5-2008

EFFECTS OF WARM ASPHALT ADDITIVES ON ASPHALT BINDER AND MIXTURE PROPERTIES

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EFFECTS OF WARM ASPHALT ADDITIVES ON ASPHALT BINDER AND MIXTURE PROPERTIES

A Dissertation
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
Civil Engineering

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by
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May 2008

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ABSTRACT

With increasing concerns of global warming and increasing emissions, the asphalt industry is making a constant effort to lower its emissions by reducing the mixing and compaction temperatures of the asphalt mixture without affecting the properties of the mix. Several proprietary chemicals are available in the industry that can help reduce the mixing and compaction temperatures. A significant reduction of required heat can be achieved in most cases. While some studies have been conducted to evaluate the properties of warm mix asphalt; properties of binders and mixtures, in fresh and aged conditions, containing these chemicals have not been studied in great detail. This research presents the results of tests conducted to evaluate the properties of warm mix asphalt binders and mixtures, in fresh and aged conditions. This study was broadly classified into two; study of binder properties, where 3 binder sources were studied with and without Asphamin® and Sasobit® as the warm asphalt additives; and study of mixture properties, where two binder sources and two aggregate sources were studied with and without Asphamin® and Sasobit® as the warm asphalt additives.

The results of the study indicated that the two warm asphalt additives affected the binder and mixture properties differently. It was observed that the addition of Sasobit® significantly reduced the viscosity of the binders at 135 °C and 120 °C, whereas, the addition of Asphamin® did not have any significant effect on the viscosity of the binders at 135 °C and 120 °C. However, both the additives improved the mid-temperature rheological properties of the binders namely creep response, creep recovery, and the complex modulus.

Tests on binders aged in the laboratory and binders extracted from freshly mixed and aged mixtures indicated that the WMA binders extracted from WMA mixtures had

significantly lower viscosities and G* / sin δ compared to binders extracted from HMA and binders aged in the RTFO at 163 °C, indicating that the lower mixing and compaction temperatures reduce the aging of the binders.

When the mixture properties were compared, it was observed that Asphamin® reduced the M_R values of the mixes, Sasobit® reduced the rut depths of the mixes, and both the additives improved the TSR of the mixes. When the laboratory aged mixtures were compared, it was observed that either of the two warm asphalt additives did not have significantly different rutting depth, TSR or M_R values compared to the control mixes.

DEDICATION

I wish to dedicate this dissertation to my parents. Without their love and support, I would not be where I am today.

ACKNOWLEDGEMENTS

I would like to sincerely thank everyone who has helped me complete my dissertation. First, I thank Dr. Serji Amirkhanian, my academic advisor, for all his guidance, both academic and personal during the course of my masters and doctoral programs. My association with him in the past five years has been greatly cherished. I am also grateful to other committee members, Dr. Brad Putman, Dr. Prasad Rangaraju and Dr. Hsein Juang, for their inputs and support over the course of my masters and doctoral programs.

I owe a lot to all the students at the Asphalt Rubber Technology Services (ARTS) Laboratory, who have made life much easier over the last five years with all their cheer and help. I would also like to thank Ms. Mary Corley, Ms. Teri Oswald, Ms. Kristy Baker and other staff members at the Department of Civil Engineering at Clemson University for all their support throughout my stay at Clemson.

Finally, I would like to thank my family and friends for their love and support.

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Chapter I

1. INTRODUCTION

Hot mix asphalt (HMA) is used as the primary paving material, as about 94% of the paved roads in the United States are made of HMA, which consists of aggregate and asphalt binder which are heated and mixed together. The primary sources of emissions in an asphalt plant are the mixers, dryers, and hot bins, which emit particulate matter, such as dust, smoke, exhaust vapor, and other gaseous pollutants. Some other sources of emissions found at an asphalt plant are the storage silos, truck loading operations, binder storage tanks, conveyers, stockpiles, etc.

Typically, the emissions from hot mix asphalt are classified into two major categories – visible emissions and invisible emissions *(Sutton, 2002)*. Invisible emissions are the emissions that primarily consist of non – condensable volatile organic compounds (VOCs) which precipitate in the production of ground level ozone. The visible emissions consist of fugitive dust emissions generated at the conveyers, stockpiles, and roadways and other heavier hydrocarbons that readily vaporize at temperatures around 150 °C (300 °F). The visible emissions condense in ambient air, absorb to dust and water particles, and have a characteristic fuel odor. The Environmental Protection Agency (EPA) estimates that on average, a drum mix asphalt plant produces about 200,000 tons of asphalt mix in a year, and would emit about 13 tons of carbon monoxide (CO) emissions during that period, 5 tons of volatile organic compounds, 0.4 tons of sulfur oxides, 2.9 tons of nitrogen oxides and about 0.65 tons of total hazardous air pollutants (HAP) *(US EPA Report, 2000)*.

In order to reduce the emissions from the asphalt plants, the asphalt industry is constantly trying to reduce the mixing and compaction temperatures of the mixes, without significantly affecting the properties of the mixes. The asphalt industry has been experimenting with warm and cold asphalt mixtures for decades to reduce energy requirements and for environmental benefits. However, until now, most of the cold products are inferior to hot mix asphalt. Emulsion binders usually result in higher air voids, require longer curing times, and tend to work only with open and coarse graded mixtures. Cutback bitumens also have environmental concerns due to the volatile chemicals and require longer curing times. Foamed bitumen does not require long curing times, but it has been reported that it only coats fine aggregate well, and is more suitable for recycling applications *(Rajagopal, A., 2004)*. Another problem with these methods is that the extra costs are not offset by the savings in energy. Thus, since the cold mixes have not achieved the same overall long term performance as hot mixes, it appears they will not be able to replace hot mixes as the primary road surfacing material.

In the recent years, the asphalt industry has investigated the warm asphalt technology as a means to reduce the mixing and compaction temperatures of asphalt mixes. Warm mix asphalt (WMA) is an asphalt mixture which is mixed at temperatures lower than conventional hot mix asphalt. Typically, the mixing temperatures of warm mix asphalt range from 100 to 140 °C (212 to 280 °F) compared to the mixing temperatures of 150 to 180 °C (300 to 350 °F) for hot mix asphalt *(Australian Asphalt Pavement Association, 2001)*. Thus, warm asphalt has been gaining increasing popularity in the recent years. Rising energy prices, global warming, and more stringent environmental regulations have resulted in an interest in warm mix asphalt technologies as a mean to decrease the energy consumption and emissions associated with conventional hot mix asphalt production.

European countries are already using warm asphalt technologies that allow reductions in mixing and compaction temperatures of about 20 to 55 °C (50 to 100 °F). The asphalt industry has developed several methods to reduce the mixing and lay down temperatures of asphalt mixtures. In principle, there are three major methods for the production of asphalt mixtures at low temperatures. These methods are based on foaming, water bearing agents, and special bitumen additives.

The foaming process generally produces tiny steam bubbles inside the asphalt binder, which causes a volume increase in the asphalt binder, leading to increased wetability of the binder and lower high shear viscosities. An example for such a process is WAM-foam, a patented process developed jointly by Shell Global Solutions and Kolo Veidekke in Norway. In the WAM-foam production process, two different bitumen grades, soft bitumen and hard bitumen, are combined with the mineral aggregate. The aggregates are first mixed with the softer binder, which is fluid enough at lower temperatures, and then the harder binder is foamed and mixed with the aggregates pre-mixed with the softer binder. This process makes it possible to produce the asphalt mixture at temperatures between 100 °C and 120 °C (212 and 250 °F) and compact it at 80 to 110 °C (175 to 230 °F) *(Koenders et al. 2000)*.

The method with the water bearing agents is based on the release of chemically bound water from the additives into the binder during the mixing process. The release of this water leads to a finely dispersed steam when it comes in contact with the heated aggregate and binder. The fine steam bubbles lead to micro-pores that improve the compaction properties of the binders. An example of such an additive would be Asphamin®, which is a sodium – aluminum – silicate, hydro-thermally crystallized into a fine powder. It is added at the rate of 0.3% by weight of the mixture, and added at the same time

as the binder. The crystals contain about 21% water, inducing a fine spray in the binder causing a volume expansion, thereby increasing the workability and compactibility of the mixture at lower temperatures. It has been reported, by the manufacturer, that a reduction of about 20 to 30 °C (40 to 50 °F) is possible *(Eurovia Services)*.

The third method is based on adding special additives to the binder to reduce the viscosity of the binder. Such types of additives typically consist of paraffinic hydrocarbons. The paraffins are generally soluble in the asphalt binder above temperatures of 80 to 120 °C (175 to 250 °F). When dissolved in the binders, they lead to a significant reduction in the viscosity. Unlike the naturally occurring saturates in the binder, the added paraffins are long chained hydrocarbons that do not adversely affect the properties of the base binder. An example of such an additive is Sasobit®, a long chain aliphatic hydrocarbon (chain lengths of 40 to 115 carbon atoms) obtained from coal gasification using the Fischer – Tropsch process. Sasobit® melts in the asphalt binder at temperatures of 85 to 115 °C (185 to 240 °F), causing a marked reduction in the viscosity of the binder. The manufacturer reports a reduction in mixing and handling temperatures of 30 to 50 °C (50 to 90 °F) *(Sasol Wax)*.

The Bitumen forum of Germany, in 1997, began to investigate the ways to lower emissions, and "Warm Mix Technology" was one of the avenues they pursued. The European interest in reducing the emission of green house gasses was mainly a result of the Kyoto agreement. Warm mix asphalt was introduced to the United States when the National Asphalt Pavement Association (NAPA) sponsored an industry scanning tour to Europe for the asphalt paving contractors in 2002. In 2003, NAPA, Federal Highway Administration (FHWA) and National Center for Asphalt Technology (NCAT) convened a meeting to explore the potential of the technologies in the United States. The same year, the three

technologies were presented at the NAPA convention in San Diego. The 'World of Asphalt', 2004, featured a demonstration project on Warm mix asphalt, and since then, the major warm asphalt additive companies have carried out several demonstration projects in the United States.

Apart from the obvious advantages such as reduced fuel consumption and reduced emissions in the plant, there are several other advantages of using warm asphalt like longer paving 'seasons', longer hauling distances, reduced wear and tear of the plants, reduced aging of binders, reduced oxidative hardening of binders and thus reduced cracking in the pavements, ability of opening the site to traffic sooner, etc. *(Hurley and Powell, 2006)*. In addition, paving with warm asphalt also provides the workers with a safer working environment with lower emissions. With the availability of several proprietary chemicals and processes to produce warm asphalt, it is now possible to produce warm asphalt without affecting the properties of the mix. The concept driving warm mix technologies is reduction in asphalt binder viscosity, which allows the asphalt to attain suitable viscosity to coat the aggregates and compact the mixes at lower temperatures. The implementation of warm mix technology as a viable option for paving operations is a promising concept. However, further investigation of the effects of the warm asphalt additives on the constituent materials of asphalt mixtures and pavement performance in the United States is needed, since the environmental conditions, equipments, standards, and work practices, are different, a thorough investigation of warm asphalt is necessary before it is implemented in the United States.

Several laboratory studies have been conducted on mixes containing the warm asphalt additives. However, it is a known fact that the properties of the aggregates and the

binders used can also affect the properties of the mixtures. Thus, a thorough understanding of the properties and performance of WMA is necessary in order to implement it successfully, especially, since it is an emerging technology. The significance of this research was to investigate the effects of different aggregate and binder sources on the properties of WMA and to study the properties of the binders containing the warm asphalt additives in great detail. This is important as not much research has been conducted to investigate the effects of adding the warm asphalt additives to the binders to date. Also, binders behave differently at different temperatures, and thus, it was important to study the properties of the binders containing the warm asphalt additives at high, mid-range and low temperatures. Another importance of this research was to evaluate the aging characteristics of the warm asphalt binders and mixtures. Since the first warm asphalt field trial was conducted as recently as 1999, the long term performance and the aging characteristics of the WMA are not known in great detail. This research addresses some of the issues related to the aging of WMA.

1.1 Objectives

The main objective of the research project was to evaluate the effects of the warm asphalt additives on the properties of asphalt binders and mixtures. The specific objectives of the research project included the following.

- Conducting a thorough literature review on the topic of warm mix asphalt;
- Determining the performance of warm mix asphalt with respect to hot mix asphalt in terms of indirect tensile strength, rutting performance and resilient modulus;

- Investigating the rheological properties of the warm asphalt binder at different temperatures - High temperature (135 °C and 120 °C or 275 and 248 °F); Mid-range temperature (64 °C and 60 °C or 147 and 140 °F); and low temperature (-12 °C or 10.4 °F); and

- Investigating the effects of aging of binders and mixtures containing warm asphalt additives.

1.2 Scope of Research

The objectives of this research were achieved through the completion of the following.

- Comparing the indirect tensile strengths (ITS), resilient modulus, and APA rutting depths of HMA mixtures with WMA mixtures. This was done by using two aggregate sources, two binder sources and three warm asphalt additives (control, Asphamin® and Sasobit®). A total of 240 ITS and APA samples were prepared and tested to compare the properties of WMA and HMA.

- Comparing the binder rheological properties at high, medium and low temperatures for virgin binders as well as binders containing the warm asphalt additives. This was done by testing three binder sources and three warm asphalt additives (control, Asphamin® and Sasobit®). The specific parameters that were evaluated are below.

- Effects of temperature on the viscosity of the binders containing the warm asphalt additives by measuring the viscosity in a rotational viscometer at different temperatures (135 and 120 °C or 275 and 248 °F).

- Effects of time on the viscosity of the warm asphalt binders, after the addition of the additives, by measuring the viscosity 30, 60 and 90 minutes after adding the warm asphalt additive. A total of 72 viscosity tests were conducted to evaluate the effects of time and temperature on the properties of the warm asphalt binders.

- Effects of the warm asphalt additives on the complex modulus (G*) and the phase angle (δ) of the binders.

- Effects of the warm asphalt additives on creep response, creep recovery, flow, frequency sweep, and temperature sweep of the binders. The mid-temperature rheological properties of the binders with and without the warm asphalt additives were evaluated by running 96 dynamic shear rheometer tests.

- Effects of the warm asphalt additives on the low temperature stiffness and m-value of binders. This consisted of running 24 bending beam rheometer tests.

- The effects of aging of binders containing the warm asphalt additives were evaluated by conducting the rolling thin film oven test at two different temperatures. The residue was further aged in a pressure aging vessel to

simulate long term aging. Following the aging procedures, the viscosities, G* and δ values, binder stiffness and m-values were determined. In order to age the binders, a total of 24 rolling thin film oven and 24 pressure aging vessel test procedures were carried out.

- The effects of aging of WMA mixtures were evaluated by artificially aging the samples in the oven for 120 hours at 85 °C (185 °F). The aged samples were then tested for indirect tensile strength, resilient modulus, and APA rut depths. A total of 120 ITS / APA samples were prepared and tested to evaluate the aging of warm asphalt mixtures. Additionally, the binders were extracted from the aged and fresh samples, and tested to compare with binders aged in the rolling thin film oven and the pressure aging vessel.

- Additionally, Fourier transform infrared spectroscopy and gel permeation chromatography were employed to quantify the amount of aging in the binders with and without the warm asphalt additives. A total of 36 gel permeation chromatography tests and 27 Fourier transform infrared spectrometry tests were run to quantify the amount of aging in the binders.

1.3 Organization of the Dissertation

This dissertation is divided into six chapters. Chapter I contains an introduction to the problem and the objectives of the research. A literature review of related research is included in Chapter II. The literature review includes background information about warm asphalt products, some of the advantages and disadvantages of using warm asphalt, earlier laboratory studies conducted on the warm asphalt binders and mixtures, information about

the field trials conducted using the warm asphalt mixtures, and the significance of this research project. The materials used in this study, the research approach and the test methods are described in Chapter III. The statistical analysis methods that were used to analyze the results obtained in this research are explained in Chapter IV. The experimental results and discussions are presented in Chapter V, and finally, the conclusions from this study and recommendations for future studies are included in Chapter VI.

Chapter II

2. LITERATURE REVIEW

As the asphalt industry is getting more aware of the warm mix technology, there is an increasing need to perform research to determine the feasibility of these technologies. Some European countries are already using the warm mixture technology to be able to produce asphalt mixes at lower temperatures without significantly affecting the quality of the mixes. While the energy savings and the air quality improvements by using warm asphalt are appealing, the performance of warm asphalt in the United States is not well known. The mix designs, binder sources, equipment, climate conditions, work practices, among many other factors, are quite different in the United States than in Europe and thus warm asphalt requires more investigation and research before being incorporated in the United States.

2.1 Advantages and Disadvantages of Warm Asphalt

One of the major advantages of warm asphalt is the reduction in the mixing and compaction temperatures. Decreasing the temperature in the production of WMA will lower fuel usage and decrease emissions directly connected to fuel use. This should lower the emissions of greenhouse gases (CO_2) and traditional gaseous pollutants (CO, NO_x, and SO_2). Decreasing the temperature of the asphalt should decrease emissions of hazardous air pollutants (HAP) in general. Another advantage of lower emissions is that the asphalt plant can be sited even in regions of strict air pollution regulations. Because of limited experience with WMA in the United States, there are few data published on WMA emissions. Table 2-1 gives an example of the emissions measured from WMA field demonstration projects for each WMA technology as a percentage of reduction from the emissions from HMA

construction projects. The data has been provided by the producers of the WMA technologies.

Table 2-1: Percentage reduction in emissions during construction of WMA compared to conventional HMA projects

	Warm Mix Asphalt Processes			
	Aspha-Min®[1)]	**Sasobit®[2)]**	**Evotherm™ [3)]**	**WAM-foam[4)]**
SO_2 (%)	17.6%	-	81%	n/a
CO_2 (%)	3.2%	18%	46%	31%
CO (%)	n/a	n/a	63%	29%
NOx (%)	6.1%	34%	58%	62%
THC (%)	35.3%	n/a	n/a	n/a
VOC (%)	n/a	8%	25%	n/a

[1)] Data from Charlotte, North Carolina in September 2004
[2)] Data from M-95 Iron Mountain, Michigan in September 2006
[3)] Data from Road #46 in Ramara, Canada in 2005
[4)] Data from FV 82 Frogn in Nesodden, Norway in April 2001

Apart from the reductions in emissions, lowering the mixing and compaction temperatures of asphalt mixtures can also lower the fuel requirements at the plant. Though there are no extensive studies conducted to quantify the reduction in fuel requirements at the asphalt plants due to the reduction in the mixing and compaction temperatures, it was estimated during some field trials that a reduction in fuel consumption of 10 to 30% is possible depending on how much the production temperature is reduced *(Astec Inc, 2007; Kristjansdottir, 2006; The Asphalt Pavement Association, Oregon, 2003).*

Apart from reduced fuel requirements and emissions, another advantage of using warm asphalt additives is its ability to reduce the viscosity of the binders. This will allow

using stiffer binders and higher percentages of recycled pavement material in the mixes. The reduced viscosity of the binders will also improve the workability and the compactibility of the mixes. Yet another advantage of reducing the mixing temperature of the mixes is that this will decrease the cooling rate of the mixes as the gap between the mix and ambient temperature will be lesser. This decreased rate of cooling will allow for longer haul distances, and more time for compaction of the mixes, which would be beneficial during extreme weather conditions and can help extend the paving season.

While earlier research have indicated several advantages of using WMA, the first WMA field trial was conducted in 1999, and thus, the long term performance of WMA is still not known in great detail. It is also unclear as to how the warm asphalt additives affect the aging of the binders and mixtures, and thus, the pavement performance. Although the use of WMA may reduce the initial cost of production due to lower fuel consumption, if the overall life cycle cost of using WMA is higher, using WMA will have no advantages. Thus, a thorough life cycle cost analysis of a WMA pavement needs to be performed and compared to a HMA pavement. Kristjánsdóttir, et al. have indicated that HMA producers are unlikely to adopt WMA technology purely for the benefits of lowered emissions and reduced fuel costs *(Kristjánsdóttir, et al., 2007)*. They indicated that the current environmental regulations and relatively clean nature of HMA make it unprofitable to use WMA unless in certain areas where the air pollution is high and the regulations are strict. Also, the reductions in fuel costs can be offset by the price for the WMA technologies, unless the producers are in an energy expensive market.

Another disadvantage of WMA is that most of the field experience is from Europe, and WMA is relatively new in the United States. Since the construction practices, equipment

types and specifications are different in the US than in Europe, the European experiences may not be directly applicable in the US.

Studies conducted at National Center for Asphalt Technology (NCAT) *(Hurley and Prowell, 2006; Hurley and Prowell, 2005)* indicate that as the mixing temperatures are reduced for WMA, the mixes show increased tendencies towards rutting and moisture susceptibility. This is as a result of the aggregates used in the mix not drying completely. Thus, the WMA producers should find the right balance between lowering the mixing temperatures, using sufficient amount of antistripping agents and sufficiently drying the aggregates used in the mixes.

2.2 Available Warm Asphalt Technologies

With the availability of several proprietary chemicals and processes to produce warm asphalt, it is now possible to produce warm asphalt without affecting the properties of the mix. Some of the most common processes / chemicals available today are as described below.

2.2.1 Asphamin®

It is a Sodium – Aluminum – Silicate which has been hydro thermally crystallized as a very fine powder. It contains about 21% crystalline water by weight and is added to the mixture at a rate of 0.3% by weight of the mixture. By adding it to the mixture at the same time as the binder, a very fine water spray is created as all the crystalline water is released, which causes volume expansion in the binder, thereby increasing the workability and compatibility of the mixture at lower temperatures. It has been reported, by the

manufacturer, that a reduction of about 25 to 30 °C (40 to 50 °F) has been observed. This specific property of Asphamin® is maintained over a long duration of time *(Eurovia Services)*.

2.2.2 Evotherm™

It uses a chemical additive technology and a "Dispersed Asphalt Technology", (DAT), delivery system. The producer states that by using this technology a unique chemistry customized for aggregate compatibility is delivered into a dispersed asphalt phase (emulsion). During production, the asphalt emulsion with Evotherm chemical package is used in place of the traditional asphalt binder. The emulsion is then mixed with the aggregate in the HMA plant. The manufacturer reports that this chemistry provides better aggregate coating, workability, adhesion, and improved compaction with no change in materials or job mix formula required. In addition, they report that field testing has demonstrated a 55 °C (100 °F) reduction in production temperatures *(MeadWestvaco)*.

2.2.3 Foamed Asphalt

Foamed asphalt is formed by combining hot asphalt binder with cold water. When the cold water comes in contact with the hot asphalt binder, it turns into tiny steam bubbles trapped inside the asphalt binder. This leads to an expansion in the volume of the binder and improves the coating potential of the binder. Warm asphalt mix using foamed asphalt technology (WAM-foam) is a patented process developed jointly by Shell Global Solutions and Kolo Veidekke in Norway. In the WAM-foam production process, two different bitumen grades, soft bitumen and hard bitumen, are combined with the mineral aggregate. The aggregate are first mixed with the softer binder, which is fluid enough at lower temperatures, and then the harder binder is foamed and mixed with the aggregates pre-mixes with the softer binder. However, selecting the right grades of the soft and hard binders is

critical to this process. This process makes it possible to produce the asphalt mixture at temperatures between 100°C and 120°C (212 and 250 °F) and compact it at 80 to 110°C (175 to 230 °F) *(Koenders et al. 2000)*. Recently, Astec Inc. in Chattanooga, TN also developed a Double Barrel Green System, where a multi-nozzle device is fitted to a double barrel drum plant. The multi-nozzle device is used to produce microscopic bubbles in the asphalt binder by combining a small amount of water with the asphalt binder before it is introduced to the aggregate. The manufacture claims that this process can reduce the fuel consumption by as much as 11% *(Astec Inc., 2007)*.

2.2.4 Sasobit®

It is a long chain aliphatic hydrocarbon (chain lengths of 40 to 115 carbon atoms) obtained from coal gasification using the Fischer – Tropsch process. The Fischer-Tropsch process is a catalyzed chemical reaction in which carbon monoxide and hydrogen are converted into liquid hydrocarbons of various forms in the presence of iron and cobalt as catalysts. The melting point of Sasobit® is around 85 to 115 °C (185 to 240 °F). Sasobit® forms a homogeneous solution with the base binder on stirring, and produces a marked reduction in the binder's viscosity. Reductions of about 25 to 50 °C (50 to 90 °F) in the mixing and handling temperatures of the mixture have been reported by the producer. After crystallization, Sasobit® forms a lattice structure in the binder which is the basis of the structural stability of the binder containing Sasobit® (*Sasol Wax)*.

