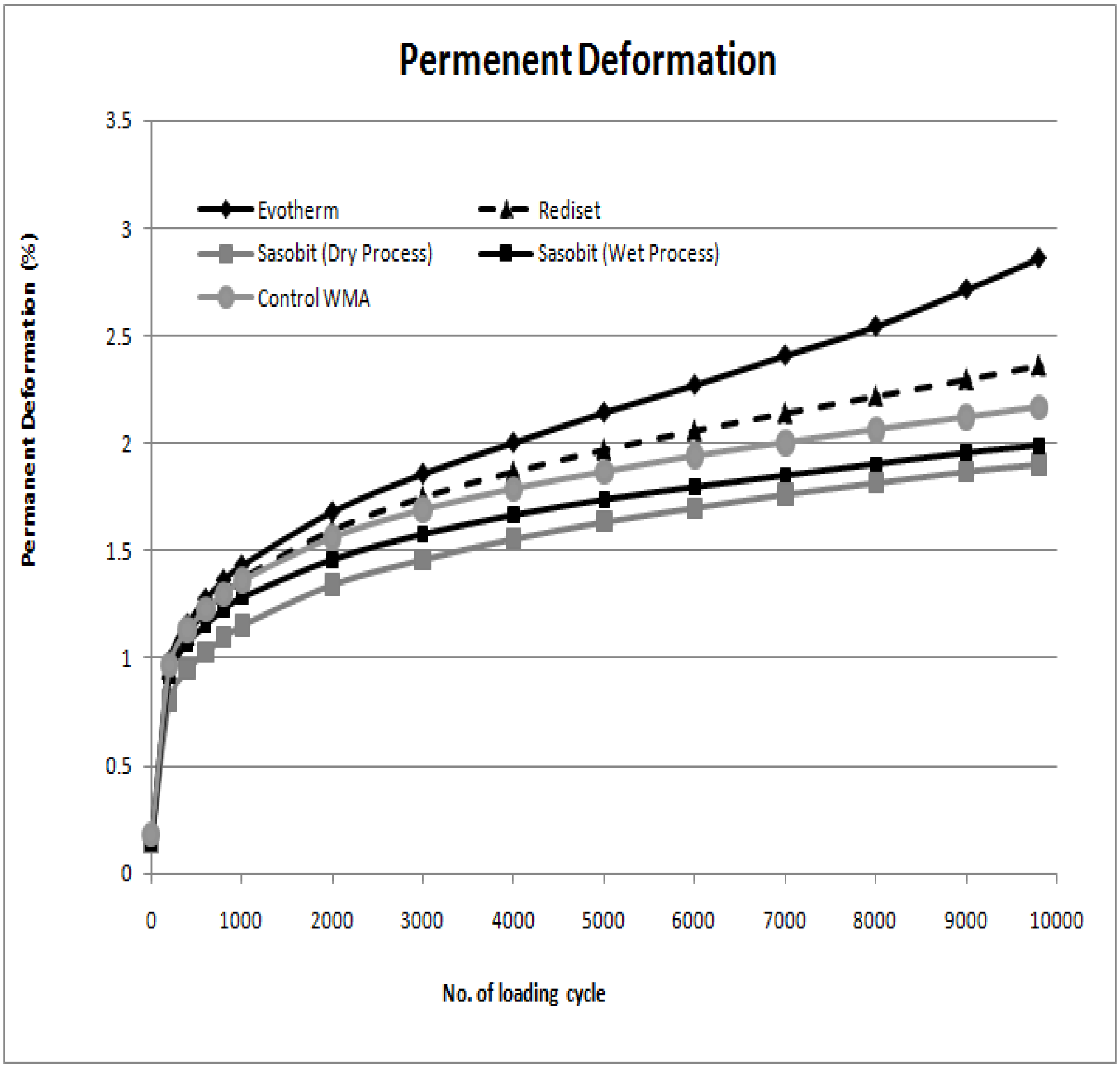

Figure 18: Figure showing the cumulative strain of the different specimen

To determine if there is a correlation between air voids and cumulative permanent strain, as shown in Table 12, specimens were ranked in an increasing order of air voids and a cumulative permanent strain. WMA mixtures with Sasobit® (both wet and dry processes) exhibited the lowest permanent deformation followed by the control WMA mixture, Evotherm J1 and Rediset™. Overall, the specimens with higher air voids exhibited the higher permanent deformation.