2.3 Warm Asphalt Laboratory Studies

The properties of the warm asphalt, like indirect tensile strength, rutting, moisture susceptibility, etc. in comparison to hot mix asphalt properties are some of the primary

concerns of warm asphalts. Additionally, the increased curing times and aging behavior of warm asphalt have unknown effects on the mixture properties. The compatibility with current construction practices and equipments, compatibility with polymerized binder (eg. rubberized asphalt binder), compatibility with recycled asphalt pavements, etc. are some of the immediate concerns with warm asphalts. While some studies have been conducted to address some of these issues *(Hurley and Prowell, 2006; Barthel, et al.; Hurley and Prowell, 2005)*, there is still a need for more work in this area.

NCAT conducted studies on some of the properties of warm asphalt prepared using Asphamin®, Sasobit® and Evotherm™. They concluded that all three technologies were capable of reducing the mixing and compaction temperatures of the asphalt mixtures. It was also concluded that all three technologies improved the compatibility of the asphalt mixture and resulted in lower air voids using Superpave gyratory and vibratory compactors. With the exception of Sasobit®, the other technologies seemed to increase the resilient modulus of the mixes. There were also some problems with the warm mixtures, like all three technologies showed increasing tendencies to rutting and moisture susceptibility as the mixing and compaction temperatures were lowered. This was attributed to decreased aging of the binder, possible presence of moisture in the mixture, and incomplete drying of the aggregates due to lower temperatures. Also, it was observed that the addition of Sasobit® to the binder increased the PG grade of the binder, and necessary corrections need to be made, by using a lower grade binder. The reduction of air voids in the mixture could also mean that the optimum asphalt binder could be lowered. However, NCAT does not recommend this, as more research is needed to investigate this issue, and also the lowering of asphalt content could negate the improved compactibility of the mixtures.

While some of the primary concerns of WMA, like the moisture susceptibility, rutting potential, curing time requirements, etc. have been addressed to an extent *(Hurley and Prowell, 2006; Barthel, et al.,; Hurley and Prowell, 2005)*, it is still unclear as to how the warm asphalt binders behave. While NCAT reported that addition of Sasobit® increased the PG grade of the binders, some studies conducted at Clemson University *(Gandhi and Amirkhanian, 2007)* showed that two of the three binders had the same PG grading after the addition of Sasobit®. In other studies conducted on the properties of asphalt binder modified with fischer-tropsch (FT) paraffins *(Butz, et al., 2001; Damm, et al., 2002)*, it was concluded that the addition of the FT paraffins significantly increases the penetration resistance of the binders, reduces the softening point of the binders by about 40 to 50 °C (70 to 90 °F), increases the low temperature tensile strength, and increases the stiffness and elasticity of the binders tested in the temperature range of 10 to 60 °C (50 to 140 °F).

Rheological tests like flow and viscosity can reveal many things about the effects of the reduction in viscosity by the warm mix technologies. Historically, asphalt has been selected for use in paving largely based on its rheological properties. These properties are still the most important measure of what is necessary to select proper paving asphalts *(Davis, R., L., 1987)*. Dynamic mechanical analyses can be used to determine the elastic and viscous moduli of the binders, and the relationship of the moduli to the mixture and pavement performance *(Sisco, A. W., and Brunstrum, L. C., 1969)*. Correlations between the binder rheology at low temperatures have been established with low temperature creep response of mixtures *(Goodrich, J. L., 1988; Goodrich, J. L., 1991)*. From low temperature creep studies of mixtures, it was shown that the binder rheological properties like the temperature at which the viscous modulus peaked and temperature where the ratio of the elastic to viscous moduli was about 2.5 were well associated with the limiting stiffness temperature of the mixtures.

Similarly, asphalt rheology at mid-range temperatures has been related to the plastic strain in asphalt concrete *(Goodrich, J. L., 1988; Goodrich, J. L., 1991)*. It was shown that the asphalt binders that performed best in dense graded asphalt concrete creep experiments had elastic properties at high ambient temperatures. In terms of the flexural fatigue life of the asphalt concrete also, a good correlation was observed with the elastic and viscous moduli of the binder *(Goodrich, J. L., 1988; Goodrich, J. L., 1991)*. Based on the study, it was concluded that the elastic structure within an asphalt binder provides fatigue resistance in low strain rate conditions, and thus asphalt binders which have a higher elastic modulus compared to the viscous modulus at low temperatures have a good low strain fatigue life. On the other hand, asphalts which have low temperature viscous flow properties provide fatigue resistance in high strain rate conditions.

In a preliminary study conducted at Clemson University, the viscosity and flow properties of the binders were studied at mid-range temperatures (60 °C or 140 °F). The results indicated that the addition of Sasobit® changed the flow properties of certain binders from Newtonian flow to shear thinning flow. It was also observed that addition of the warm asphalt additives increased the viscosity of the binders at mid-range temperatures (60 °C or 140 °F). This means that the addition of the warm asphalt additives reduce the viscosity of the binders at high temperatures *(Gandhi and Amirkhanian, 2007),* and increase the viscosity at mid-range temperatures, which makes the binders more workable at higher temperatures and stiff, and therefore, more resistant to penetration and rutting at mid-range temperatures. Sasobit® also improved the complex modulus 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. While binders containing Asphamin®

also showed increased resistance to rutting and permanent deformation, different binders showed different trends.

Since Sasobit® is a long chain aliphatic hydrocarbon of 40 to 115 carbon atoms, it is important to investigate the effects of crystallization of the wax in different binders. Based on the nature, size and melting point of the crystals in different binders, it is possible to investigate the different effects that the addition of Sasobit® has on different binders. Generally, waxes in asphalt binder are classified in three categories: Macro-crystalline, Micro-crystalline, and amorphous. Macro-crystalline waxes generally have chain lengths of about 30 carbon atoms and crystallize in large crystals *(Edwards et al., 2006)*. They mainly are composed of n-paraffins (n-alkanes) with minor amounts of iso- and cyclo-paraffins. They crystallize as plates and needles. The melting point of isolated macro-crystalline paraffin waxes lies around 50 to 70 °C (120 to 160 °F), but in asphalt binder, the melting point decreases by about 20 to 30 °C (35 to 55 °F) *(Edwards and Redelius, 2003)*.

Chains of 40 or more carbon atoms generally form smaller crystals, and are Micro-crystalline in nature. Microcrystalline waxes are aliphatic hydrocarbon compounds containing a considerable portions of iso- and cyclo-paraffins and small portions of n-paraffins. They crystallize as small needles. A micro-crystalline wax is also characterized by a less distinct melting area and its high average molecular weight giving higher viscosity compared to macro-crystalline waxes *(Edwards and Redelius, 2003)*.

Wax with branched carbon chains, aromatic and alicyclic components show difficulty in crystallizing, and therefore are amorphous in nature *(Boucher, 1991)*. The origin, chemical composition of the asphalt binder, rheological properties of the binder, wax content in the asphalt binder, chemical composition of the waxes and the crystalline structures of the waxes

are some of the parameters that govern the effects of waxes on asphalt binder. According to literature *(Edwards and Redelius, 2003; Edwards, et., Al., 2006)*, the negative effects of high wax contents in asphalt binders may be in different ways. A sudden decrease in the viscosity of the binder around the melting point of the wax crystals is of primary concern. If the melting point of the wax crystals is below the high ambient temperatures of the pavement, the viscosity of the binder may be lower than usual, leading to an increase in rutting. Another way in which waxes in binder can adversely affect is by increasing the brittleness of the binder due to the presence of wax crystals in the binder at low temperatures. These wax crystals cause in-homogeneity in the binders, leading to reduced ductility at low temperatures, leading to increased cracking in the asphalt mixtures at low temperatures. Yet another way in which the presence of wax can affect the binder is the decreasing ability of the binder to wet aggregates as the waxes are hydrophobic in nature. Thus, in order to minimize the effects of waxes on the binders, it is suggested that the wax content in the binder be below 3% by weight of the binder *(Gawel, et al., 1996)*.

It is therefore important to evaluate the wax content in the binders before and after adding the warm asphalt additives, especially Sasobit®, and the type of wax crystals in the binder, to be able to understand the effects of the wax crystals. Ho et. al. *(Ho, et al., 2003)* indicated that micro-crystalline waxes were found to be less harmful to the base asphalts used in a study compared to paraffin waxes. Binders containing micro-crystalline waxes showed better softening point and high temperature parameters and their low temperature properties were also almost unchanged. It was also concluded in the study that the molecular weight of the wax had significant effects on the crystallization and melting temperature ranges of the waxes in the binders. Waxes with a wider molecular weight distribution would

result in a more gradual crystallization of the waxes over a wider range of temperatures, easing the harmful effects of sudden wax crystallization *(Ho, et., Al., 2003)*.

Gel permeation chromatography is a well known technique for characterizing the molecular size distribution of asphalt binders *(Kim, et al., 2006)*. In some of the first studies conducted on asphalt binders using GPC *(Bynum and Traxler, 1970)*, aged samples of asphalt binder from the pavement were taken after several years of construction, and compared to unaged samples. The research concluded that the GPC was an effective tool to quantify aging in the binders. In another study *(Jennings, 1980)*, it was observed that the cracking potential of the binders could be correlated to the % large molecular size section of the binder chromatograms. In yet another study form the same authors *(Jennings and Pribanic, 1985)*, it was observed that binders with low asphaltene contents showed increased tendencies to rutting, and binders with lower naphtene aromatics showed higher resistance to rutting. These research findings have concluded that the GPC could be used as an effective tool to indicate the rutting potential of the mixes. In some other studies conducted *(Garrick and Wood, 1988; Price, 1988)*, strong correlation between absolute viscosity, kinematic viscosity, penetration, thin film oven hardening, resilient modulus, and indirect tensile strength of asphalt mixtures to the GPC chromatograms.

Differential scanning calorimetry (DSC) has been found to be an effective tool to study the thermal properties and behavior of asphalt binders *(Noel and Corbett, 1970; Claudy, et al., 1998; Harrison, et al., 1992; Chamberion, et al., 1995; Edwards, et al., 2006)*. In DSC analysis, a small sample is exposed to cooling and heating cycles, and the thermal effects like melting, dissolution, crystallization / precipitation, etc. are registered. From earlier studies, it was found that the glass and melting transitions of the asphalts were attributed to saturates

(waxes) and naphthene aromatic fractions in the binders. It was also observed that the DSC curves for asphalt binders are complicated due to several overlapping phenomena *(Edwards, et al., 2006)*. However, there are certain trends that are common to all asphalt binders. Claudy, et al. *(Claudy, et al., 1998)* observed that at room temperature, asphalt binder is made of two liquid phases and some crystallized fractions.

As a result of the two liquid phases, asphalt binders exhibit two glass-transition temperatures over a broad range of temperatures, depending on the proportion of the liquid phases in the binders and the complex mixture of different molecules. The glass transition temperatures maybe followed by a weak exothermic effect caused by the cold crystallization of waxes in certain binders of high natural wax contents. At higher temperatures, a broad exothermic effect can be observed in the DSC heat flow diagrams of asphalt binders, due to the melting of the crystalline fractions in the binders. At around 60 to 90 °C (140 to 195 °F), the natural bitumen wax is normally completely melted out *(Edwards, 2005)*. In a study conducted on asphalt binders containing commercial waxes *(Edwards, et al, 2005; Edwards, et al., 2006)*, it was observed that the melting out temperatures of bitumen / wax mixtures were around 100 to 130 °C (212 to 265 °F). It was also observed that depending on the molecular weight distribution of the waxes, the melting temperature range differed. Another study which correlated the molecular weights of waxes and thermal behavior of the asphalt binders *(Harmon, 1978)* concluded that higher the molecular weight of the waxes, wider were the temperature ranges of crystallization and melting.

Infrared analysis, using the attenuated total refraction (ATR) method is an extremely useful tool to study the chemical functionality of asphalt binders *(Jemison, et al., 1992)*. FTIR analysis enables the identification and quantification of functional groups present in

bitumen. Infrared spectroscopy measures the infrared light absorbed by covalent bonds in molecules (or vibrations of lattice crystals). The absorption of different types of bonds differs in the intensity and frequency of light absorbed, which enables the identification of chemical functionalities *(Karlsson and Isacsson, 2003)*. Values of IR absorbance (peak heights) at wave number 1700 cm^{-1} and 1030 cm^{-1} are indicative of binder carbonyl compounds and sulfoxides, respectively, and are often used to characterize the aging in the binders *(Edwards, et al., 2006)*. Similar correlations were found between aging in binders and carbonyl and sulfoxides in another study *(Martin, et al., 1990)*. In a study conducted on asphalt binders containing commercial waxes *(Edwards, et al, 2005; Edwards, et al., 2006)*, it was observed that the addition of the waxes did not increase the sulfoxide absorbance for any of the binders after aging, however, the carbonyl absorbance increased or decreased after aging, depending on the amount of natural wax in the binders.

2.4 Warm Asphalt Field Trials

Apart from the above mentioned laboratory studies, several field trials have been performed with each of the available warm asphalt technologies. While most of the field trials have been small-scale, there have been some field trials at the city/county levels in the United States. Some of the field trials that have been conducted are listed in Table 2-2 *(Astec Inc., 2007; Eurovia Services; Sasol Wax; MeadWestvaco; Diefenderfer, et al., 2007; de Groot, et al., 2001; Hurley and Prowell, 2005; Hurley and Prowell, 2006; FHWA Webpage; Kristjánsdóttir, 2006; Koenders, et al., 2000; Koenders, et al., 2002; Larsen, et al., 2004; Michael, et al., 2006; Newcom, 2005; Prowell, et al., 2007; P Q Corporation; Shell; Flexible Pavement in Ohio, 2006)*.

Table 2-2: Partial list of field demonstration trials using the warm asphalt technologies to date

Technology	Field Demonstrations
Asphamin®	• With Polymer modified asphalt in Germany (2003) • Parking lot in Orlando, Florida (February 2004) • Charlotte, North Carolina (September 2004) • Montreal, Quebec, Canada (2004) • Columbus, Ohio (October 2005) • Hookest, New Hampshire (December 2005) • Belmont, New Hampshire (March 2006) • OGFC in Orlando, Florida (February 2006) • Wearing course at SR 541 in Cambridge, Ohio (2006)
Sasobit®	• Surface and base mixtures in Maryland (2005) • OGFC in Beijing, China (2005) • SMA mixes on I 95/I 495 in Washington D.C. (2005) • 1.5" overlay on Route 211, Rappahannock County, Virginia (August 2006) • 1.5" overlay on Route 220, Highland County, Virginia, (August 2006) • With 10% RAP in Missouri (May 2006) • With 14% RAP in Oak Creek, Wisconsin (June 2006) • M-95 Iron Mountain, Michigan (September 2006) • Wearing course at SR 541, Cambridge, Ohio (September 2006)
Evotherm™	• County Road 900 in Boone County, Indianapolis, Indiana (July 2005) • Branch road 110 in Beijing, China(September 2005) • County road with low ADT, Greenwich, New York (September 2005) • Binder layer in Calgary, Canada (September 2005) • Eskimo road in San Antonio (November 2005) • NCAT test track in Auburn, Alabama(November 2005) • Miller Paving in Aurora Ontario, Canada (August 8, 2005) • Residential subdivision in the northeast Calgary, Canada (September 30, 2005) • 3 kilometer section of Road #46 in Ramara, Canada (October 5, 2005) • 1.5-in overlay on Route 143 in York County, Virginia (October 2006) • Wearing course on SR 541 in Cambridge, Ohio (September 2006)
Foamed Asphalt	• First field trial in Norway using a Midland Mix-Paver (paver and pugmill combined) modified for foaming (May 1999) • Close to Oslo in Norway using a batch plant (May 2000) • First large scale trial on RV120 in Hobøl, Norway, (September 2000) • Wearing course on FV 82 Frogn in Nesodden, Norway (April 2001) • 20 mm dense road basecourse, UK (April 2001) • Nordic Construction Company road in Sweden (2002) • Ooms Abenhorn in Netherlands (2003) • Conglobit in Italy (2004) • Double Barrel Green system developed by Astec Inc. in Chattanooga, Tennessee (June 2007)

In most cases, it was observed that the WMA sections could achieve comparable densities to the conventional HMA sections at significantly lower temperatures. It was also observed that the WMA mixtures were more workable compared to the HMA mixtures *(Kristjánsdóttir, et al., 2007)*.

When laboratory tests were conducted on field samples containing Asphamin®, NCAT observed that the results corresponded with the trends observed in the laboratory studies of mixes containing Asphamin® *(Hurley and Prowell, 2005)*. It was also observed by the crew that the mixes containing Asphamin® had better workability than the control mix. Similar densities were observed in the warm asphalt and hot asphalt sections, and an assessment one year after placement did not show any signs of distress in terms of rutting or moisture damage. In addition, from several comparisons made by Eurovia Services, it was observed that sections containing Asphamin® had significantly similar surface characteristics as compared to control HMA sections even after three years of construction *(Barthel, et al.)*.

From laboratory testing of plant-produced samples of mixtures containing Sasobit®, it was observed that the addition of Sasobit® as a compaction aid had only a minor effect on the mechanical properties of the mixtures *(Hurley and Prowell, 2005)*. It was observed that Sasobit® marginally increased the stiffness of the mixes and improved the moisture susceptibility of the mixtures. However, the addition of Sasobit® did not significantly affect the aging, rutting, fatigue cracking and thermal cracking resistance of the mixes. In another study conducted *(Advance Asphalt Technologies, 2005)*, it was concluded that Sasobit® could also be used as an effective compaction aid to mixes containing high recycled asphalt pavement (RAP) material. It was reported in one of the field studies *(NAPA, 2005)* that

mixes containing Sasobit® were much easier to handle, and that the compaction targets were achieved by 40% lower compaction effort.

The NCAT test track study on Evotherm™ revealed that the WMA test section showed significantly similar performance with respect to rutting as compared to the HMA control section after being subjected to half a million ESALs in 43 days *(Prowell, et al., 2007)*. Other tests conducted by NCAT *(NCAT, 2005)* on mixes containing Evotherm™ obtained from the field trials indicated that Evotherm™ improved the compactibility of the mixes in a vibratory compactor. It was also found that mixers containing Evotherm™ had better rutting resistance and similar resilient modulus values compared to control mixes. From other field studies conducted *(Davison, 2005)* on mixes containing Evotherm™ in Aurora, Calgary and Ramara (all in Canada), it was observed that using mixes containing Evotherm™ did not have any issues during the construction process, and could be placed and compacted using the conventional equipments. It was also observed that the void properties were also comparable to the control sections. Another observation made at these field trials was that the amount of fuel consumed during the production of the mixes containing Evotherm™ was considerably lower than the amount of fuel consumed during HMA production, and there were no signs of visible emissions and tenderness in the mixes containing Evotherm™ *(Prowell and Hurley, 2005)*.

WAM-foam was one of the first warm asphalt products developed, and the first WAM-foam field trial was carried out in May 1999 in Norway *(Kristjánsdóttir, 2006)*. Based on field trials on mixes prepared with the WAM-foam process, it was observed that the void contents measured along the WMA and HMA sections were significantly similar. Additionally, rutting, smoothness, and surface texture were monitored twice a year, and measurements between the years 2000 and 2003 showed very similar results for both WMA

and HMA *(Kristjánsdóttir, 2006)*. Additionally, in spite of the high percentage of studded tires (60%) in Norway, WAM-foam sections and control sections performed similarly *(Larsen, et al., 2004)*. From another trial in 2001 in the United Kingdom, it was observed that fatigue properties of the plant produced WAM-foam and HMA were statistically comparable.

2.5 Significance of Work

As seen in the literature review, various binder properties affect the performance of the warm mix technologies differently. Also, the aggregate sources can affect the moisture susceptibility, rutting potential and resilient modulus of WMA in a different manor. Therefore, a thorough understanding of the properties and performance of the warm mixture technologies is necessary in order to be able to implement WMA safely, especially since WMA is a relatively new topic in the United States, and no thorough research has been conducted to investigate many aspects of warm asphalt. The significance of this research will be as follows:

- To investigate, in depth, the various factors affecting the warm asphalt mixtures, such as binder and aggregate sources, and warm asphalt additive type. While the NCAT study investigated some of these factors, the main focus was to determine the effects of mixing and compaction temperatures on the volumetric properties, the indirect tensile strength and rutting potential of the mixtures and the effects of binder sources were not studied.

- Also, most research conducted on warm asphalt so far has been on the mixture properties *(Hurley and Prowell, 2006; Barthel, et al.; Hurley and Prowell, 2005)*, and not much research has been completed on the binder properties of warm asphalt. Another significance of this research will be to investigate the effects

of addition of the warm asphalt additives on different binder properties. In this research, the low, mid-range and high temperature rheological properties of the warm asphalt binders will be investigated. These topics have not been studied in great detail.

- Another aspect that will be investigated is the aging characteristics of the warm asphalt, both mixture and binder aging. While it is important to study the effects of various factors affecting WMA, it is also important to investigate the effects of aging on the properties of WMA and the warm asphalt binder. Since the aging of warm asphalt mixtures and binders have not been studied in great detail, it is proposed to study the effects of aging on warm asphalt mixtures and binders in this research study.

Chapter III

3. MATERIALS AND TEST PROCEDURES

This chapter provides a description of the materials used in this study, the experimental plan to complete the proposed research and the experimental procedures employed to accomplish the objectives of the research.

3.1 Materials Used

Three different binders were selected for this study. The first binder was from different sources blended together; the second binder was from a Venezuelan crude source, and the third binder was from a crude source in Texas. The binders were transported to the laboratory in sealed 5 gallon containers to prevent oxidation and premature aging. All the binders were of PG 64 -22 grade, and their properties are shown in Table 3-1.

Table 3-1: Binder properties

Property	**Binder 1**	**Binder 2**	**Binder 3**
Original Binder			
Viscosity, Pa-s (135˚C)	0.405	0.626	0.420
G*/sin δ, kPa (64˚C)	1.207	1.801	1.686
RTFO Residue			
Mass Loss, % (163˚C)	-0.02	-0.24	-0.01
G*/sin δ, kPa (64˚C)	2.815	4.608	3.780
PAV Residue			
G*sin δ, kPa (25˚C)	2970	2420	1704
Stiffness (60), MPa (-12˚C)	183	129	117
m-Value (60) (-12˚C)	0.311	0.345	0.320
PG Grade	64 -22	64 -22	64 -22
Mixing Temp.[+], ˚C	150–155	163–170	150–155
Compaction Temp.[+], ˚C	139-144	150–155	139-144

[+]*Information provided by the suppliers*

The aggregates used in this study were obtained from two sources, denoted as Aggregate sources A and B. The types of aggregate received from each quarry consisted of #57, #789, Regular Screenings (RS), and Manufactured Sand (MS). Each type of the aggregate was randomly obtained from quarry stockpiles and transported to the laboratory. Aggregate A is micaceous granite and is prone to stripping, and Aggregate B is marble schist and known to perform well against stripping. The aggregates obtained were then tested for gradation as per ASTM C 136, *Method for Sieve Analysis for Fine and Coarse Aggregate (ASTM Standards, 2005)*. Table 3-2 contains the gradation and properties of the aggregates used, and the percentage of each aggregate type used. The combined gradations of the two aggregates used are shown in Figure 3-1.

Table 3-2: Aggregate gradation properties

Sieve Size (mm)	Gradation Specs	Combined Gradation (% Passing)	
		Agg. A	Agg. B
38	100	100	100
25	100	100	100
19	98 – 100	99	100
12.5	90 – 100	94	94
9.5	74 – 90	89	84
4.75	46 – 62	49	49
2.36	25 – 41	30	39
0.150	4 – 12	6.6	8.5
0.075	2 – 8	3.34	5.12
Stone Type		**% Used in the mix**	
#57		9	11
#789		61	46
RS		20	17
MS		10	26
		Properties	
Aggregate Type		Micaceous Granite	Marble Schist
Bulk Specific Gravity		2.700	2.830
Absorption, %		0.77	0.49
Los Angeles Abrasion Loss, %		52	23

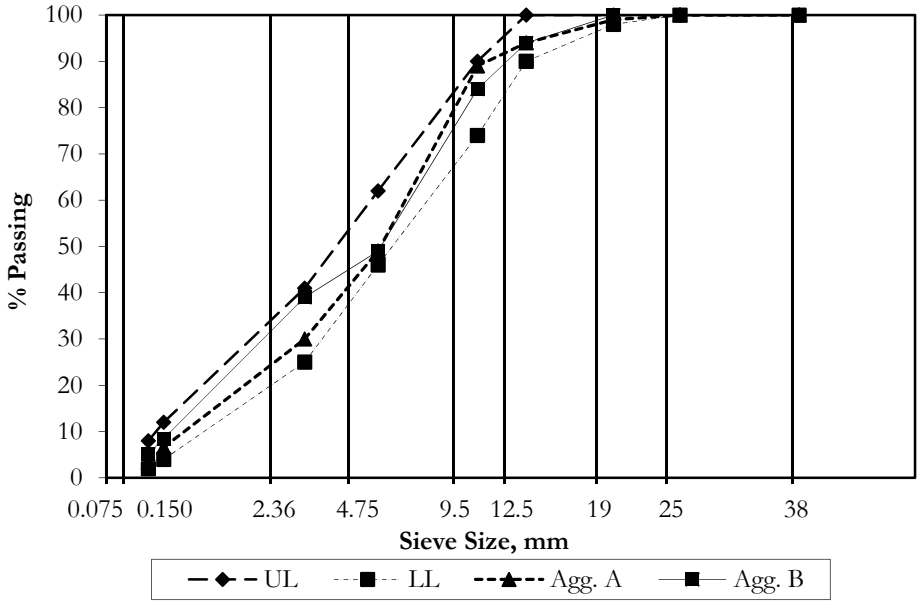

Figure 3-1: Combined aggregate gradation

Two different warm asphalt additives were used in this study. One of them was Asphamin®, (denoted as 'a') a Sodium – Aluminum – Silicate, which is hydro-thermally crystallized into a fine powder. It is added at the rate of 0.3% by weight of the mixture, as recommended by the manufacturer, and added at the same time as the binder. The crystals contain about 21% water, inducing a fine spray in the binder causing a volume expansion, thereby increasing the workability and compactibility of the mixture at lower temperatures. It has been reported, by the manufacturer, that a reduction of about 25 to 30 °C (40 to 50 °F) is possible *(Eurovia Services)*.

The second warm asphalt additive was Sasobit®, a long chain aliphatic hydrocarbon (chain lengths of 40 to 115 carbon atoms) obtained from coal gasification using the Fischer – Tropsch process. Sasobit® melts in the asphalt binder at temperatures of 85 to 115 °C (185 to 240 °F), causing a marked reduction in the viscosity of the binder. The manufacturer

reports a reduction in mixing and handling temperatures of 30 to 50 °C (50 to 90 °F) *(Sasol Wax)*.

3.2 Experimental Plan

The proposed research was carried out in three independent tasks. Each of the tasks was carried out simultaneously and addressed a specific objective of the research. The independent tasks are outlined in the following sections.

3.2.1 Task 1

Task 1 of the research was carried out to study the performance of warm mix asphalt with respect to hot mix asphalt in terms of indirect tensile strength, resilient modulus and rutting performance. This task was carried out as per the experimental plan shown in Figure 3-2. The Indirect tensile strength (ITS), resilient modulus, and Asphalt Pavement Analyzer (APA) tests were performed on the mixture samples prepared freshly, and mixture samples artificially aged in the oven at 85 °C (185 °F) for 120 hours as per AASHTO R30, *Standard Practice for Mixture Conditioning of Hot Mix Asphalt (AASHTO Standards, 2004)*. After the tests on fresh as well as the aged mixtures, the binder was extracted from the samples. Several tests (viscosity test, dynamic shear rheometer (DSR) test and gel permeation chromatography (GPC) test) were performed on the binders to determine the difference in the aging behavior of warm asphalt binders compared to the conventional HMA binders when the mixtures are exposed to similar aging conditions.

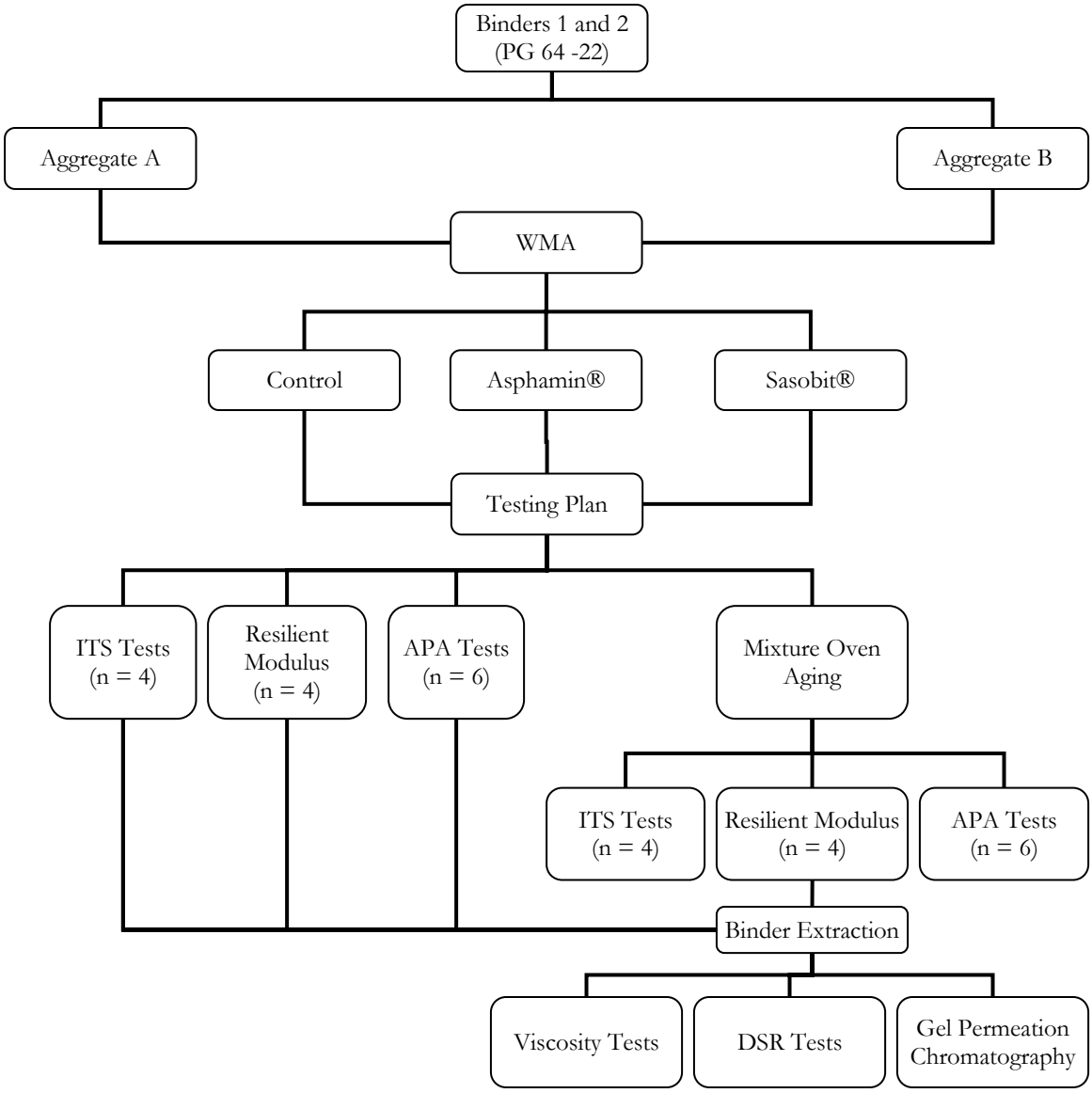

Figure 3-2: Experimental plan for investigating performance of warm mix asphalt

3.2.2 Task 2

Task 2 of the study was conducted to study the rheological properties of the binders at different temperatures - High temperature (135 and 120 °C or 275 and 248 °F); Mid-range temperature (64 and 60 °C or 147 and 140 °F); and low temperature (-12 °C or 10.4 °F).

Figures 3–3 to 3–5 show the testing plan followed to test the rheological properties of the warm asphalt binders. The rheological tests performed were able to evaluate the

effects of warm asphalt additives on the viscosity of the binders used and predict the response of the warm asphalt binders to different stress levels, different loading frequencies, creep responses of the binders, etc. The various effects that the warm asphalt additives had on the binders in terms of stress - strain relationships, gain in stiffness, creep response, etc. can also be observed from the rheological testing of the warm asphalt binders.

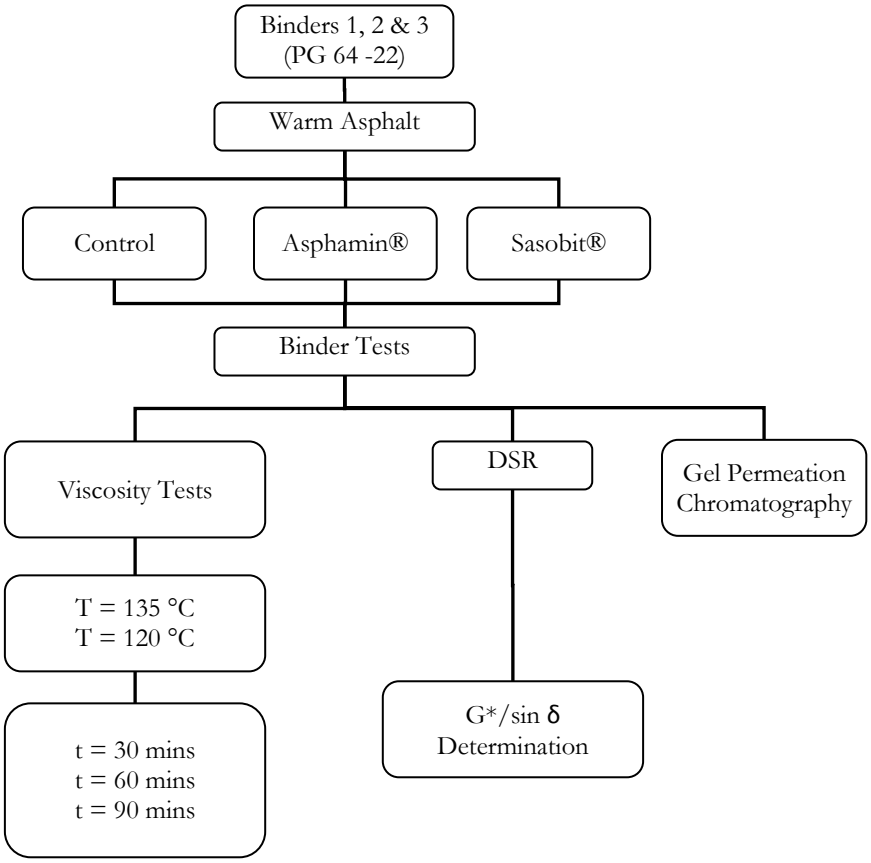

Figure 3-3: Experimental plan for high temperature rheological testing of warm asphalt binder

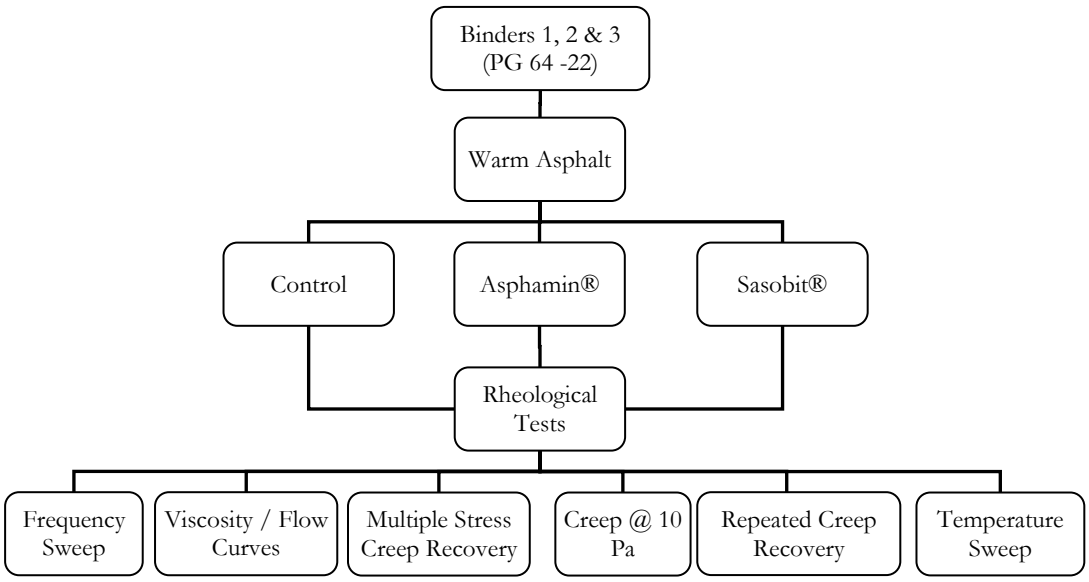

Figure 3-4: Experimental plan for mid-range temperature rheological testing of warm asphalt binder

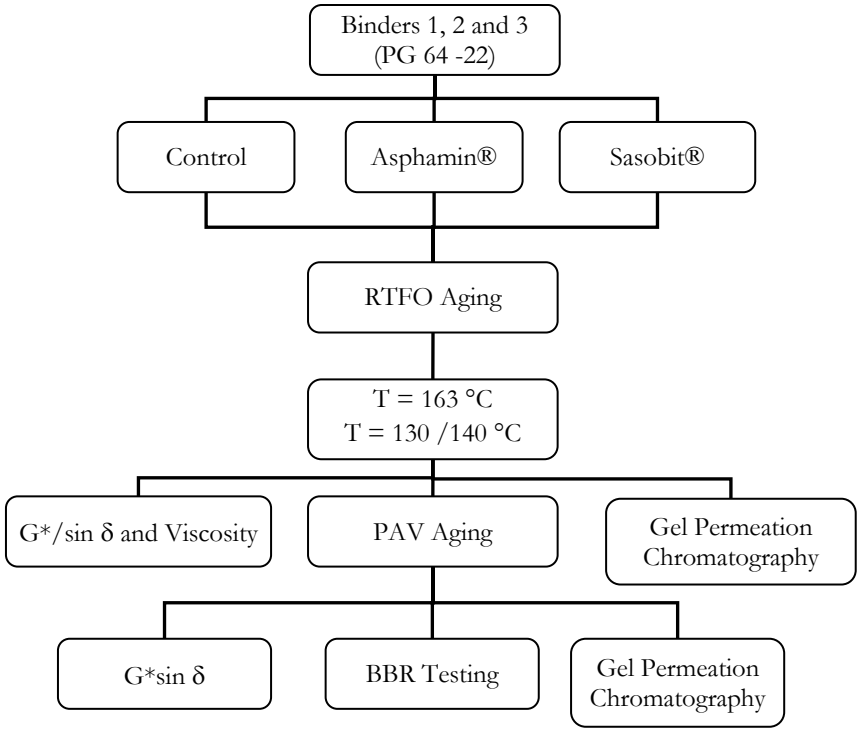

Figure 3-5: Experimental plan for low temperature rheological properties of warm asphalt binder

3.2.3 Task 3

Task 3 of this research project was to supplement the findings of Tasks 1 and 2. Fourier transform infrared (FTIR) spectroscopy was used as a tool to quantify the amount of aging in the binders with and without the warm asphalt additives. This test was carried out to verify if the increase in the complex modulus and viscosity of the binders containing the warm asphalt additives was as a result of excessive aging in the presence of the warm asphalt additives. The three binders used in this study, with and without the warm asphalt additives were scanned using the FTIR in the original, RTFO aged and the PAV aged condition.

Since Sasobit® is a long chain aliphatic hydrocarbon, the effects of melting and crystallization of the wax crystals in the binder should be studied. A differential scanning calorimeter (DSC) was used to apply heating and cooling cycles to the three binders with and without the warm asphalt additives in their original condition. From the amount of heat flow in the binders at different temperatures, the temperature ranges where the waxes crystallize and melt can be identified.

3.3 Experimental Procedures

3.3.1 Warm Asphalt Binder and Mixture Preparation

Warm asphalt binder was prepared using two of the available commercial products. Process 1 involved the addition of Asphamin®, a chemical powder at specified concentration (0.3% by weight of mixture – a binder content of 6% was assumed, and the entire additive was added to the binder) followed by mixing with a stirrer to disperse the powder throughout the binder. Process 2 involved addition of Sasobit®, pellets at specified

concentration (1.5% by weight of binder) followed by mixing for 5 min. in a shear mixer at a speed of 700 rpm to achieve consistent mixing.

The Superpave method of mix design for a 12.5mm mix was followed in this study to determine the optimum asphalt content for each mix design. A total of 4 mix designs (2 aggregate sources x 2 binder sources) were performed. The bulk specific gravity, maximum specific gravity, voids in mineral aggregate (VMA) and voids filled with asphalt (VFA) were obtained or calculated to determine the optimum asphalt content of all the mixes. Based on the recommendations from NCAT *(Hurley and Prowell, 2006)*, the mix design results for the control HMA were adopted for WMA also.

3.3.2 Binder Testing

A rotational viscometer was used to determine the viscosity of the binders with and without the warm asphalt additives. The viscosities of the warm asphalt binders were measured at 135 °C (275 °F) as per AASHTO T316, *Viscosity Determination of Asphalt Binder Using Rotational Viscometer, (AASHTO Standards, 2004)*, and at a lower temperature of 120 °C (248 °F) to investigate the effects of temperature on the viscosity of the warm asphalts. For all the viscosity tests, 8.5 grams of binder was tested with a number 21 spindle.

In addition to the effects of temperature on the viscosity of warm asphalt binders, the effects of time after the addition of the warm asphalt additives on the viscosity of the warm asphalt binders was studied by measuring the viscosity of the warm asphalt binders 30, 60 and 90 minutes after the addition of the warm asphalt additives. All the viscosity measurements were repeated three times and the binders were poured in the testing tube just

prior to testing. All the binder cans were stirred thoroughly prior to pouring the sample to ensure that the test specimen was homogenous.

A dynamic shear rheometer (DSR) was used to measure the complex shear modulus (G*) and the phase angle (δ) of the binders with and without the warm asphalt additives at 64 °C (147 °F). The binders were tested using a 25mm parallel plate setup with a gap of 1 mm and a 12% strain. Additionally, the DSR was used to measure the viscosity / flow measurements, frequency sweep, creep response, creep recovery at different stress levels and multiple creep recovery tests at 60 °C (140 °F). A temperature sweep test was also performed between the temperatures of 25 °C and 80 °C (77 and 176 °F).

The viscosity and shear stress in the binder was measured as a function of shear rate to determine the flow behavior of the binders. For the frequency sweep tests, four decades of frequencies (0.01 - 0.1Hz; 0.1 – 1Hz; 1 – 10Hz; and 10 – 100Hz) were run at the lowest possible strain and the dependence of elastic and viscous modulus were measured as a function of the frequency of loading. To study the response of the binders to creep loading, a shear stress of 10 Pa was applied and the strain was measured for a period of 300 seconds. Since the actual change of strain depends on the applied stress, compliance (J) is used as a measure of creep rather than strain. The compliance is the ratio of strain to the applied stress. This way, samples tested at different stress levels can be compared. Similarly, in a creep recovery test, the recovery from a creep loading is determined. Creep recovery tests were run at three different stresses in this project, 3Pa (loading for 100 sec. and 600 sec. recovery), 10Pa (loading for 20 sec. and 600 sec. recovery), and 50Pa (loading for 1 sec and 300 sec. recovery). These stresses represent the low, medium and high stress levels on a pavement. Stresses lower than 3Pa could not be applied due to the limitations of the DSR

used. The repeated creep recovery test simulates field conditions better as it applies a stress for a short duration of time and then leaving the material to recover for a longer duration of time, and repeats this several times. This, in a way, simulates vehicles passing on a pavement *(Binard, et al., 2004)*. The test consisted of 52 cycles of loading with a stress of 10Pa for 1 sec., and recovery for 9 sec. These testing parameters were based on the suggestions from the NCHRP 9-10 study *(NCHRP 9-10 Program, 2001)*.

The binders used in this study were aged in a rolling thin film oven (RTFO) to simulate the process of short term aging. The RTFO aging process was carried as per AASHTO T240, *Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin Film Oven), (AASHTO Standards, 2004)*, where 35 grams of the binder was poured into the RTFO bottles, and aged in the RTFO for 85 minutes. Since warm asphalt is mixed at a lower temperature than hot mix asphalt, the RTFO aging was conducted at a lower temperature to better simulate the aging process of warm asphalt binders. The lower temperatures for RTFO aging were selected by comparing the binder extracted from warm asphalt mixture – mixed at a lower temperature – and binder aged in the RTFO at different temperatures. After aging, the RTFO residues were tested for viscosity, $G^*/\sin\delta$, molecular size distribution and Fourier transform infrared spectrometry.

The RTFO aged binder residues were further aged in the pressure aging vessel (PAV) to simulate long term aging of the binders. The PAV aging process was carried out as per AASHTO R28, *Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel, (AASHTO Standards, 2004)*, where 50 grams of the RTFO residue was poured into the PAV pans and aged in the PAV for 20 hours at a temperature of 100 °C (212 °F). Since WMA and HMA are subjected to similar conditions after being placed, it was decided not to alter the

PAV aging conditions for warm asphalt binders. The PAV residues were tested for stiffness, m-value, G*.sin δ, molecular size distribution and Fourier transform infrared spectrometry.

The bending beam rheometer (BBR) was used to measure the stiffness and the rate of change of stiffness (m – value) of the binders with and without the warm asphalt additives. The BBR test was carried out as per AASHTO T313, *Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer, (AASHTO Standards, 2004)*, where asphalt beams of dimensions 125mm x 12.7mm x 6.35 mm were prepared and their mid-point deflections were measured while they were subjected to a constant loading.

The binder from warm asphalt mixes were extracted using a rotovapor as per ASTM D2172, *Standard Test Methods for Quantitative Extraction of Bitumen From Bituminous Paving Mixtures, (ASTM Standards, 2005),* and ASTM D5404, *Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator, (ASTM Standards, 2005)* in order to look at the effects of reducing the mixing and compaction temperatures on the properties of the binders in the mixture.

Gel permeation chromatography (GPC) was used as a tool to determine the molecular size distribution of the asphalt binders used in this study. The results were used to identify any changes in the molecular size distributions of the binders after the addition of the warm asphalt additives. GPC is a well known technique for characterizing the molecular size distribution of asphalt binders *(Kim, et al., 2006)*. Waters GPC equipment with a computerized software was used for the chromatographic analysis of the binders. A differential refractive meter (Waters 410) was used as a detector. A series of two columns (Waters HR 4E and Waters HR 3) were used to separate the constituents of the binder by molecular size. The columns were maintained at 35 °C (95 °F) in order to be able to test the

samples at a constant temperature. Tetrahydrofurane (THF) was used as the mobile phase flowing at a rate of 1 ml/min and a dilution of 400 : 1 (solvent : binder). Each test specimen was prepared by weighing 0.006 to 0.008 grams of binder into a 4 mL empty vial. The appropriate amount of THF was added to the vial, and the vial was sealed and agitated so that the binder is completely dissolved in the solvent. The binder solvent mixture was then transferred to a 5 mL syringe, and filtered through a 0.45μm filter into a clean vial. 75μL of the filtered binder solvent mixture was injected into the GPC. One vial was prepared for each binder, and three chromatograms were obtained from each vial.