Table 12: Comparison of ranking of air voids and permanent deformation

Type of Mix	No. of Specimen	Air Void		Ranking of Air Void	Permanent Deformation		Ranking of Deformation
		Individual	Average		Individual	Average	
Evotherm J1	# 1	1.0%	1.15%	4	2.24%	2.29%	5
	# 2	1.3%			2.34%		
Rediset™ WMX	# 1	1.2%	1.1%	3	2.21%	2.26%	4
	# 2	1.0%			2.31%		
Sasobit® (Dry Process)	# 1	0.9%	1.0%	2	1.89%	2.02%	2
	# 2	1.1%			2.14%		
Sasobit® (Wet Process)	# 1	0.8%	0.65%	1	1.96%	1.80%	1
	# 2	0.5%			1.64%		
Control WMA	# 1	3.3%	3.2%	5	2.10%	2.11%	3
	# 2	3.1%			2.11%		

SUMMARY AND CONCLUSION

Warm mix asphalt (WMA) mixtures with 3 commercially available WMA additives, that include Sasobit®, Evotherm J1, and Rediset™ WMX, the control WMA mixture without any additive were evaluated for their viscosity, air void, indirect tensile strength and moisture susceptibility. To predict a long-term performance, the dynamic modulus and the repeated load tests were conducted on these mixtures using the simple performance testing equipment.

The viscosities of different samples were determined and it was found that 0.5% of paraffin wax could produce the viscosity of 3.0% Evotherm J1. This is very encouraging for the production of a new additive which can blend the effects of generic paraffin wax into it. Among the additives Evotherm J1 had the lowest viscosity followed by Rediset™ WMX and Sasobit®. Control WMA had the highest viscosity at all temperatures. It should be noted that there was a sudden drop in viscosity with the addition of 0.5% of additives after which there is not a significant difference. Therefore, it can be concluded that a dosage rate of 0.5% to 1.0% be used.

The air void of WMA specimens with Evotherm J1 was the lowest followed by Rediset™ WMX and Sasobit®. Overall, the WMA mixtures with additives exhibited similar air voids as control WMA mixture which indicates these WMA additives are effective in compacting asphalt mixtures at a lower temperature.

The indirect tensile strengths of WMA mixtures with additives were higher than that of the control WMA mixture. This clearly shows that the additives play an important role in increasing the strength of the specimen. The tensile strength ratio

(TSR) values of all WMA mixtures were below the Superpave specification of 80%. This result indicates that the WMA mixtures maybe susceptible to moisture damage.

WMA mixtures with Evotherm J1 exhibited the highest dynamic modulus followed by Rediset$^{\text{TM}}$ WMX and Sasobit®. Particularly, the control WMA mixture lost its dynamic modulus value more than WMA mixtures with Sasobit® or Rediset$^{\text{TM}}$ WMX when a test temperature was increased from 4.4˚C to 37.8˚C. This result indicates that WMA mixtures with Sasobit® or Rediset$^{\text{TM}}$ WMX are less temperature sensitive than the control WMA mixtures.

All WMA specimens passed the requirement of 10,000 cycles of repeated loading. Particularly, the WMA mixture with Sasobit® exhibited the lowest permanent deformation followed by the control WMA mixture.

The WMA additives were compared and ranked against each other in terms of viscosity, indirect tensile strength, tensile strength ratio, dynamic modulus and permanent deformation as shown in Table 13. Based on the limited test results, Sasobit®, Evotherm J1 and Rediset$^{\text{TM}}$ WMX additives were effective in producing WMA mixtures in the laboratory.

Table 13: Overall ranking of the specimens

Type of Mix	Ranking					Total Average	Overall Ranking
	Viscosity	Indirect Tensile Strength	Tensile Strength Ratio	Dynamic Modulus	Permanent Deformation		
Evotherm J1	1	2	2	3	5	2.8	3
Rediset$^{\text{TM}}$ WMX	3	1	3	2	4	2.6	2
Sasobit® (Dry process)	NA	4	5	3	2	3.5	4
Sasobit® (Wet process)	3	3	4	1	1	2.4	1
Control WMA	5	5	1	5	3	3.8	5

Based on the test results, it can be concluded that Sasobit®, Evotherm J1 and Rediset$^{\text{TM}}$ WMX additives are effective in producing WMA mixtures in the laboratory that have good properties. None of the WMA mixtures satisfied the Superpave requirement of 80% moisture susceptibility test. Therefore, a future research should be performed to improve the moisture susceptibility of the WMA mixtures.

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