The % large molecular sizes (LMS), medium molecular size (MMS) and the small molecular size (SMS) of the binders with and without the warm asphalt additives were measured by dividing the chromatogram into 13 slices of equal width. The LMS and MMS limits were determined as the elution time at the end of slices 5 and 9, respectively. Many studies indicate that the LMS of the binder has a good correlation with the asphalt mixture properties than other sizes *(Al-Adulwahhab, et al., 1999; Jennings, 1980; Kim and Burati, 1993; Kim, et al., 1993; Price 1988).*

Fourier transform infrared (FTIR) spectroscopy was performed on the asphalt samples to quantify the difference in the aging behavior of binders with and without the warm asphalt additives. FTIR spectra were collected for binders aged in the RTFO and PAV using a Thermo – Nicolet Magna 550 FTIR spectrometer equipped with a Thermo – Spectra – Tech Foundation series diamond attenuated total reflectance (ATR). Thirty two scans at a resolution of 4 cm^{-1} were collected for each sample and background scan between wave numbers 4000 to 525 cm^{-1}. Undiluted asphalt samples were placed directly on the diamond window, and the spectra were obtained. The resultant spectra were corrected using both

ATR and baseline correction functions in the OMNIC 6.1a ESP software used to collect the spectra. Raw data was exported to ASCII format and the peak heights were measured at $1030cm^{-1}$ and $1700cm^{-1}$. Triplicate measurements were collected for each binder.

Differential scanning calorimetry (DSC) was conducted to measure the shift in the glass transition temperatures (T_g) of the binders after the addition of the warm asphalt additives, and to measure the melting temperature of the waxes in the binders using a TA Instruments MDSC 2920. Samples were prepared by weighing out 7 to 10 mg of binder into Hermetic aluminum sample pans. Three to four holes were punched on the lids of each sample pan prior to closing the pan. The sample pans were then placed in the DSC at room temperature and purged with dry nitrogen gas for 15 minutes at the rate of 40 mL / min and equilibrated at 25 °C (77 °F). The DSC was then used to ramp the temperature to 150 °C (300 °F) at the rate of 10 °C / min. (18 °F / min.), held isothermal for 1 minute, cooled at the rate of 10 °C / min (18 °F / min.) to -100 °C (-148 °F), held isothermal for 1 min, and finally ramped up to 150 °C (300 °F) at the rate of 10 °C / min. (18 °F / min.). The data was collected and analyzed using the TA Instruments Universal Analysis Version 3.9a 2000 software. The glass transition temperature of the binders were evaluated and represented as the half height between the tangents to the base line before and after the T_g. Each binder was tested twice to obtain the T_g, and the T_g values were averaged for each binder.

3.3.3 Mixture Testing

After the mix designs were conducted, for each aggregate / binder / warm asphalt additive combinations, eight pills of 150mm diameter and 95mm height were prepared with 7±1% air voids. Four of these were artificially aged in the oven as per AASHTO TP30, *Standard Practice for Mixture Conditioning of Hot Mix Asphalt (AASHTO Standards, 2004)*, before

conducting any tests. Resilient modulus tests as per ASTM D4123, *Indirect Tension test for Resilient Modulus of Bituminous Mixtures (ASTM Standards, 2005),* were carried out on the samples and then the samples were tested at 25 °C (77 °F) to determine the indirect tensile strengths. Two of the samples were tested in dry condition and two were broken in wet condition. The wet samples were saturated to 70-80% weight and submerged in a water bath at 60 °C (140 °F) for 24 hours, followed by submersion in a water bath at 25 °C (77 °F) for two hours before testing. This test was conducted as per the SCDOT procedure for determining the moisture susceptibility – SC T 70, *Laboratory Determination of Moisture Susceptibility*, *(SCDOT Test Procedures, 2007)*. The resilient modulus and indirect tensile strength tests were conducted on un-aged as well as oven aged samples. Additionally, 12 more pills of 150mm diameter and 75mm height were prepared with 4±1% air voids. Six of these were also artificially aged in the oven as per AASHTO TP30, *Standard Practice for Mixture Conditioning of Hot Mix Asphalt, (AASHTO Standards, 2004)*, before any testing was done. Rutting resistance was measured on these un-aged as well as oven aged pills using the Asphalt Pavement Analyzer (APA) as per AASHTO TP63, *Determining Rutting Susceptibility of Asphalt Paving Mixtures Using the Asphalt Pavement Analyzer, (AASHTO Standards, 2004).*

In this study, each of the mixes was given a unique code containing 3 parts. The first part is the aggregate (A or B); the second part represents the binder source; (I or II), and the third part represents the warm asphalt additive (C for control, a or s). For example, AIIs denotes a mixture prepared with aggregate A, binder source II and Sasobit® as the warm asphalt additive.

Chapter IV

4. STATISTICAL ANALYSIS

The statistical analysis systems (SAS) and Microsoft® Excel® software packages were utilized to perform all the statistical analysis on the research data. This study was broadly classified into two sections: binder properties and mixture properties.

In the study to evaluate the binder properties, the experimental design consisted of three warm asphalt additives (control, Asphamin® and Sasobit®) and three binder sources (Binders 1, 2 and 3). Since the effects of the warm asphalt additives on the binder properties are of primary interest, the warm asphalt additives were considered as the primary treatment in the experimental design. Additionally, since different binders have different properties, the binder source was considered as an extraneous source of error (blocks) in the experimental design. Thus, a randomized complete block design (RCBD) was created, with the warm asphalt additive as the primary treatment, and the binder source as the block variable (secondary treatment). The advantage of RCBD as the experimental design was that the effects of the warm asphalt additives on the properties of the binders could be observed, irrespective of the binder source, with the binder source being considered as an external source of error.

In the study to evaluate the mixture properties, the experimental design consisted of three warm asphalt additives (control, Asphamin® and Sasobit®), two binder sources (Binders 1 and 2) and two aggregate sources (Aggregates A and B). Similar to the binder study, a RCBD experimental design was selected with the warm asphalt additives as the primary treatment, and the binder source or aggregate source as the secondary treatment.

A randomized complete block design is an experimental design for comparing 't' treatments in 'b' blocks. Each block consists of 't' homogeneous experimental units, which are randomly assigned to the experimental units within each block, such that each treatment appears exactly once in each block. The advantage of using a RCBD is that it can filter out the variability due to the blocks by decreasing the error of estimation for a comparison of treatment means. The data for a RCBD is arranged as shown in Table 4-1*(Ott and Longnecker, 2001)*.

Table 4-1: Data for a randomized complete block design

	Blocks				
Treatment	**1**	**2**	**…**	**b**	**Mean**
1	y_{11}	y_{12}	…	y_{1b}	$\bar{y}_{1.}$
2	y_{21}	y_{22}	…	y_{2b}	$\bar{y}_{2.}$
…	…	…	…	…	…
t	y_{t1}	y_{t2}	…	y_{tb}	$\bar{y}_{t.}$
Mean	$\bar{y}_{.1}$	$\bar{y}_{.2}$		$\bar{y}_{.b}$	$\bar{y}_{..}$

The model for an observation in a RCBD can be written in the form of

$y_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij}$

Where the terms are defined as follows:

yij = Observation on experimental unit in ith treatment and jth block.

μ = Overall mean, an unknown constant.

α_i = An effect due to treatment I, an unknown constant.

β_j = An effect due to block j, an unknown constant.

ε_{ij} = A random error associated with the response from ith treatment and jth block.

$\bar{y}_{i.}$ = Sample mean for treatment i = $\frac{1}{b}\sum_{j=1}^{b} y_{ij}$

$\bar{y}_{.j}$ = Sample mean for block j = $\frac{1}{t}\sum_{i=1}^{t} y_{ij}$

$\bar{y}_{..}$ = Overall sample mean = $\frac{1}{tb}\sum_{ij} y_{ij}$

The analysis of variance (ANOVA) was then performed for the RCBDs developed as per Table 4-2 *(Ott and Longnecker, 2001)*. The ANOVA is performed to determine if a significant difference among sample means exist between different treatments (warm asphalt additives) and between different blocks (aggregate / binder sources). The ANOVA tests the null hypothesis (H_0) assuming that all the sample means are equal, with a confidence level of 95%. If the F –value obtained from the table is greater than the F_{crit} value (which depends on the level of significance and the degrees of freedom), H_0 is rejected, which means that the sample means between different blocks or treatments are not equal.

Table 4-2: Analysis of variance table for a randomized complete block design

Source	Sum of Squares	Degrees of freedom	Mean Square	F – Test
Treatments	SST	t – 1	MST = SST/(t – 1)	MST/MSE
Blocks	SSB	b – 1	MSB = SSB/(b – 1)	MSB/MSE
Error	SSE	(b – 1)(t – 1)	MSE = SSE/(t – 1)(b – 1)	
Total	TSS	bt – 1		

Where the terms are defined as follows:

SST = Between – Treatment sum of squares = $b\sum_i(\bar{y}_{i.} - \bar{y}_{..})^2$

SSB = Between – Block sum of squares = $t\sum_j(\bar{y}_{.j} - \bar{y}_{..})^2$

SSE = Sum of squares for error = $\sum(\varepsilon_{ij})^2$

If it was determined using ANOVA that the sample means between different treatments or blocks were different, the least significant difference (LSD) was calculated as

per Equation 4-1 *(Ott and Longnecker, 2001)*. If the difference between two means is greater than or equal to the LSD value, the two means are said to be significantly different. Thus, the LSDs were calculated for all pairs of means within different treatments and blocks, and compared with the pairs of sample means to determine which pairs were significantly similar and which pairs were significantly different.

$$LSD = t_{\frac{\alpha}{2}}\sqrt{s_w^2\left(\frac{1}{n_i} + \frac{1}{n_j}\right)} \quad \text{..... Equation 4-1}$$

Where the terms are defined as follows:

n_i and n_j = Respective sample sizes from population *i* and *j*.

α = Level of significance (0.05 used in this research)

$t_{\frac{\alpha}{2}}$ = Critical 't' value for $\alpha/2$ and the degrees of freedom

s_w^2 = Mean square within samples

When $\left|y_{i.} - y_{.j}\right| \geq LSD$, the corresponding population means μ_i and μ_j are declared to be significantly different.

Chapter V

5. RESULTS AND DISCUSSIONS

This chapter presents the experimental results obtained in this study. First, the binder properties and the effects of the warm asphalt additives on the binder properties are discussed. Rheological properties of the binders with and without the warm asphalt additives were measured at high temperatures (135 and 120 °C or 275 °F and 248 °F), mid-range temperatures (64 and 60 °C or 147 °F and 140 °F) and at low temperatures (-12 °C or 10.4 °F). In addition, the binders were aged in the laboratory at two different temperatures, and the effects of aging temperature were observed on the properties of the binders containing warm asphalt additives and they were compared with the properties of the binders extracted from freshly mixed and aged mixes.

Second, the properties of the mixtures containing warm asphalt additives were evaluated, and compared with the properties of the conventional HMA. Resilient modulus, moisture susceptibility and APA rutting were compared for freshly made mixes as well as aged WMA and HMA samples. The effects of aging on the properties of WMA are also discussed.

5.1 Binder Properties

5.1.1 Effects of Temperature and Time on Warm Asphalt Binder Viscosity

Figures 5-1 and 5-2 show the viscosity of the three binders with and without the warm asphalt additives at 135 and 120 °C (275 and 248 °F), respectively. The effect of time after the addition of the warm asphalt additives can also be seen in the graphs.

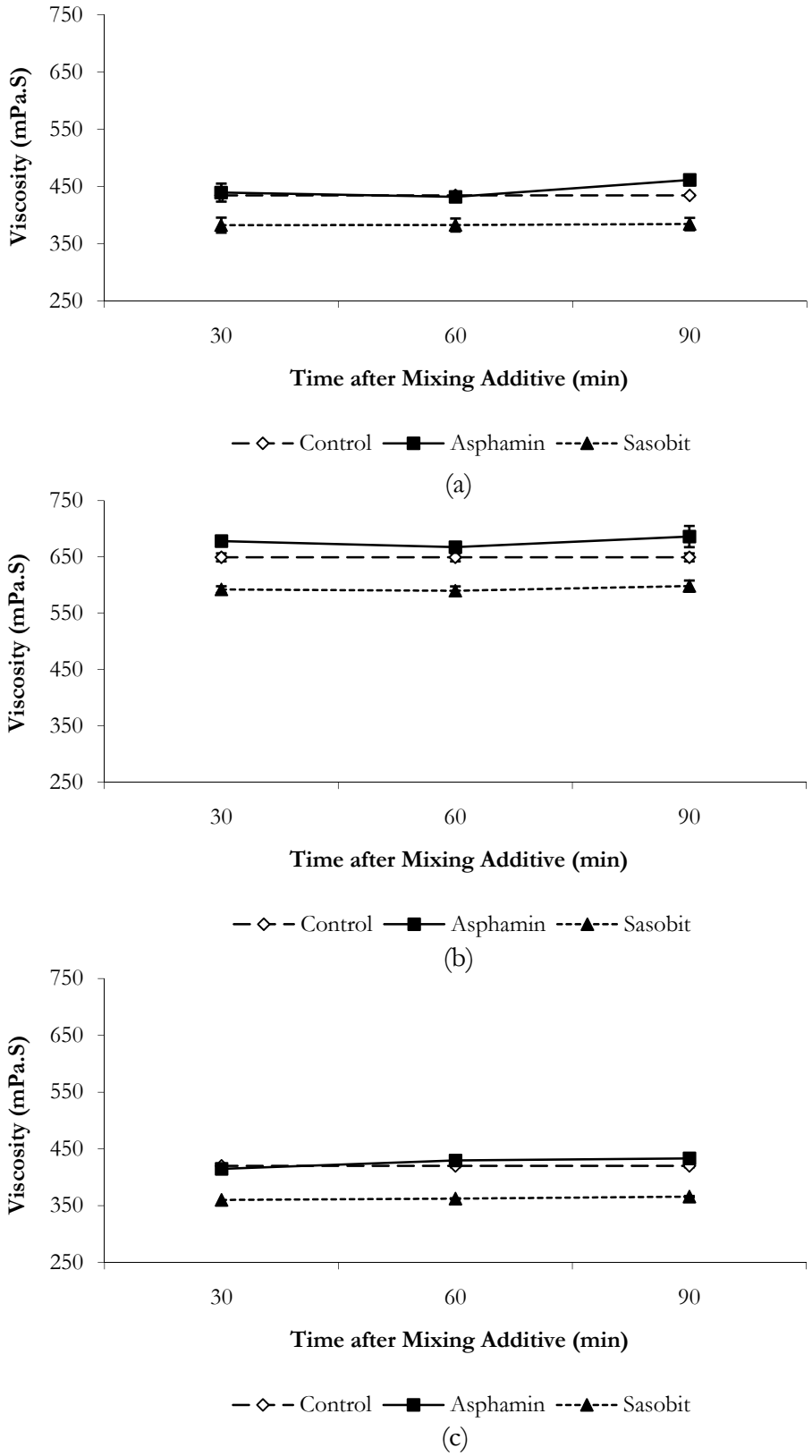

Figure 5-1: Viscosity of the binders at 135 °C: (a) Binder 1; (b) Binder 2 and (c) Binder 3

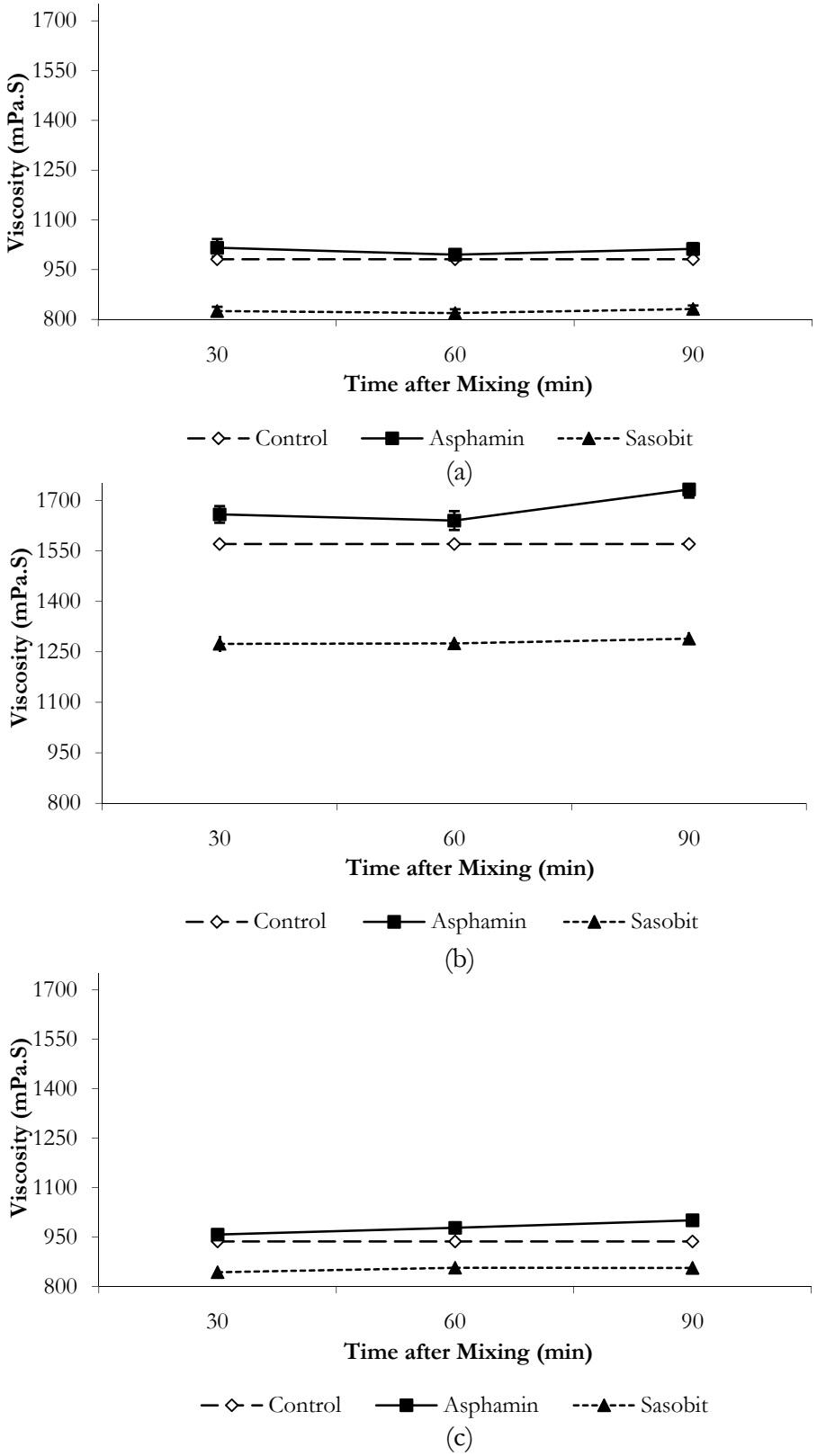

Figure 5-2: Viscosity of the binders at 120 °C: (a) Binder 1; (b) Binder 2 and (c) Binder 3

It was observed that the addition of Asphamin® did not significantly affect the viscosity of the virgin binder at 135 °C or at 120 °C. However, in some cases, the viscosity of binders containing Asphamin® was significantly higher than the virgin binder 90 minutes after Asphamin® was added to the binder. Preliminary studies on binders containing Asphamin® and Sasobit® indicated that there were no significant differences between the viscosities 90 and 180 minutes after adding the additives. Thus, the viscosity tests were conducted only up to 90 minutes after adding the additives.

On the other hand, the addition of Sasobit® significantly reduced the viscosity of the binders at 135 °C and 120 °C. It was also observed that the viscosity did not seem to change for up to 90 minutes after the addition of Sasobit® to the binders. According to the manufacturers, Sasobit® is completely soluble in the binder at temperatures beyond 115 °C (240 °F), and forms a homogeneous solution with the binder producing a marked reduction in the viscosity of the binder.

The reason for the increase in the viscosity with the addition of Asphamin® can be attributed to the addition of solid material in the form of a fine powder to the binder, which acts as a filler. There could be a slight decrease in the viscosity initially due to foaming of asphalt, however, the foaming decreases with time, and thus the increase in viscosity after about 60 to 90 minutes.

To verify the filling effect of Asphamin® in binders, a known quantity of binders containing Asphamin® were dissolved in tetrahydrofurane (THF). This solution was then injected through a pre weighed 0.45μm filter, with additional THF until the filtrate was clear. The filter was then allowed to dry, and weighed again. It was observed that the filters retained about 3.2% of the weight of the binder dissolved on an average, which is close to

the amount of Asphamin® added to the binders (5% by weight of the binder, assuming 6% asphalt content in the mixture). Additionally, it was observed that when a solution of Asphamin® and THF was injected through the filter, majority (>85%) of the weight of Asphamin® was retained on the filter, indicating that Asphamin® does not dissolve in THF. Also, a solution of unmodified binder did not retain anything on the filter. Thus, it can be concluded that when the solution of binder containing Asphamin® was filtered, the zeolite particles are retained on the filter, indicating the presence of solid zeolite particles in the binder, which act like a filler in the binder.

5.1.2 Effects of Warm Asphalt Additives on Mid-Temperature Rheological Properties

Since the warm mix additives were developed to reduce the mixing and compaction temperatures of asphalt mixtures, they would most significantly affect the flow properties of the asphalt binder. Rheological measurements were taken at 60 °C (140 °F) ($G^*/\sin\delta$ measurements at 64 °C or 147 °F), within the linear viscoelastic region of the binders, so that the stress and strain relationship was influenced by the frequency of loading only and not by the magnitude of the stresses and strains *(Ferry, 1980)*. The results of the mid-range temperature rheological tests are discussed below.

Effects of Warm Asphalt Additives on $G^*/\sin\delta$

While it was observed in an earlier study that the addition of Sasobit® increased the PG grade of the binders *(Hurley and Prowell, 2005)*, it was decided to investigate the effects of the addition of the warm asphalt additives on the $G^*/\sin\delta$ values of unaged binders. The $G^*/\sin\delta$ values of the unaged binders with and without the warm asphalt additives are shown in Figure 5-3.

As can be seen from this graph, the addition of the warm asphalt additives did not have any significant effect on the G*/sin δ values of Binder 1. The addition of Asphamin® significantly increased the G*/sin δ value of Binder 2 only. When Sasobit® was added to Binders 2 and 3, there was a significant increase in the G*/sin δ values of the binders. While Sasobit® dissolves in the binders causing a marked reduction in the viscosity of the binders, after the binders cool, Sasobit®, which is a wax, re-crystallizes in the binders *(Edwards, et al., 2006; Sasol Wax)*, thereby increasing the complex modulus of the binders.

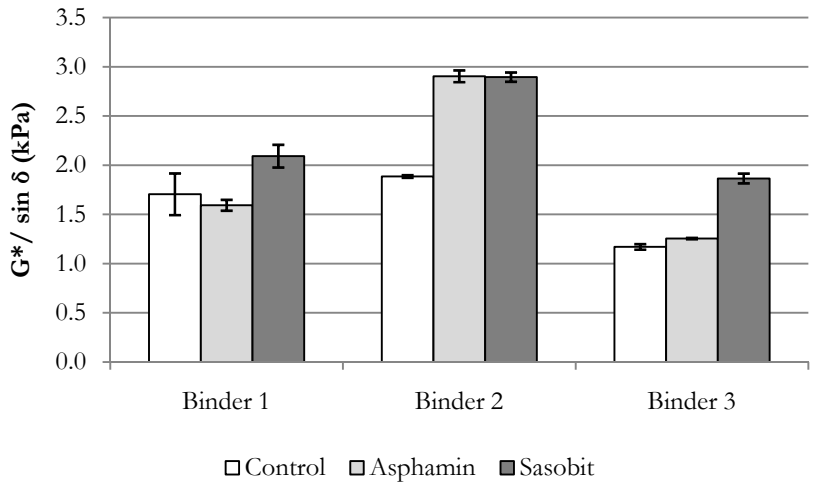

Figure 5-3: G*/ sin δ values of the unaged binders with and without the warm asphalt additives

Viscosity / Flow Tests

Figure 5-4 shows the relationship of shear stress and viscosity to the shear rate for the three binders, with and without the warm mix additives. All three virgin binders seem to follow Newtonian flow at 60 °C, as the viscosities are independent of the shear rates. The addition of Asphamin® also does not seem to influence the flow of the binders. However, the addition of Sasobit® to these binders influences the flow behavior of the binders.

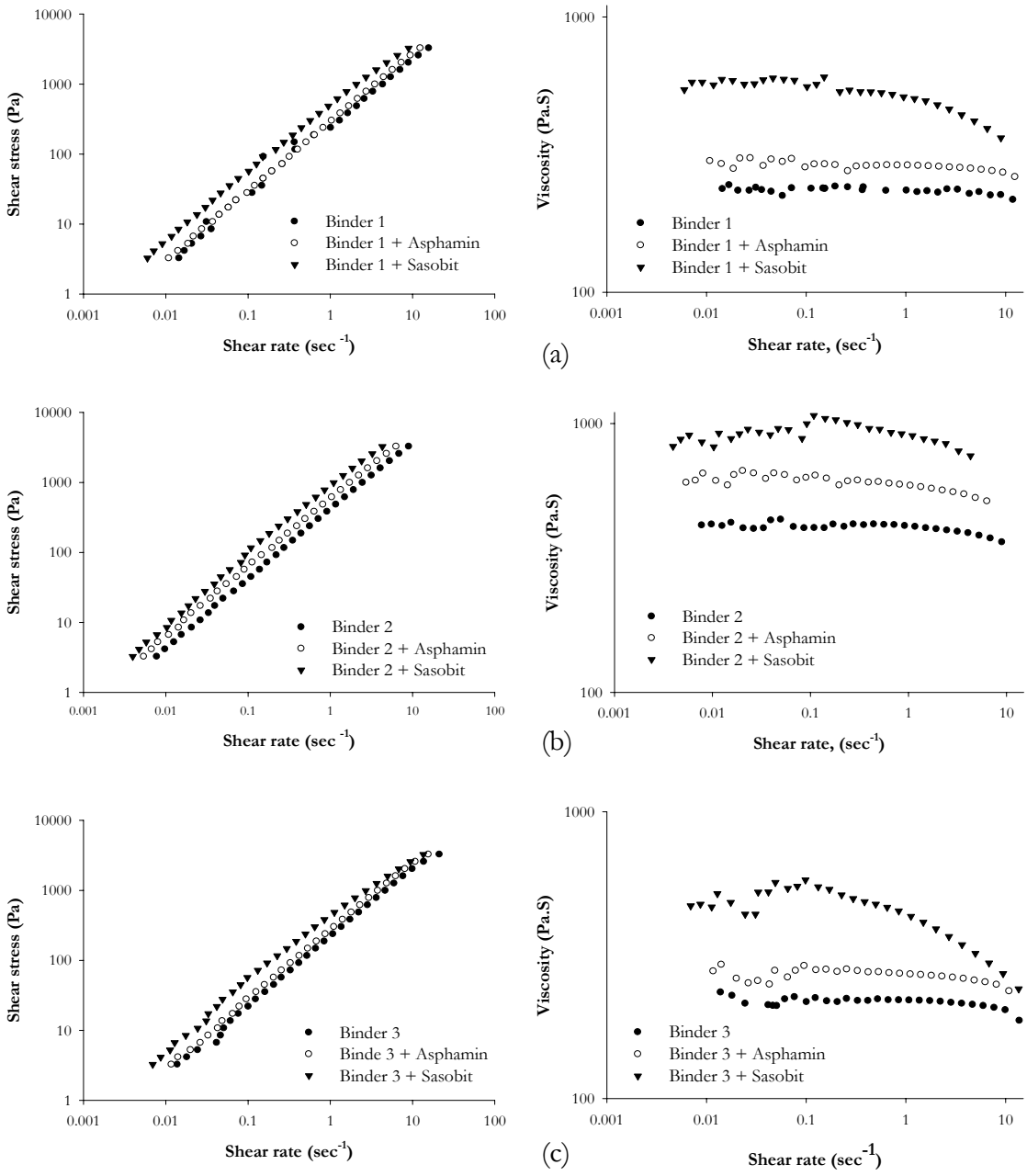

Figure 5-4: Effects of warm asphalt additives on flow curves and viscosity curves: (a) Binder 1; (b) Binder 2 and (c) Binder 3

When Sasobit® was added to the binders, the viscosity decreased with increase in shear rate, thereby exhibiting a shear thinning flow at 60 °C. This suggests that the addition of Sasobit® to different binders affects the flow behavior of the binders, which may be due to the increase in the complex modulus of the binders. The shear thinning flow at 60 °C also

suggests that the addition of Sasobit® shifts the linear viscoelastic range of the binders towards higher temperatures.

It can also be seen from the graphs that the addition of the warm mix additives increased the viscosities of the three binders at 60 °C. The addition of Sasobit® especially increases the viscosity of the binders more than Asphamin®. In another study *(Gandhi and Amirkhanian, 2007)*, it was observed that adding Sasobit® to the binder reduced the viscosity of the binder at high temperatures (120 and 135 °C or 248 and 275 °F). This means that Sasobit® decreases the viscosity of the binders at higher temperatures, but increases the viscosity at mid-range temperatures, which makes it more workable at high temperatures and stiff and therefore, more resistant to penetration and rutting at mid-range temperatures.

Frequency Sweep Tests

For the frequency sweep tests, four decades of frequencies (0.01 - 0.1; 0.1 - 1; 1 - 10; and 10 – 100Hz) were run at the lowest possible strain. Figure 5-5 shows the elastic and viscous moduli for the three binders as a function of frequency of loading. Typically, a frequency of 1.59 Hz simulates the shearing action corresponding to traffic speed of about 55 mph *(Roberts, et al., 1996)*. From the graphs, it can be seen that as the frequency increases, the difference between the viscous and elastic moduli decreases for all the binders. In case of Binder 1 with Sasobit®, the elastic modulus is more than or equal to the viscous modulus beyond frequencies of 1 Hz. This suggests that the binder will undergo less permanent deformation at these frequencies, and therefore the mixture will be less prone to rutting at higher traffic speeds compared to the other binders. Also, when Sasobit® was added to these binders, it produced the highest elastic and viscous components at any given

frequency, suggesting that Sasobit® improves the complex modulus of the binders when compared to the base binders and binders containing Asphamin® at any given frequency.

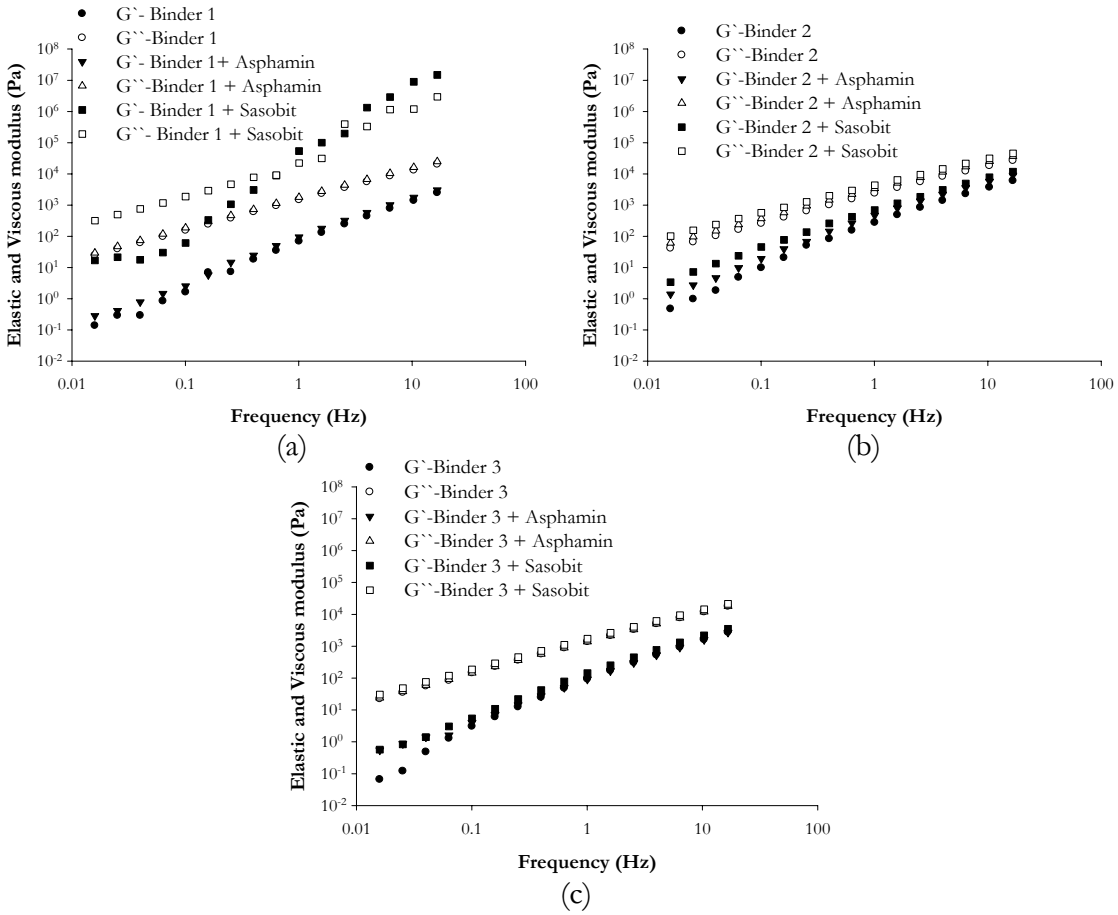

Figure 5-5: Frequency dependence of elastic and viscous moduli: (a) Binder 1; (b) Binder 2 and (c) Binder 3

Creep Tests

Figure 5-6 shows the compliances for the binders used in this project with and without the warm asphalt additives. It can be seen from the graphs that binders with Sasobit® have lower compliance values implying that Sasobit® improves the penetration resistance and the complex modulus of the binders at mid-range temperatures. When Asphamin® was added to the binders, the compliance values were lowered compared to the base binders; whereas the addition of Asphamin® to Binder 3 had increased compliance values compared to the base binder. Since Asphamin® acts only as mineral filler after the

initial foaming, the stiffening effect of the additive seems to be binder dependant, and may not always act to stiffen the binder.

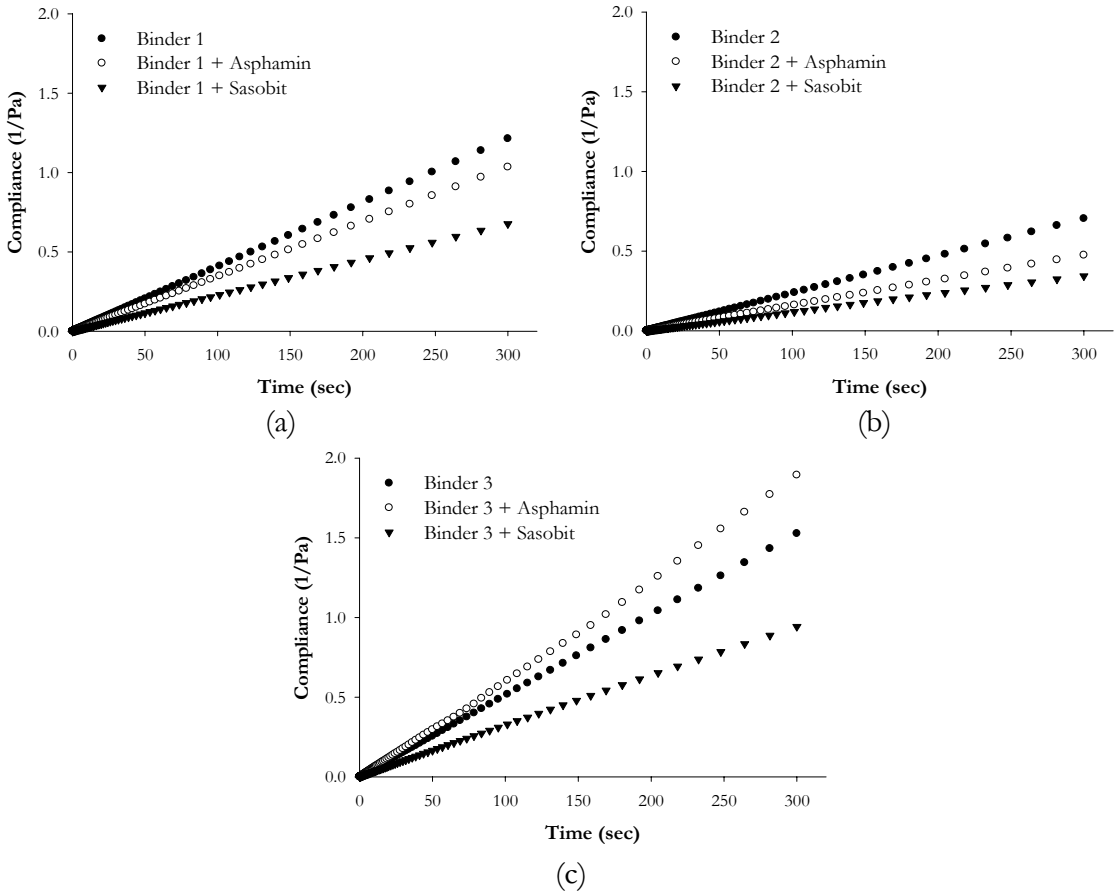

Figure 5-6: Creep curves affected by Asphamin® and Sasobit®: (a) Binder 1; (b) Binder 2 and (c) Binder 3

Creep Recovery Tests

Creep recovery tests were run at three different stresses for this project, 3Pa (loading for 100 sec. and 600 sec. recovery), 10Pa (loading for 20 sec. and 600 sec. recovery), and 50Pa (loading for 1 sec and 300 sec. recovery). These stresses represent the low, medium and high stress levels on a pavement. Stresses lower than 3Pa could not be applied due to the limitations of the DSR used. Figure 5-7 shows the creep recovery curves for Binder 1 with

and without the warm asphalt additives at different stress levels. Other binders followed similar trends.

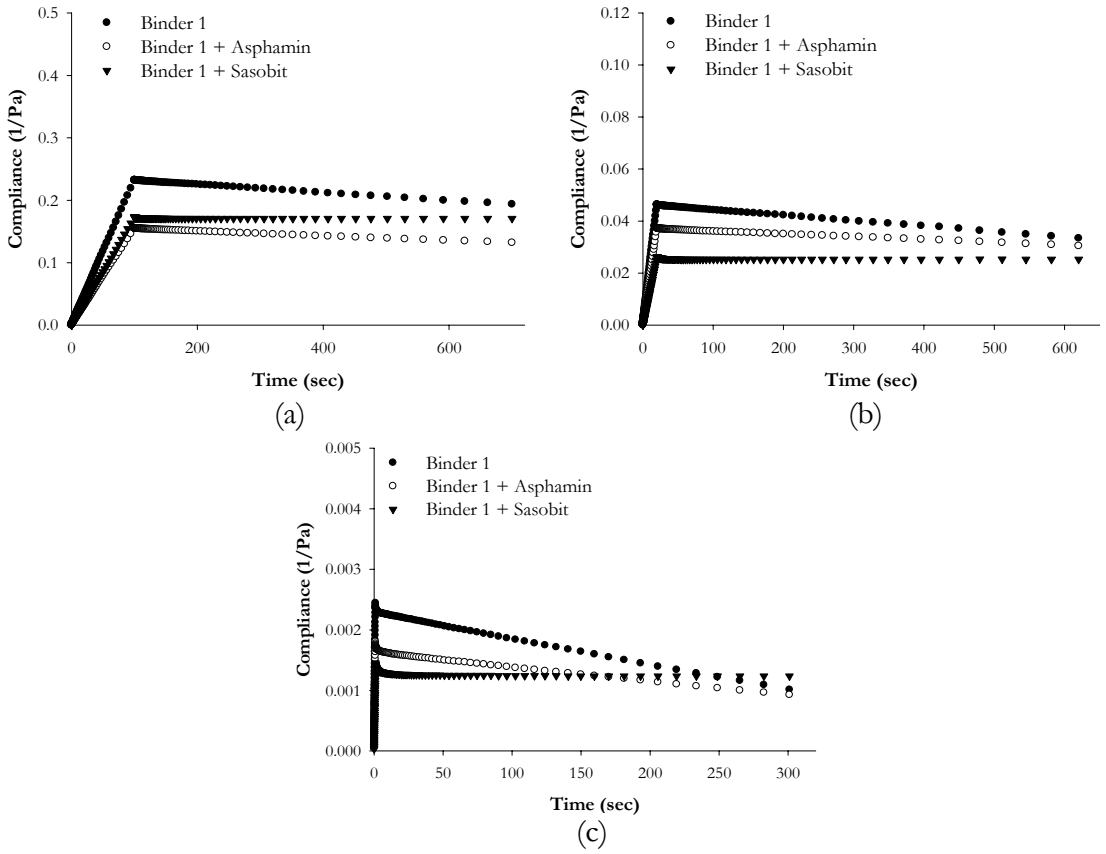

Figure 5-7: Creep recovery curves for Asphamin® and Sasobit® modified Binder 1: (a) 3Pa loading; (b) 10 Pa loading and (c) 50 Pa loading

From the curves, it can be seen that for most of the cases, the addition of Sasobit® has the lowest maximum deformation. Also, after the stresses are removed, binders with Sasobit® show the least permanent deformation. This could be due to the increased complex modulus of the binders containing Sasobit® at 60 °C. However, in some cases, especially at high stress values (50 Pa), the binders had not yet attained the steady state viscous flow, and thus different results may have been obtained if the strain was measured for a longer duration after the stress was removed.

Repeated Creep Recovery Tests

The repeated creep recovery test was conducted on the three binders with and without the warm asphalt additives based on the suggestions from the NCHRP 9-10 study *(NCHRP 9-10 Program, 2001)*. Figure 5-8 shows the accumulated compliance for the binders over the 52 cycles. From the graphs, it is observed that the addition of Sasobit® significantly lowers the deflections in the binder compared to the base binder. The addition of Asphamin®, however, had different effects when added to the three binders. Since Asphamin® is inorganic, the response to the repeated creep and recovery cycles may have to do with the physical filling effect of the additive in the binders.

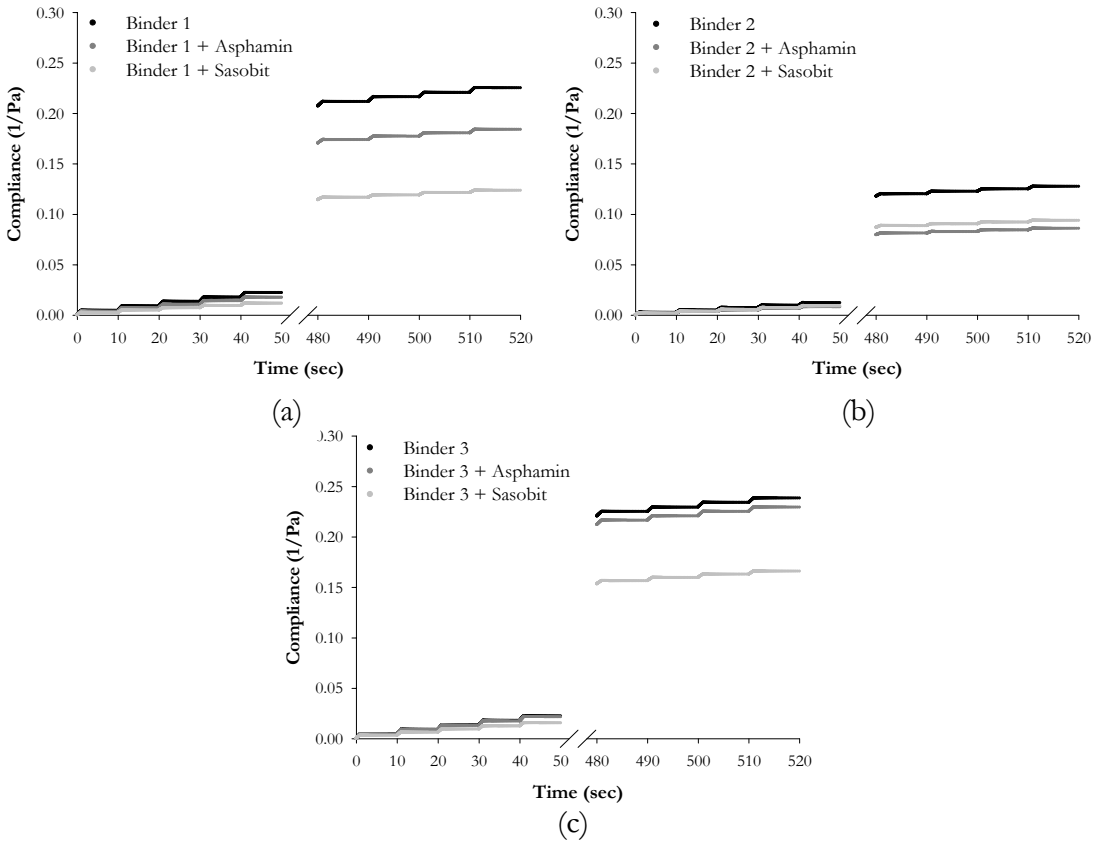

Figure 5-8: Repeated creep recovery curves for Asphamin® and Sasobit® modified binders: (a) Binder 1; (b) Binder 2 and (c) Binder 3

Temperature Sweep Tests

A temperature sweep test was conducted between 25°C (77 °F) and 80°C (176 °F) to determine the dependence of the complex modulus, G* and the phase angle, δ of the three binders on temperature. The results of the temperature sweep tests are shown in Figure 5-9.

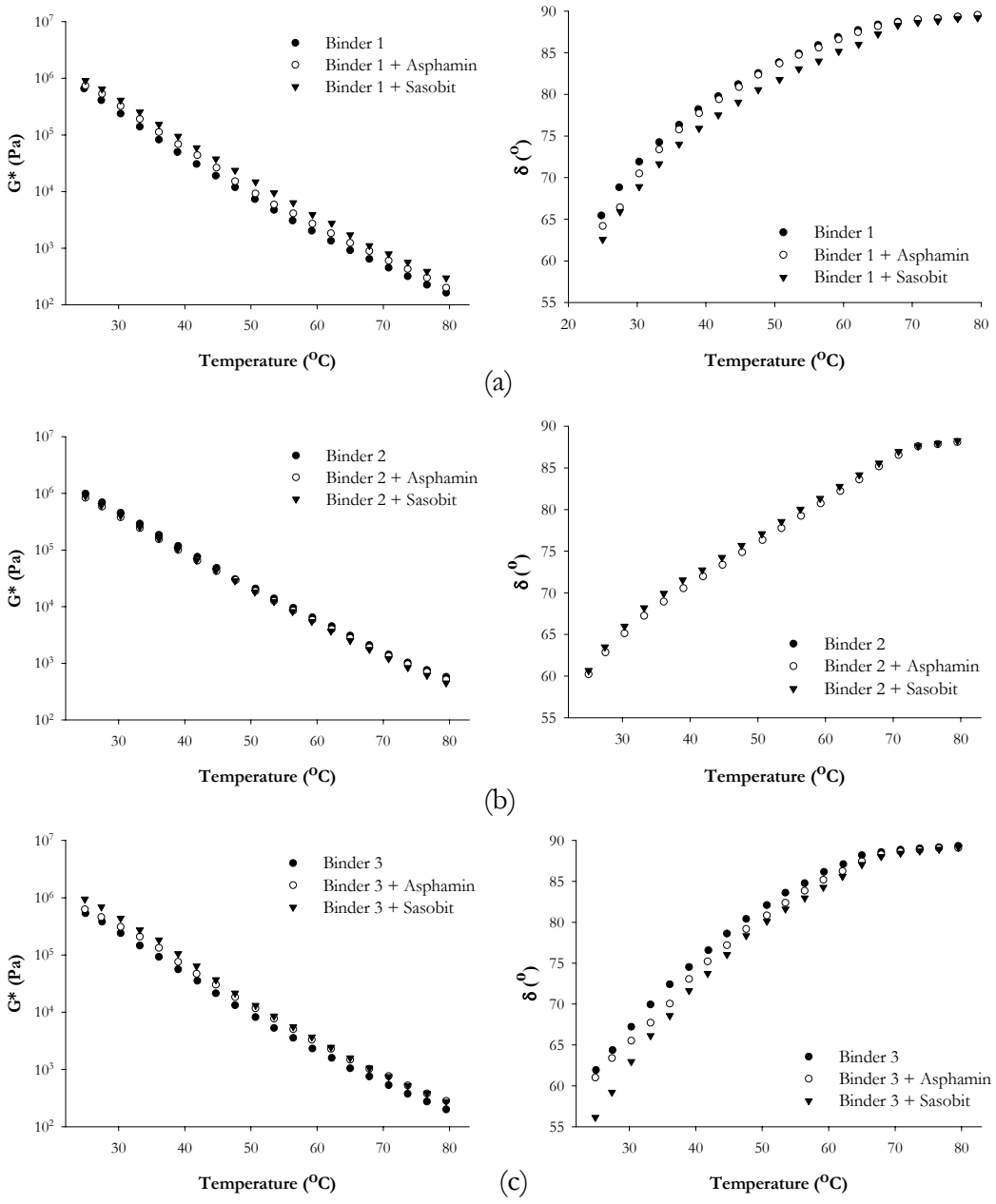

Figure 5-9: Temperature dependence of complex modulus and phase angle: (a) Binder 1; (b) Binder 2 and (c) Binder 3

From the graphs, it can be seen that the warm asphalt additives do not have much effect on the complex modulus, G*, of the binders over the entire range of temperatures. However, the addition of Sasobit® to binders 1 and 3 tends to lower the phase angle, δ, especially at lower temperatures. This suggests that certain binders containing Sasobit® have improved elasticity at lower temperatures, and different binders behave differently to the addition of Sasobit®.

5.1.3 Effects of Warm Asphalt Additives on Binder Aging Characteristics

The binders used in this study were aged in the RTFO and the PAV. Two different temperatures, 163 °C (325 °F) and a lower temperature 130 °C (266 °F) or 140 °C (284 °F), were used to age the binders in the RTFO. The lower temperatures for RTFO were selected by comparing the binder extracted from warm asphalt mixture – mixed at a lower temperature – and binder aged in the RTFO at different temperatures. Figure 5-10 shows the comparison of the G*/sin δ values for Binder 1 (with and without Asphamin®) aged in the RTFO at 163 °C and extracted from the mixture.

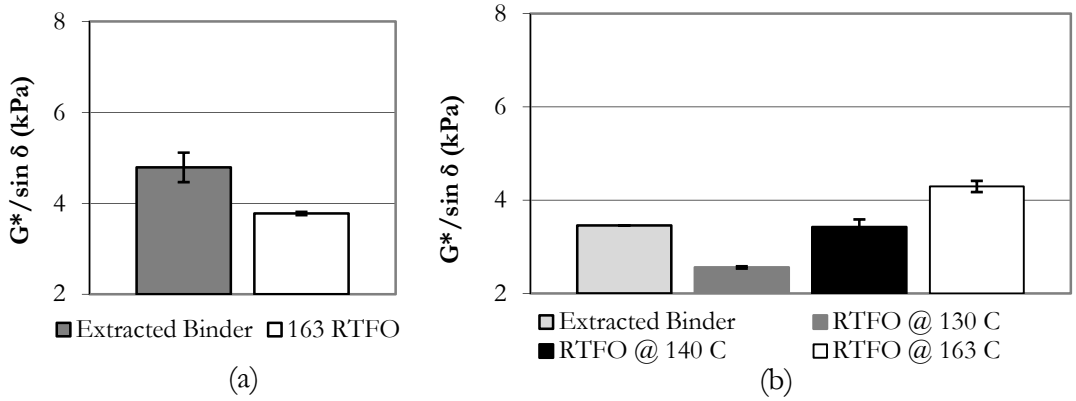

Figure 5-10: RTFO aged binder: (a) Binder 1 and (b) Binder 1 + Asphamin®

From Figure 5-10 (a) it is seen that unmodified Binder 1 extracted from hot mix asphalt had a G*/sin δ of about 1.25 times the G*/sin δ value for unmodified binder aged in

the RTFO at 163 °C. Thus, the temperature at which the G*/sin δ for RTFO aged binder with the warm asphalt additive was about 75% of the G*/sin δ value for binder plus additive extracted from warm mix asphalt, was selected as the reduced RTFO aging temperature. Similarly other binder combinations were compared and the reduced RTFO temperatures were selected to be 130 °C (266 °F) for Binders 1 and 3; and 140 °C (284 °F) for Binder 2.

After the binders were aged in the RTFO and PAV, the G*/sin δ, viscosity, G*.sin δ, stiffness and m-values of the binders with and without warm asphalt additives were compared to determine the effects of the warm asphalt additives and binder sources on these properties. The following sections discuss the properties of the warm asphalt additives and binder sources on binder aging characteristics.

Effects on Viscosity

After the binders were aged in the RTFO at 163 ºC (325 °F) and the lower temperature 130 °C (266 °F) or 140 °C (284 °F), irrespective of the binder source, it was observed that binders containing Asphamin® had the highest viscosities. Binders with no warm asphalt additives followed, and the binders containing Sasobit® had the lowest viscosities. It is believed that the increase in the viscosities of the binders with Asphamin® after RTFO aging may not be entirely due to increased aging of the binder in the presence of Asphamin®, but due to the subsidence of the foaming effect of Asphamin® during the aging process. After initial foaming, the Asphamin® particles remain undissolved in the binder, thereby increasing the viscosities of the binders.

During the mixing process, asphalt binder undergoes maximum hardening as thin films of the binder are exposed to high temperatures. As a result of this hardening, there

could be significant increase in the viscosity of the binder, and the extent of the hardening can be quantified in terms of viscosity as per Equation 1 *(Roberts, et al., 1996).*

$$\text{Aging Index} = \frac{\text{Viscosity of Aged Binder}}{\text{Viscosity of Original Binder}} \quad \text{..... (1)}$$

Since warm asphalt is mixed at lower temperatures than normal hot mix asphalt, it was decided to measure the decrease in the aging index of the binders when aged in the RTFO at a lower temperature. The RTFO residues – after aging in RTFO at 163 ºC (325 °F) and lower temperature – were tested for the viscosity of the binders, and the aging index of the binders was calculated as per Equation 1. Figure 5-11 shows the aging indices of the binders used in this study after aging in the RTFO at 163 ºC and the lower temperature. From the figure, as expected, it is observed that the aging indices for binders aged in the RTFO at a lower temperature are significantly lower than binders aged in the RTFO at 163 ºC.

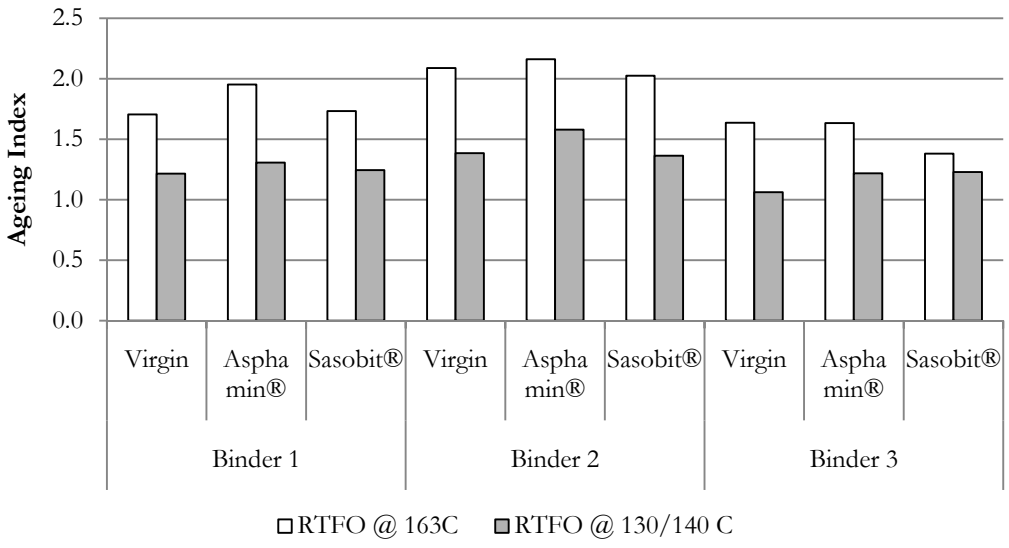

Figure 5-11: Aging indices for the binders aged in the RTFO at 163 °C and 130/140 °C

Irrespective of the warm asphalt additive, Binder 2 had the highest viscosities, followed by Binders 1 and 3 with no significant differences in their viscosities. This was observed with original binder and binders aged in the RTFO at all temperatures. This is due to the fact that the base viscosity of Binder 2 is higher than other binders (Table 3-1).

Effects on Rutting Parameter (G/ sin δ)*

The effects of warm asphalt additives as well as the effects of binder sources on the rutting parameter (G*/sin δ) was evaluated after conducting the RTFO at 163 °C (325 °F) as well as the lower temperatures. From the statistical analysis, it was observed that when the RTFO was performed at 163 °C, irrespective of the binder source, binders containing Sasobit® had the highest G*/sin δ value. Binders containing Asphamin® and control binder (no warm asphalt additive) followed with no significant differences in the G*/sin δ values. This suggests that binders containing Sasobit® will have increased rutting resistance.

However, when the RTFO aging was conducted at the lower temperature, irrespective of the binder sources, binders containing Sasobit® and Asphamin® had significantly higher G*/sin δ values compared to binders containing no warm asphalt additives. Thus, even if the mixing and compaction temperatures are reduced, binders containing Asphamin® and Sasobit® will have better resistance to rutting than unmodified binders mixed at lower temperatures. This increase in the rutting resistance of the binders containing Sasobit® is attributed to the presence of wax crystals in the binders, which causes an increase in the complex modulus of the binders *(Edwards and Redelius, 2003; Edwards, et al., 2006)*, and not due to increased aging. When Asphamin® is added to the binders, it is hypothesized that the zeolite particles act as fillers in the binders, thereby increasing the complex modulus of the binders.

It was also observed that the G*/sin δ values for binders containing warm asphalt additives were significantly similar when aged in the RTFO at 163 °C and the lower temperature. Figure 5-12 shows the G*/sin δ values for the three binders with and without the warm asphalt additives.

As per the effects of binder sources, Binder 2 had the highest G*/sin δ values irrespective of the warm asphalt additives followed by Binders 1 and 3. This was observed after RTFO at 163 °C as well as the reduced temperatures. This is due to the higher complex modulus of unmodified and unaged Binder 2 (Table 3-1).

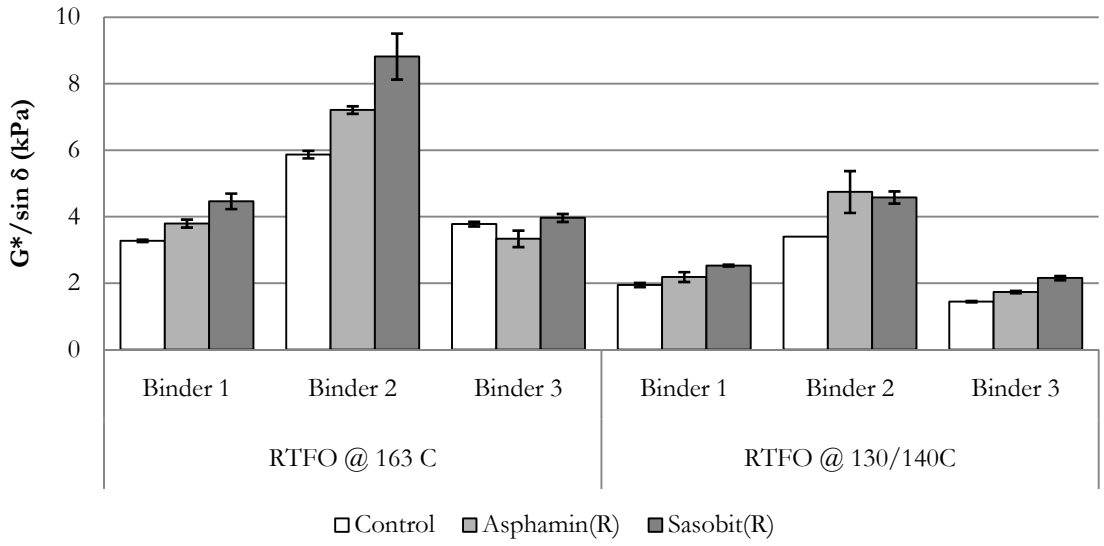

Figure 5-12: Effects of the warm asphalt additives on rutting parameter

Effects on Fatigue Parameter (G.sin δ)*

The effects of the warm asphalt additives and binder sources were studied on the fatigue parameter (G*.sin δ) of the binders with and without the warm asphalt additives. The RTFO residues – aged in the RTFO at 163 °C (325 °F) and a lower temperature – were further aged in the PAV to simulate long term aging. The PAV residues were then tested to

determine the G*sin δ values. Figure 5-13 shows the G*sin δ values for three binders with and without warm asphalt additives. From the statistical analysis, it was observed that when the binders were aged in the RTFO at 163 °C, irrespective of the binder sources, binders containing Asphamin®, Sasobit® and no warm asphalt additive had significantly similar G*sin δ values. This trend was also observed for binders aged in the RTFO at the lower temperature. Thus, the addition of the warm asphalt additives does not seem to influence the fatigue resistance of the binders. It was also observed that the RTFO temperature did not have any significant influence on the G*sin δ values of the binders.

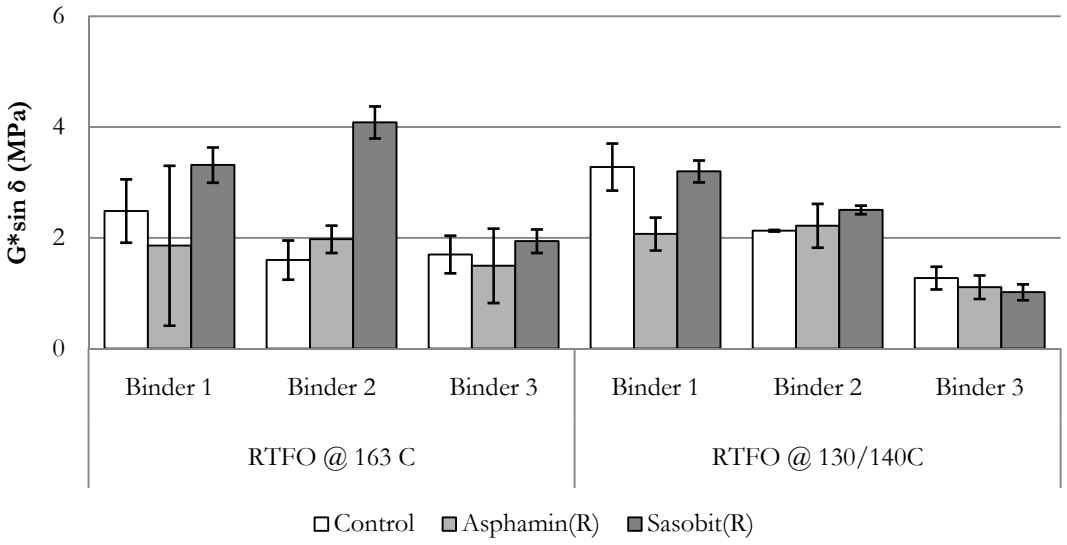

Figure 5-13: Effects of the warm asphalt additives on fatigue parameter

When the binders were aged in the RTFO at 163 °C, the binder source did not have any significant affect on the G*sin δ values, whereas when the binders were aged in the RTFO at the lower temperature, Binder 1 had significantly higher G*sin δ values compared to the other binders. Additionally, Binder 2 had significantly higher G*sin δ values compared to Binder 3, suggesting that certain binders show better resistance to fatigue cracking when mixed and compacted at lower than usual temperatures.

Effects on Stiffness and m-value

The bending beam rheometer (BBR) test was conducted on the PAV residues in order to evaluate the stiffness and the m-value of the binders with and without the warm asphalt additives. Figure 5-14 shows the stiffness and m-value for Binder 1 with and without the warm asphalt additives. From the statistical analysis, it was observed that irrespective of the binder source, binders containing Asphamin® and Sasobit® had significantly higher stiffness values compared to unmodified binders. This was observed in case of binders aged in the RTFO at 163 °C as well as the lower temperature. Similarly, it was also observed that binders containing Asphamin® and Sasobit® had significantly lower m-values compared to unmodified binders when aged in the RTFO at 163 °C. However, when aged in the RTFO at lower temperatures, binders containing Sasobit® had significantly lower m-values compared to binders containing Asphamin® and no warm asphalt additives. This shows an increase in the tendency towards cracking at low temperatures for binders containing Sasobit®, when mixed at lower temperatures. The reason for the increase in the stiffness of binders containing Sasobit® and the reduction in m-values is due to wax crystallization, which causes an increase in the resistance to plastic deformation in the binder *(Edwards, et al., 2006)*. It is hypothesized that the increase in the stiffness of the binders containing Asphamin® may be due to the mineral filling effect of the zeolite, which is an insoluble solid in the binder, and not due to increased aging of the binders. Binders 2 and 3 followed similar trends.

When the stiffness values for binders aged in the RTFO at 163 °C were compared to the binders aged in the RTFO at a lower temperature, it was observed that in most cases, the stiffness values were significantly similar. However, the m-values for binders aged in the RTFO at a lower temperature were significantly higher than the m-values of binders aged in

the RTFO at 163 °C. This shows that while there may not be any significant reduction in the stiffness of the binders when mixed and compacted at lower temperatures, there is a significant increase in the rate of change of stiffness, which resists the tendency of the binders to cracking at low temperatures, when mixed and compacted at reduced temperatures. Since warm asphalt would be ideally mixed and compacted at lower temperatures in the field, this is more indicative of the actually low temperature properties of warm asphalt.

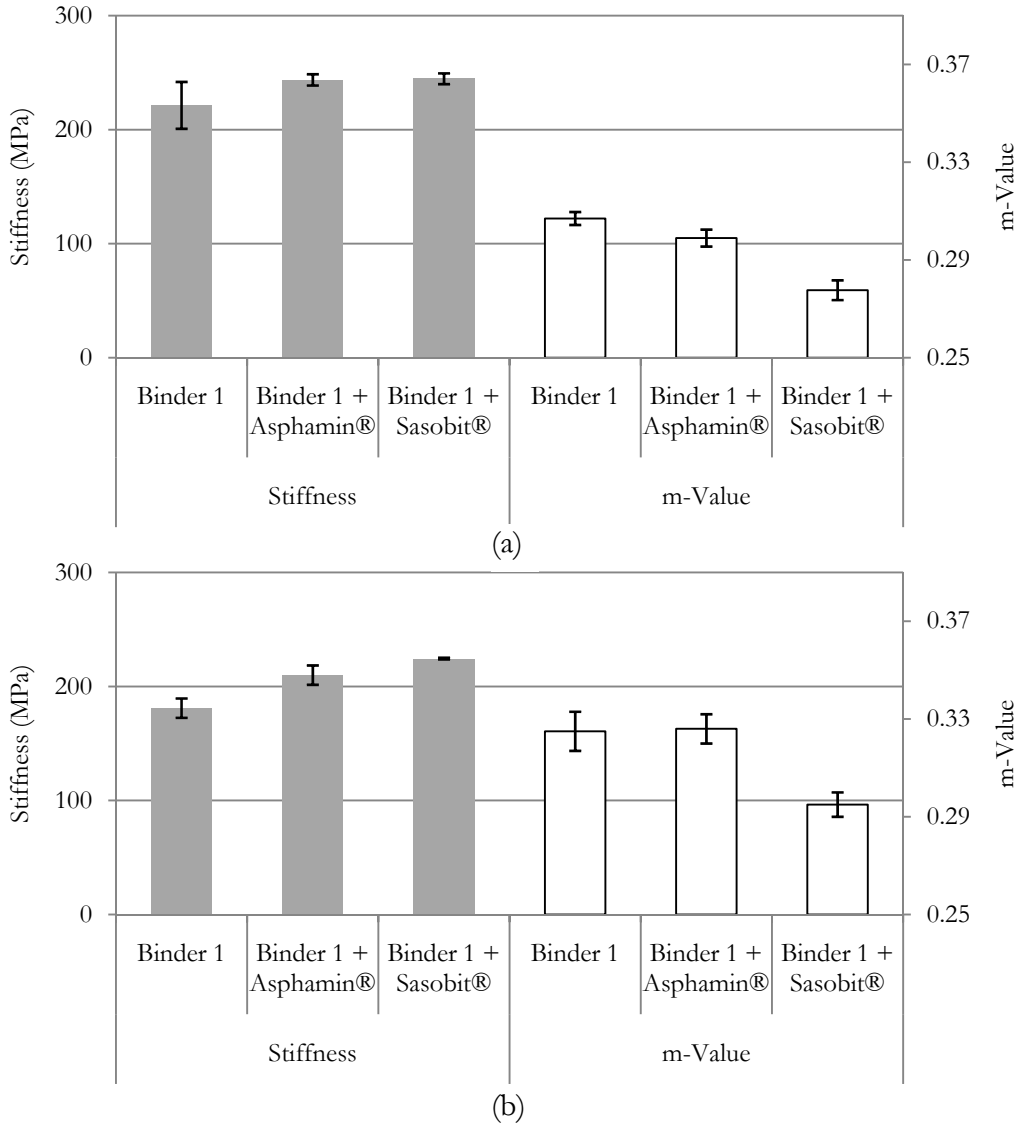

Figure 5-14: Stiffness and m-value for Binder 1: (a) RTFO at 163 °C and (b) RTFO at 130 °C

Among the three binders used, irrespective of the warm asphalt additive, Binder 1 had significantly higher stiffness compared to the other binders, and Binder 2 had significantly higher stiffness compared to Binder 3. This was observed for binders aged in the RTFO at 163 °C and the lower temperature. When the m-values for the binders were compared, it was observed that Binder 2 had significantly higher m-values compared to Binders 1 and 3. Thus, it can be seen that various binder sources show different properties when the warm asphalt additives are added.

Fourier Transform Infrared (FTIR) Spectrometry

Since it was observed that the addition of Asphamin® increased the viscosity of the binders after aging in the RTFO, and the addition of Asphamin® and Sasobit® increased the complex modulus of the binders after aging in the RTFO, it was decided to use FTIR spectroscopy as a tool to quantify the aging in the binders with and without the warm asphalt additives. FTIR analysis enables the identification and quantification of functional groups present in bitumen. Infrared spectroscopy measures the infrared light absorbed by covalent bonds in molecules (or vibrations of lattice crystals). The absorption of different types of bonds differs in the intensity and frequency of light absorbed, which enables the identification of chemical functionalities *(Karlsson and Isacsson, 2003)*. The binders with and without the warm asphalt additives were tested in a FTIR spectrometer, and the peaks of their IR absorbance were measured at wave numbers 1030 cm^{-1} and 1700 cm^{-1}. The IR absorbance peaks at these wave numbers represent the amount of sulfoxide and carbonyl bonds in the binders respectively, which is an indication of aging in the binder *(Edwards, 2005)*. Binders were tested in their original condition, RTFO aged condition and PAV aged condition. The absorbance of the binders at 1700cm^{-1} and 1030 cm^{-1} are shown in Figures 5-15 and 5-16.

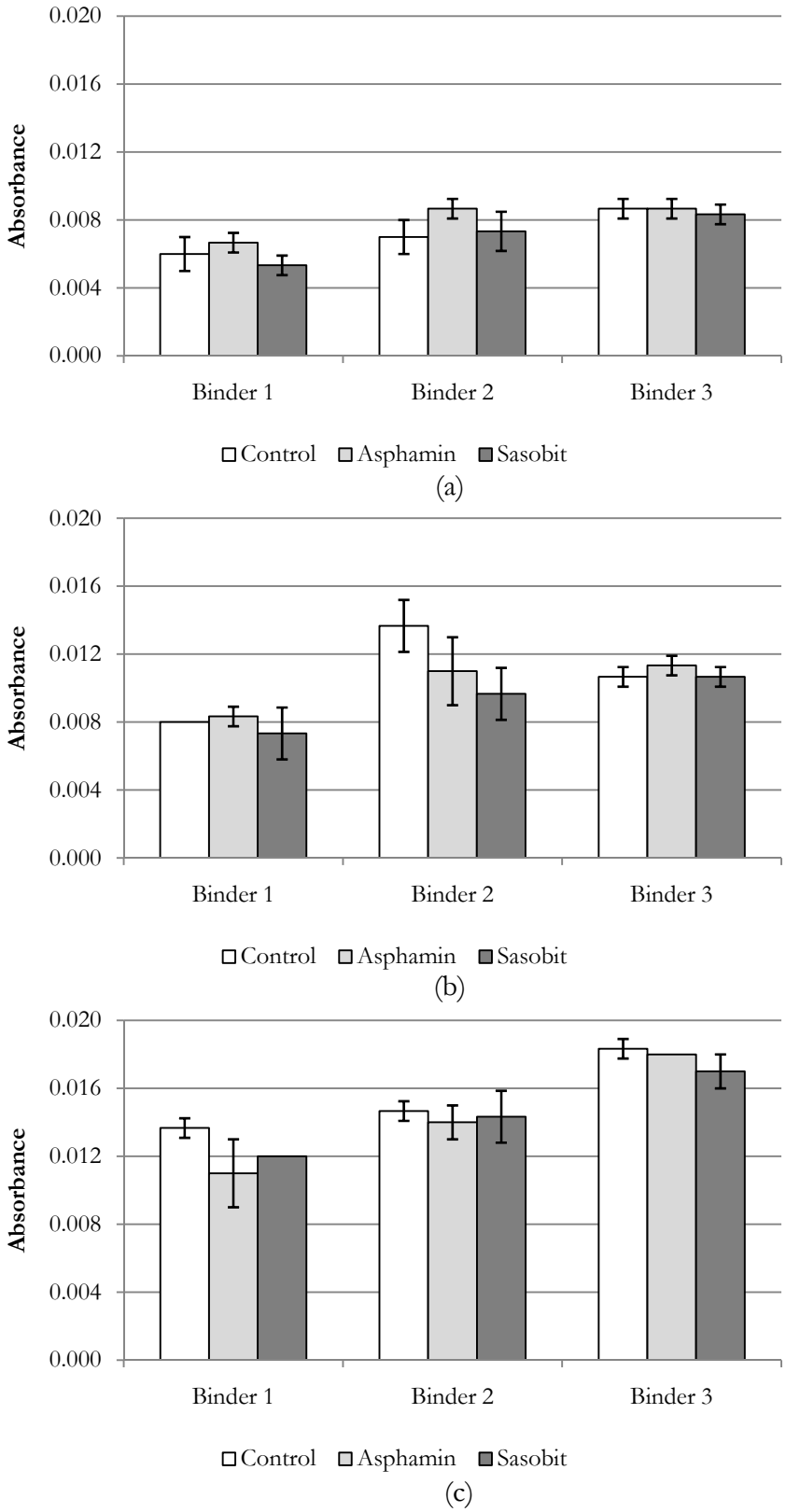

Figure 5-15: FTIR absorbance of the binders at 1700 cm^{-1}: (a) Original binder; (b) RTFO aged binder and (c) PAV aged binder

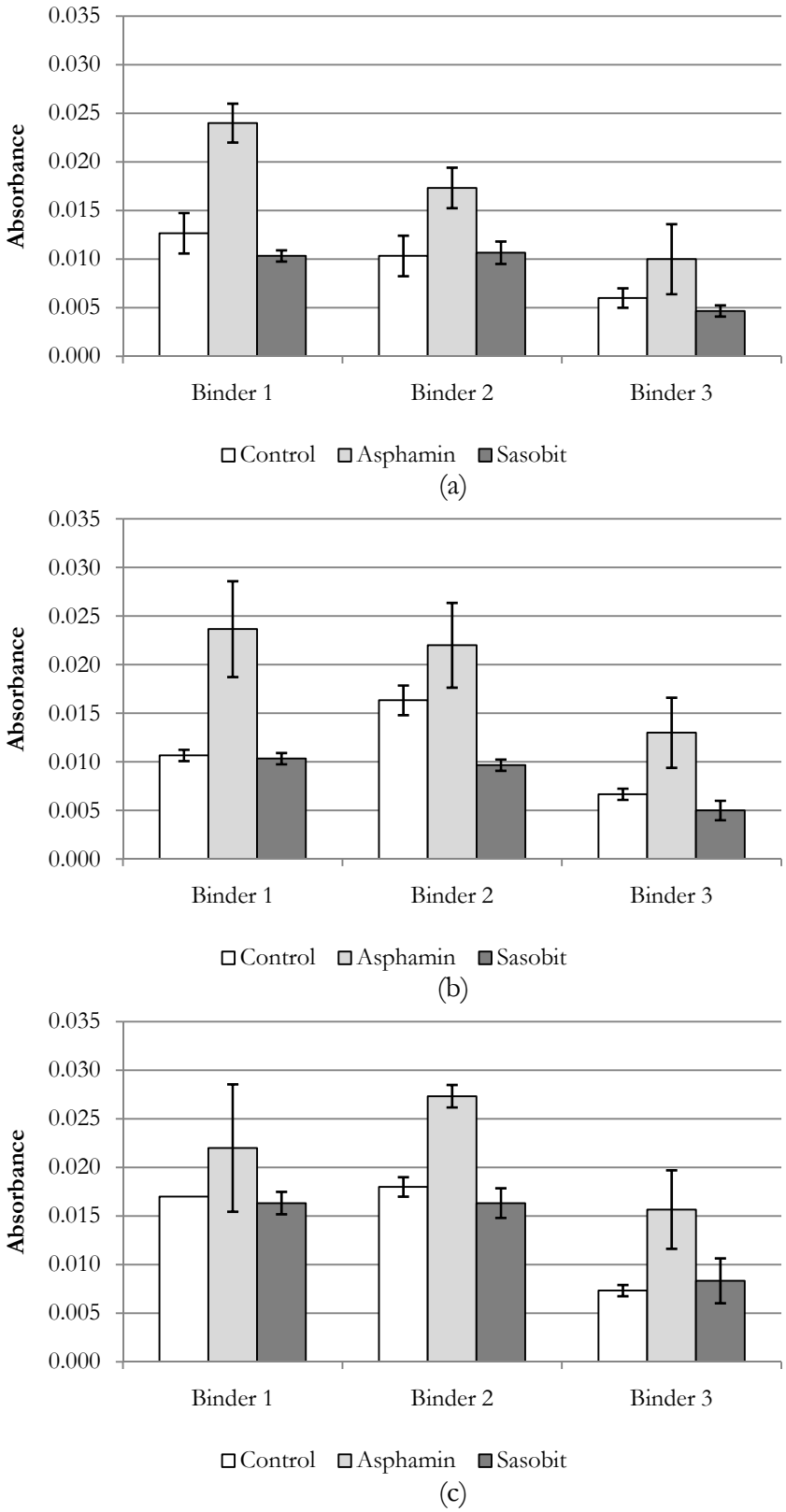

Figure 5-16: FTIR absorbance of the binders at 1030 cm^{-1}: (a) Original binder; (b) RTFO aged binder and (c) PAV aged binder

As it can be seen from the graphs, the presence of Asphamin® or Sasobit® does not significantly affect the absorbance of the binders at 1700 cm^{-1}, indicating that the presence of Asphamin® or Sasobit® does not increase the amount of carbonyl bonds in the binders. The binders containing Asphamin® seem to show significantly higher absorbance at wave number 1030 cm^{-1} compared to control binders and binders containing Sasobit®. However, FTIR spectroscopy of the Asphamin® additive (Figure 5-17) shows high absorbance at 1030 cm^{-1}. This indicates that the increase in the absorbance at 1030 cm^{-1} for binders containing Asphamin® was not due to increase in the number of sulfoxide bonds, but due to the overlapping of absorbance of the sulfoxide bonds in the binders and Asphamin® at that wave number.

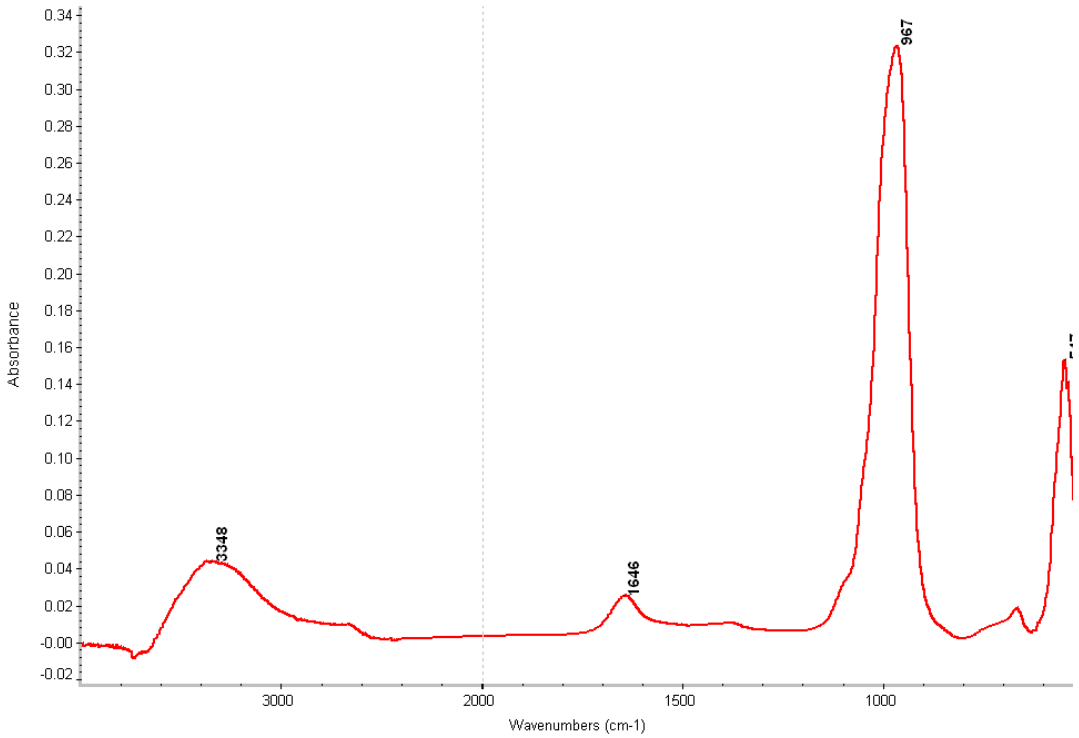

Figure 5-17: Infrared spectra of Asphamin® by contact attenuated total refraction

Thus, it could be concluded that the increase in the complex modulus and viscosities of the binders containing the warm asphalt additives were not due to excessive aging in the

presence of the warm asphalt additives but due to the mineral filling effect in case of binders containing Asphamin® and wax crystallization in case of binders containing Sasobit®.

5.1.4 Effects of Warm Asphalt Additives on Thermal Behavior of Binders

Since Sasobit® is a long chain aliphatic hydrocarbon of 40 to 115 carbon atoms, it is important to investigate the effects of crystallization of the wax in the binders. The crystallization and the melting of the wax can affect different properties of the binders. For example, when the wax in the binder melts, there will be a sudden decrease in the viscosity and the complex modulus of the binder, leading to increased rutting at temperatures beyond the melting point of the waxes. Similarly, at temperatures below the glass transition temperature of the binders containing Sasobit®, the waxes would be in a crystalline state, making the binders more prone to cracking. Differential scanning calorimetry (DSC) was used to measure the shift in the glass transition temperatures (T_g) of the binders after the addition of the warm asphalt additives, and to measure the melting temperature of the waxes in the binders. Before conducting the DSC, a thermo gravimetric analysis (TGA) of the binders containing the warm asphalt additives was performed to make sure the binders do not disintegrate within the temperature range they are subjected to in the DSC.

Figure 5-18 shows the second DSC heat cycle from -100 °C (-148 °F) to 150 °C (300 °F) for the three binders with and without the warm asphalt additives. There are two observations that can be made from the heat flows observed for binders containing Sasobit®. Firstly, at lower temperatures, the addition of Sasobit® significantly increased the glass transition (T_g) temperature of the three binders compared to the control binder. This suggests that the addition of Sasobit® makes the binders tested in this study more prone to cracking and brittle at lower temperatures.

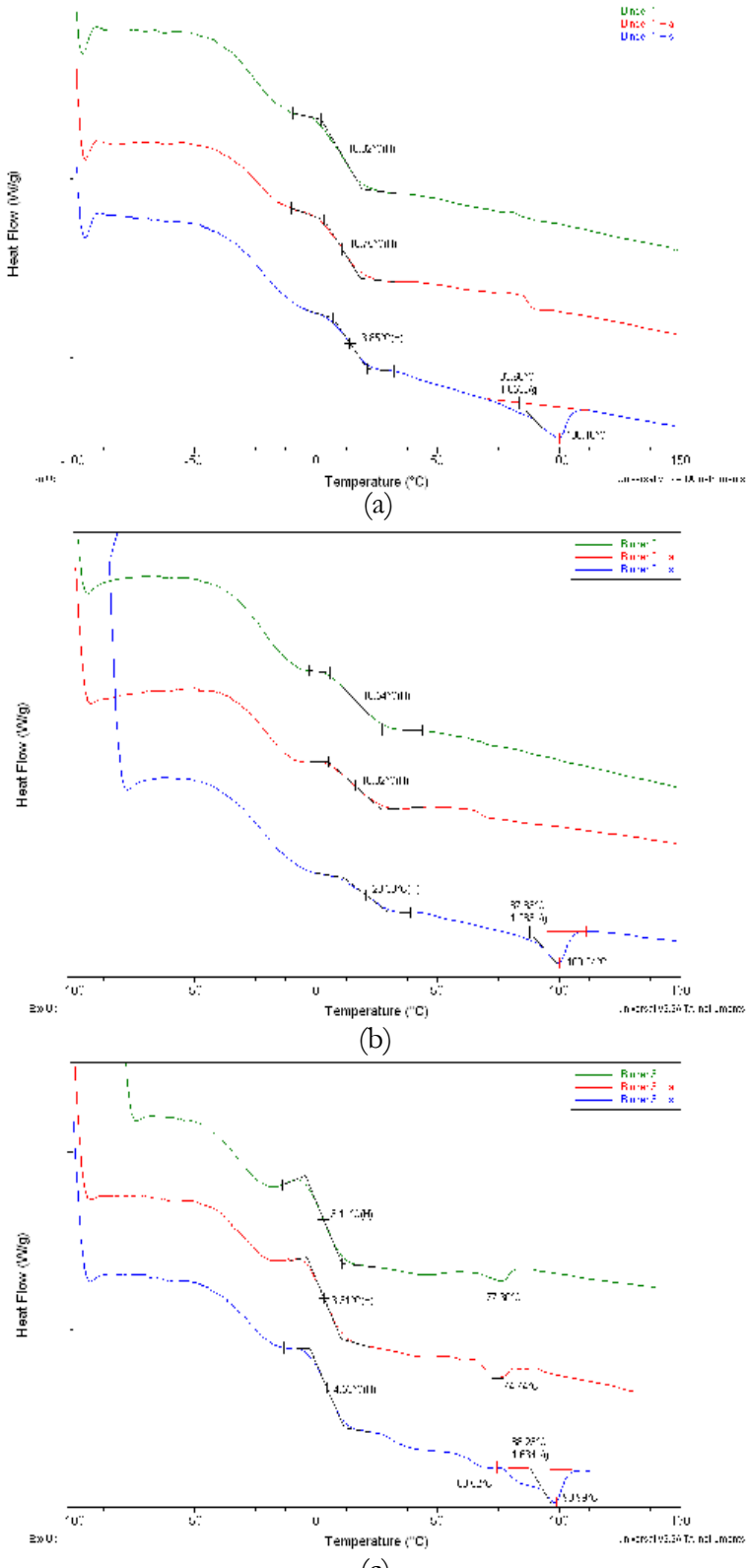

Figure 5-18: Second DSC heat cycle from -100 °C to 150 °C: (a) Binder 1; (b) Binder 2 and (c) Binder 3

The second observation was that beyond 80 °C, all binders containing Sasobit® showed a decrease in heat flow, indicating the melting of the wax at that temperature. It was observed that the wax starts melting beyond 80 °C, and completely melts at around 100 °C. This suggests that the viscosity and the complex modulus of the binders containing Sasobit® will start to decrease beyond temperatures of 80 °C, and drastically reduce beyond 100 °C. This is consistent with the manufacturer's claim that Sasobit® melts between temperatures of 85 °C and 115 °C (185 and 240 °F). However, the binders containing Asphamin® did not seem to show any significant difference in heat flows compared to the control binders.

5.1.5 Comparison of Aged Binder with Extracted Binder

Binders 1 and 2 extracted from the warm mix asphalt and the hot mix asphalt were compared with Binders 1 and 2 (with and without the warm asphalt additives) aged in the laboratory in the RTFO and PAV apparatus. The binders extracted from the hot mix asphalt were compared with the control binders aged in the RTFO at 163 °C (325 °F), and the binders extracted from the warm mix asphalt were compared with the binders containing the warm asphalt additives and aged in the RTFO at lower temperatures (130 and 140 °C or 266 and 284 °F).

Comparison of Viscosity

The aging index (Equation 1) was used to compare the viscosities of the binders with and without the warm asphalt additives extracted from the mixes and aged in the laboratory in a RTFO apparatus. The aging indices of the binders are as shown in Figure 5-19.

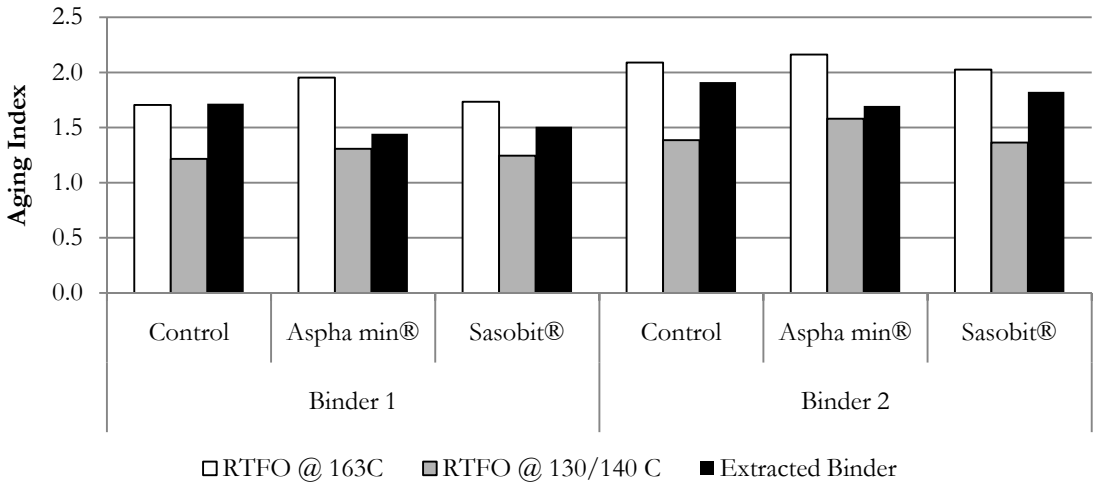

Figure 5-19: Aging indices for the binders aged in the RTFO and binders extracted from mixes

As it can be seen in the graph, control binder extracted from the hot mix asphalt had similar aging indices as the binders aged in the RTFO at 163 °C. However, binders containing warm asphalt additives, extracted from warm asphalt mixes had lower aging indices compared to the warm asphalt binders aged in the RTFO at 163 °C. Their aging indices were comparable to the aging indices of the binders aged in the RTFO at a lower temperature (130 °C / 140 °C). The slight increase in the aging could be due to the extraction process, where the binders are subjected to additional heat and pressure. This suggests that the warm asphalt binders undergo lesser aging during the mixing and compaction process compared to the control binders.

Comparison of Rutting Parameter ($G^*/\sin\delta$)

The rutting parameters of the extracted binders were compared with the rutting parameters of the binders aged in the RTFO. The rutting parameters of the binders with and without the warm asphalt additives are shown in Figure 5-20.

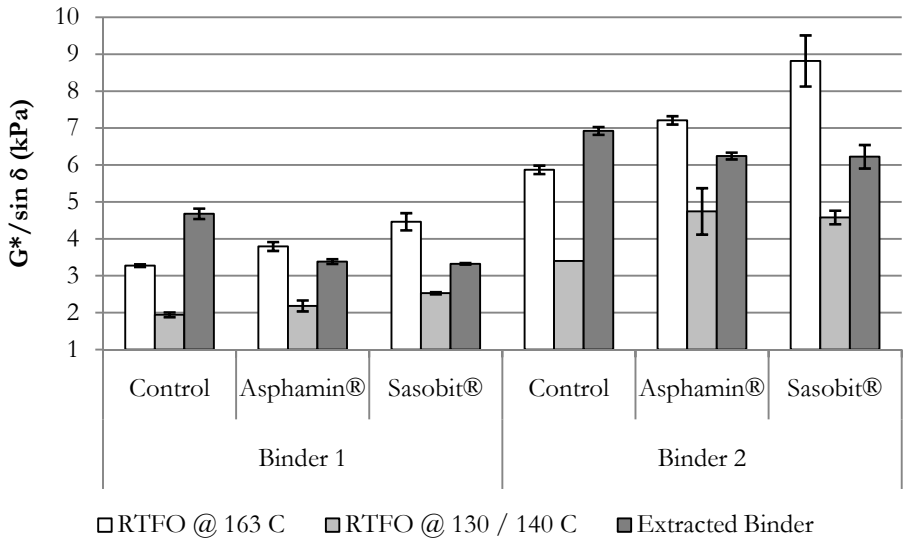

Figure 5-20: Rutting parameters of the binders aged in the RTFO and binders extracted from mixes

As can be seen from the graph, only the control binders extracted from hot mix asphalt had significantly higher G*/sin δ values compared to the binders aged in the RTFO at 163 °C. The binders containing the warm asphalt additives that were extracted from the warm asphalt mixes had significantly lower G*/sin δ values compared to warm asphalt additive containing binders aged in the RTFO at 163 °C. Again, their G*/sin δ values were slightly higher than the binders aged in the RTFO at lower temperatures, due to the additional aging during the extraction process. This further suggests that the warm asphalt binders age less compared to the binders in hot mix asphalt during the mixing and compaction process.

*Comparison of Fatigue Parameter (G*sin δ)*

The fatigue parameters of the binders aged in the RTFO and the binders extracted from the mixes are shown in Figure 5-21. No general trends were observed from the graph, but it was observed that none of the extracted binders containing warm asphalt additives had significantly higher G*sin δ values compared to binders containing the warm asphalt

additives aged in the RTFO at 163 °C. Thus, the mixing and compaction of the warm mix asphalt at a lower temperature could resist the fatigue cracking in the mixes.

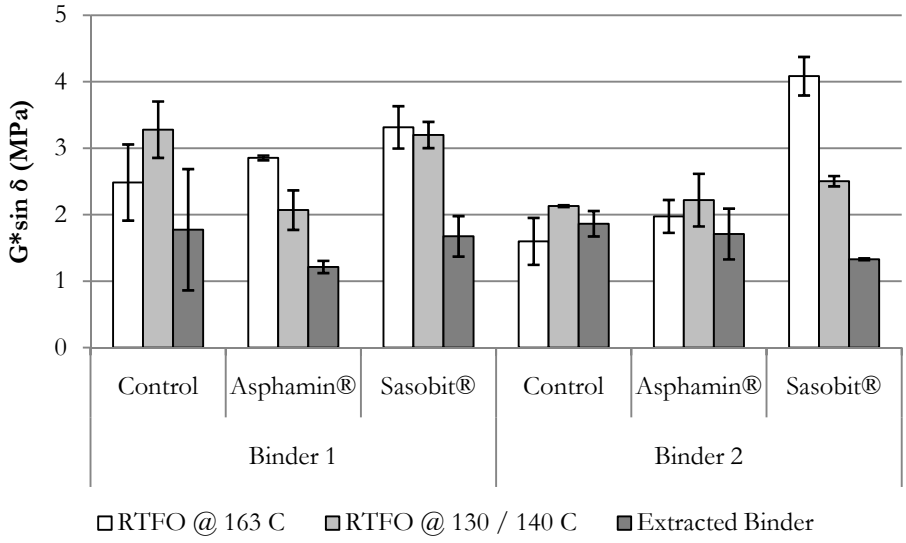

Figure 5-21: Fatigue parameters of the binders aged in the RTFO and binders extracted from mixes

Comparison of Stiffness and 'm-value'

The stiffness and the m-values of the binders aged in the RTFO and the binders extracted from the mixes are shown in Figure 5-22. From the graphs, it can be observed that the binders containing warm asphalt additives extracted from the warm mix asphalt have significantly lower stiffness values compared to the binders containing warm asphalt additives aged in the RTFO at 163 °C. Similarly, it was observed that the binders containing warm asphalt additives extracted from warm mix asphalt had significantly higher m-values compared to the binders containing warm asphalt additives aged in the RTFO at 163 °C. Thus, reducing the mixing and compaction temperatures of the warm asphalt mixes reduces the stiffness of the binders and improves the resistance of the mixes to low temperature cracking.

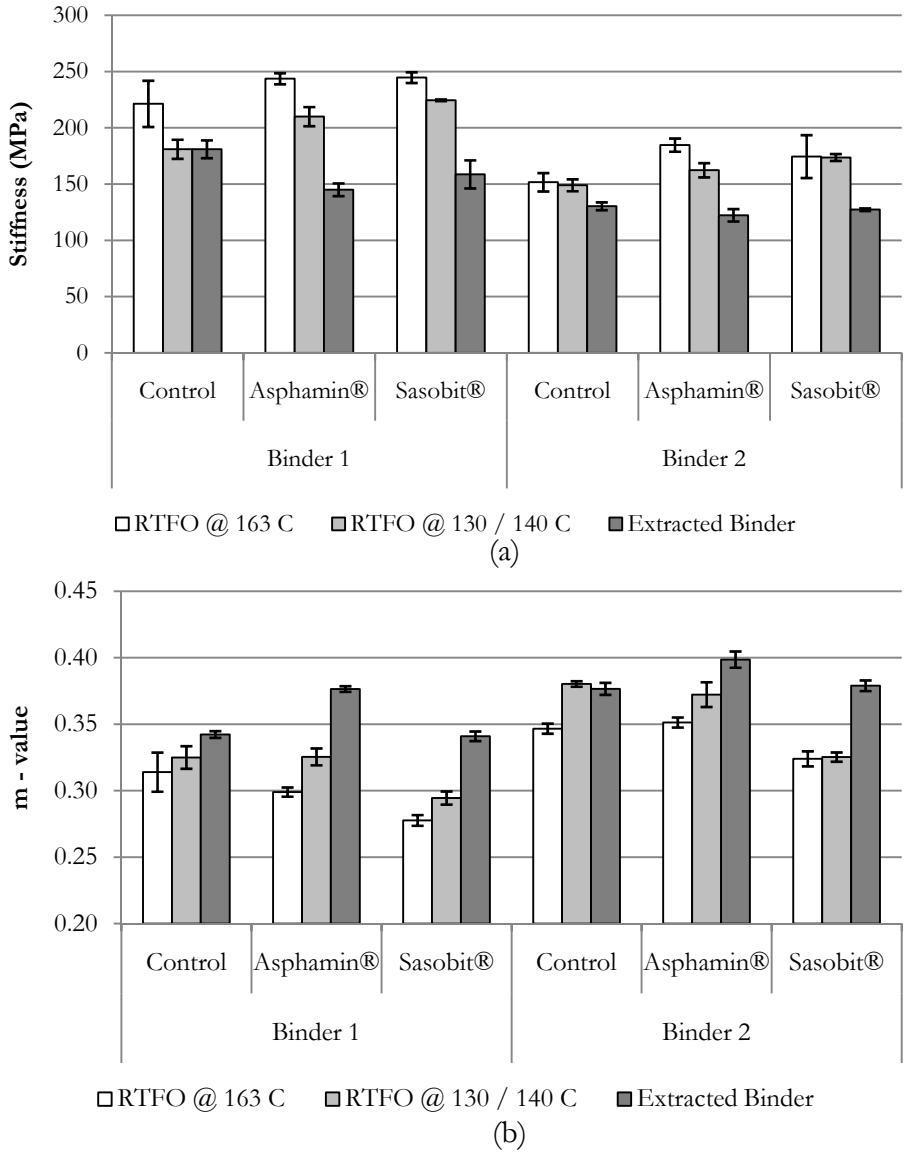

Figure 5-22: (a) Stiffness and (b) m-values of binders aged in the RTFO and binders extracted from mixes

In addition, while earlier it was observed that the addition of Sasobit® significantly lowered the m-values of the binders, it can be observed here that the binders containing Sasobit® extracted from warm asphalt mixes have significantly higher m-values compared to binders aged in the laboratory. Thus, this suggests that the lower mixing and compaction temperatures of the mixes containing Sasobit® reduce the low temperature cracking tendency of the binders containing Sasobit®.

Comparison of Gel Permeation Chromatographs (GPC)

GPC analysis was also conducted to identify any changes in the molecular size distributions in the binders after the addition of the warm asphalt additives, and to identify the effects of aging in the binders with and without the warm asphalt additives. The % large molecular sizes (LMS) of the three unaged binders with and without the additives are shown in Figure 5-23. The results indicated that the addition of the warm asphalt additives did not have any significant effect on the %LMS of the binders used in this study. Several studies have indicated that the %LMS of the binders have a good correlation with the properties of the binders, and are a good indicator of aging in the binders *(Al-Adulwahhab, et al., 1999; Jennings, 1980; Kim and Burati, 1993; Kim, et al., 1993; Price 1988).*

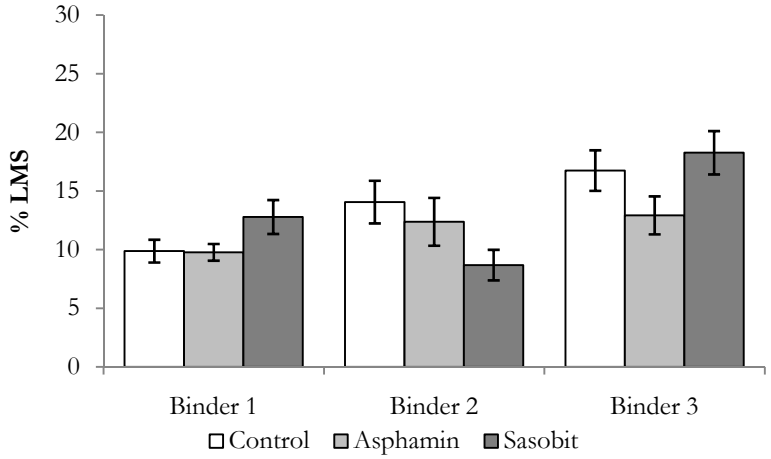

Figure 5-23: % LMS of the three unaged binders with and without the warm asphalt additives

In order to evaluate the effects of the warm asphalt additives on aging of the binders, the %LMS of the binders extracted from mixes were compared to the %LMS of the binders aged in the laboratory in a RTFO. Figure 5-24 shows the %LMS for all types of binders after short term and long term aging.

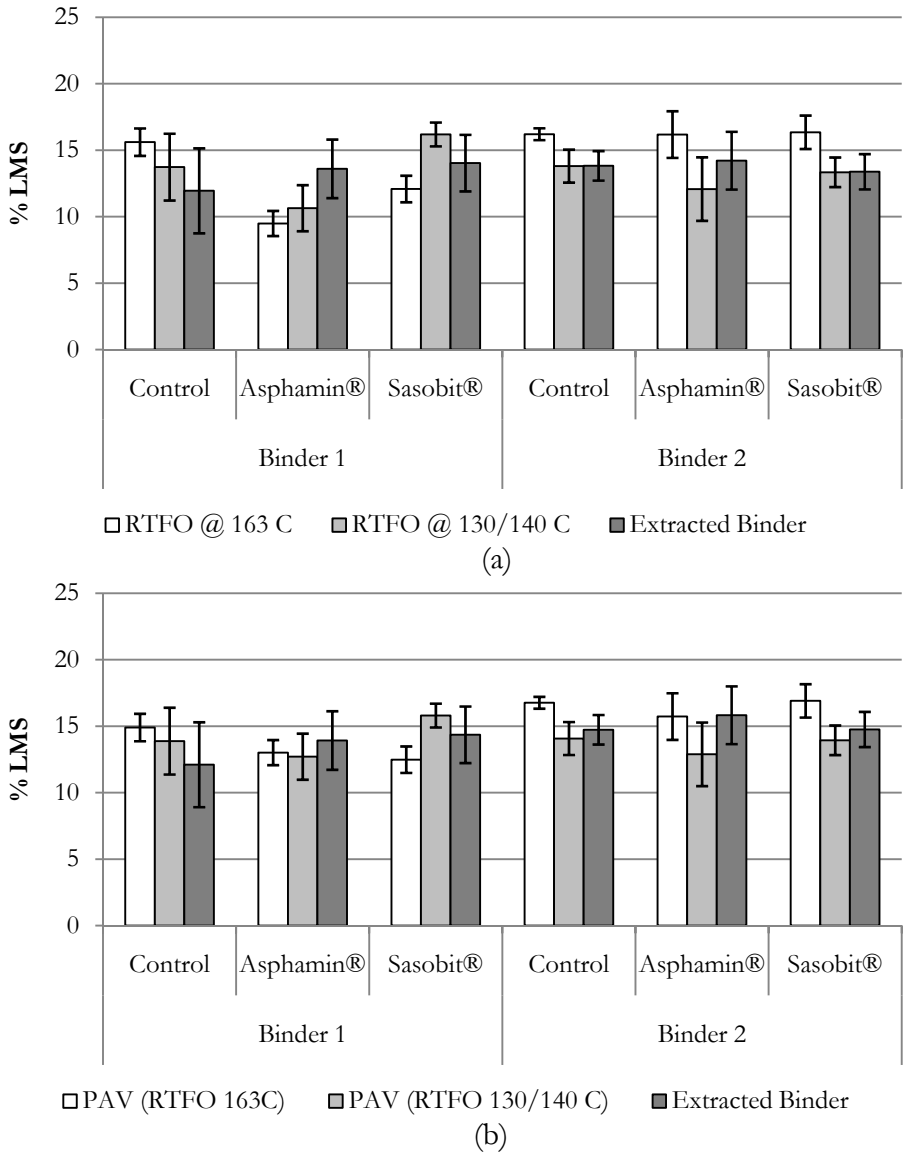

Figure 5-24: %LMS of binders aged in the RTFO and binders extracted from mixes after: (a) Short term aging and (b) Long term aging.

The results indicated that there were no statistical differences between control binders and binders containing the warm asphalt additives regarding the aging of samples. Also, none of the binders containing warm asphalt additives extracted from the warm mix asphalt had aged significantly more than the laboratory aged binders. This could be due to the reason that when the binder / THF solution was filtered through a 0.45 μm filter before injecting into the GPC, the Asphamin® particles and the Sasobit® crystals were retained on

the filter, and only the binder would have passed through the GPC. Thus, it could be concluded that the addition of the warm asphalt additives does not affect aging in the binders, and thus, the increases in the complex modulus and viscosities of the binders due to the addition of the warm asphalt additives was not as a result of excessive aging in the binders.

5.2 Mixture Properties

5.2.1 Resilient Modulus (M_R) Test

The resilient modulus test is a common test method to measure the stiffness modulus of a mixture. The resilient modulus at low temperatures is somewhat related to cracking. It has been shown that the stiffer mixtures at lower temperatures are more prone to cracking *(Roberts, et al., 1996)*. Figures 5-25 and 5-26 show the resilient modulus of the mixes in unaged and aged conditions, respectively. The statistical analysis indicated that unaged mixes containing Sasobit® had significantly similar M_R values compared to the unaged control mixes at all the temperatures. However, unaged mixes containing Asphamin® had significantly lower M_R values compared to the control mixes at 25 and 40 °C. This indicates that the reduced aging of the binders containing Asphamin® during the mixing process makes the mixes containing Asphamin® softer.

In case of aged samples, the warm asphalt additives had no significant effects on the M_R values of the mixes, with the exception of Asphamin® at 25 °C, where the mixes containing Asphamin® had significantly lower M_R values compared to other mixes. Thus, it could be concluded that the addition of the warm asphalt additives does not make the mixtures stiffer and thus more prone to cracking compared to the control mixes.

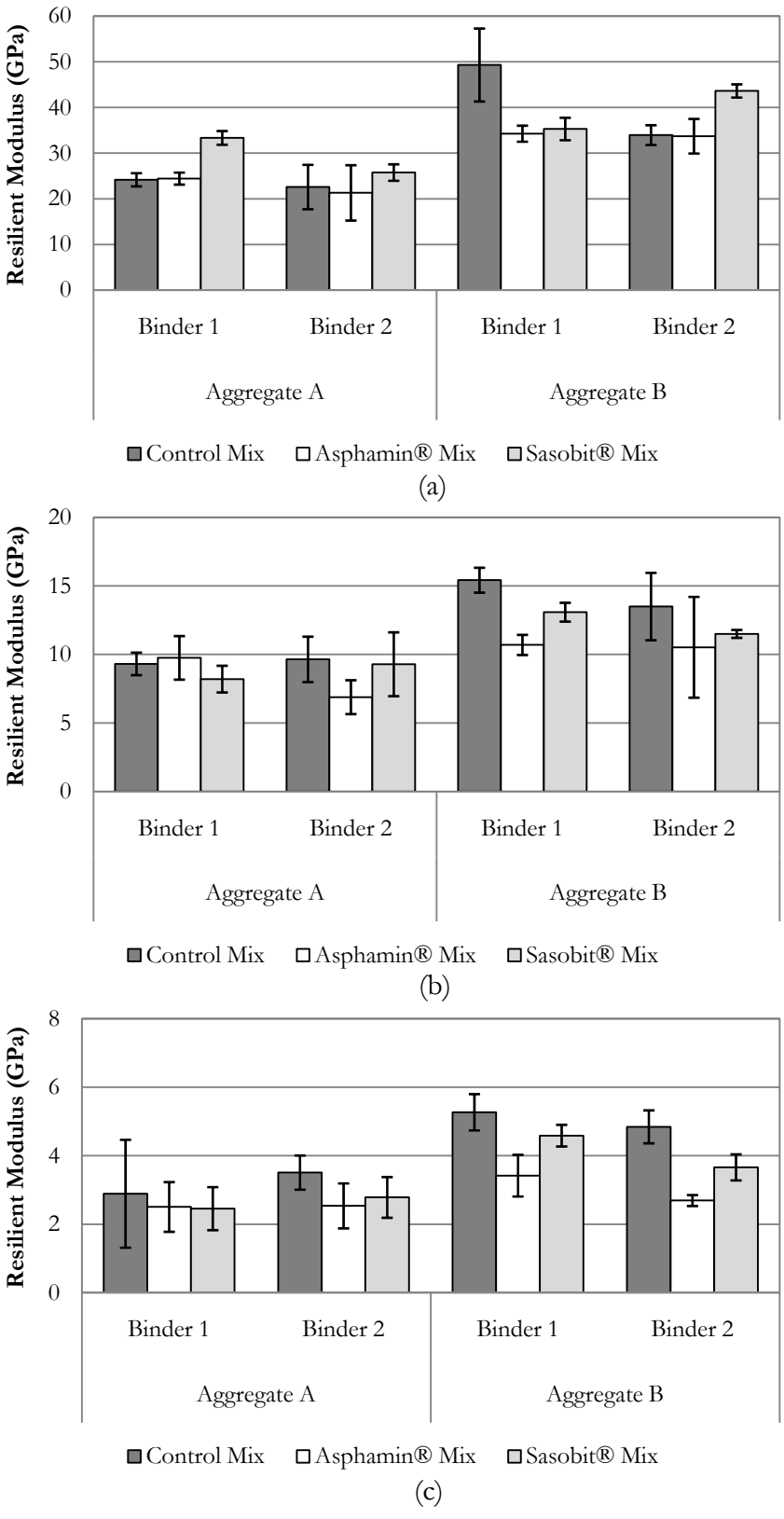

Figure 5-25: Resilient modulus of unaged samples: (a) 5 °C; (b) 25 °C and (c) 40 °C

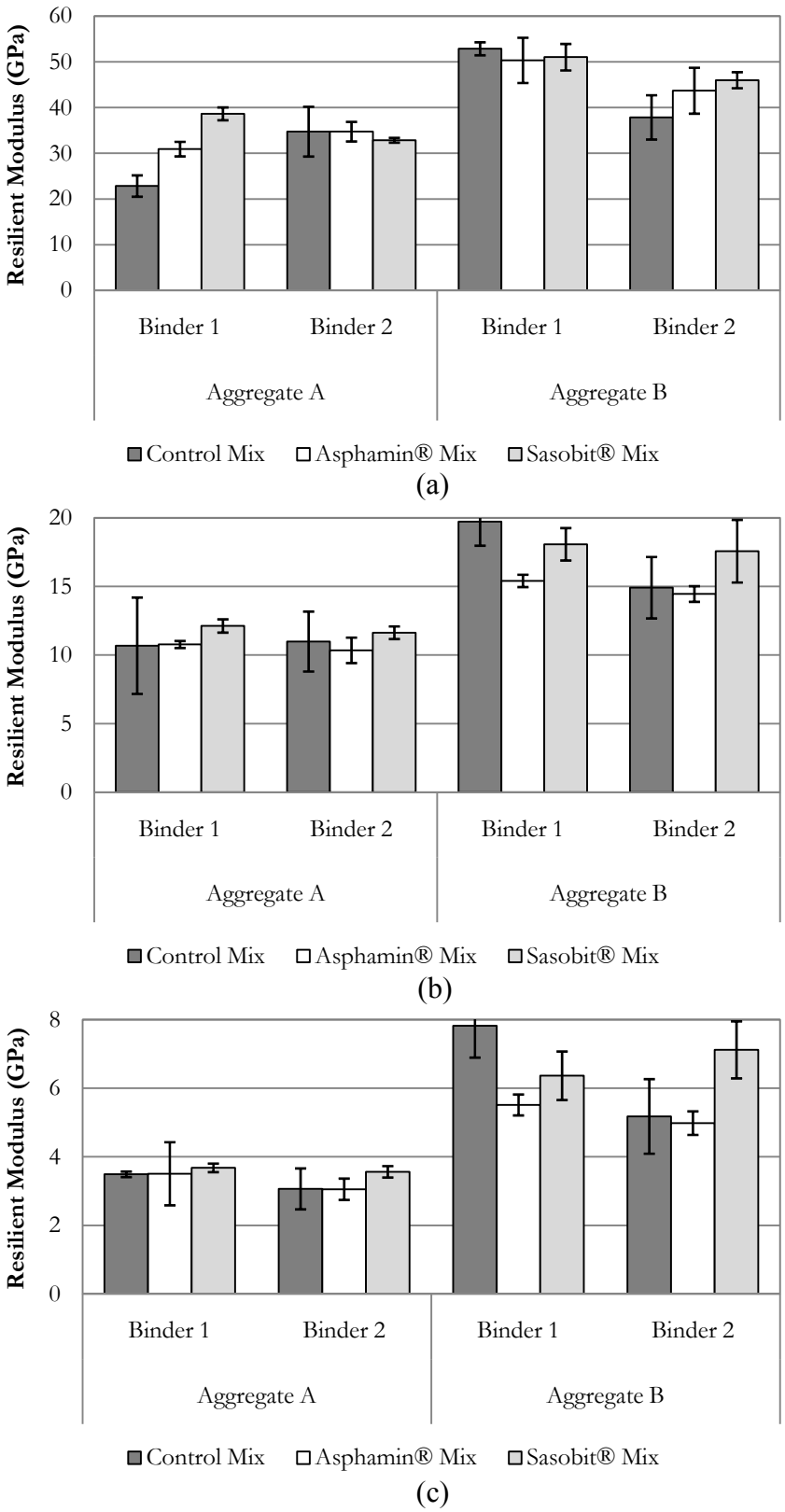

Figure 5-26: Resilient modulus of aged samples: (a) 5 °C; (b) 25 °C and (c) 40 °C

In addition, the binder source did not seem to have any significant effect on the M_R values for aged or unaged samples. However, for all cases, mixes with Aggregate B had significantly higher M_R values at all testing temperatures. It is hypothesized that the reason for this could be the high toughness of aggregate B and higher fractured face count.

5.2.2 Moisture Susceptibility Test

The wet indirect tensile strength (ITS) and the tensile strength ratio (TSR) were used as a measure of moisture susceptibility in this study. Figures 5-27 and 5-28 show the wet ITS and TSR values for the unaged and aged samples, respectively. It was observed that the warm asphalt additives did not have any significant effect on the wet ITS of the unaged samples. However, unaged mixes containing the warm asphalt additives had significantly higher TSR values compared to the control mixes. Thus, it appears that the addition of the warm asphalt additives improves the tensile strength ratio of the unaged mixes, and thus the moisture susceptibility of the mixes tested in this study.

In case of aged mixes, it was observed that the mixes containing Sasobit® had significantly lower TSR values compared to mixes containing Asphamin®. However, none of the additives significantly lowered the TSR values of the mixes compared to the control mixes (with the exception mixes containing Aggregate A, Binder 1 and Sasobit®). Thus, the warm asphalt additives did not seem to have any effect on the moisture susceptibility of the aged mixes tested in this study.

For the unaged mixes, the aggregate or the binder source did not seem to have any significant effect on the wet ITS values, but the mixes prepared with Binder 1 had significantly higher TSR values compared to mixes prepared with Binder 2. In case of the

aged mixes, the binder source did not have any significant effect on the wet ITS or TSR of the samples. However, mixes prepared with Aggregate B seemed to have higher wet ITS and TSR values compared to mixes prepared with Aggregate A, as a result of the higher toughness and fracture face count of Aggregate B.

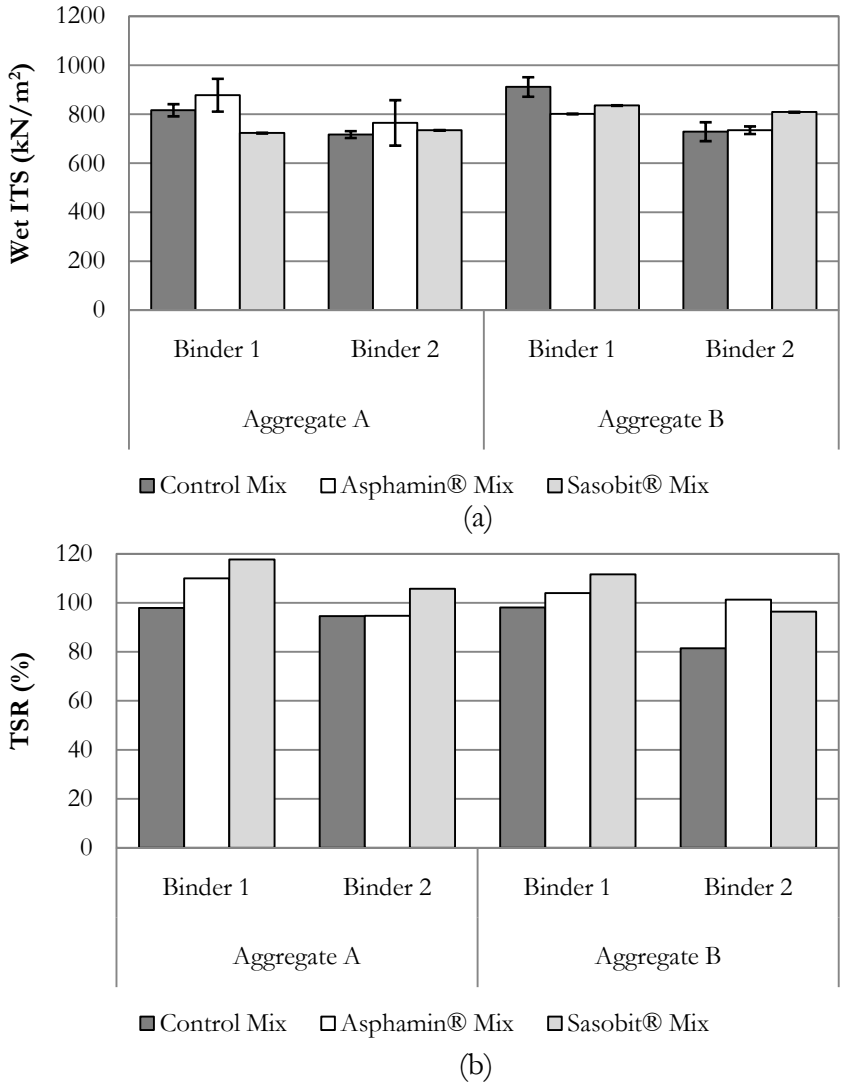

Figure 5-27: Moisture susceptibility of unaged samples: (a) Wet ITS and (b) TSR

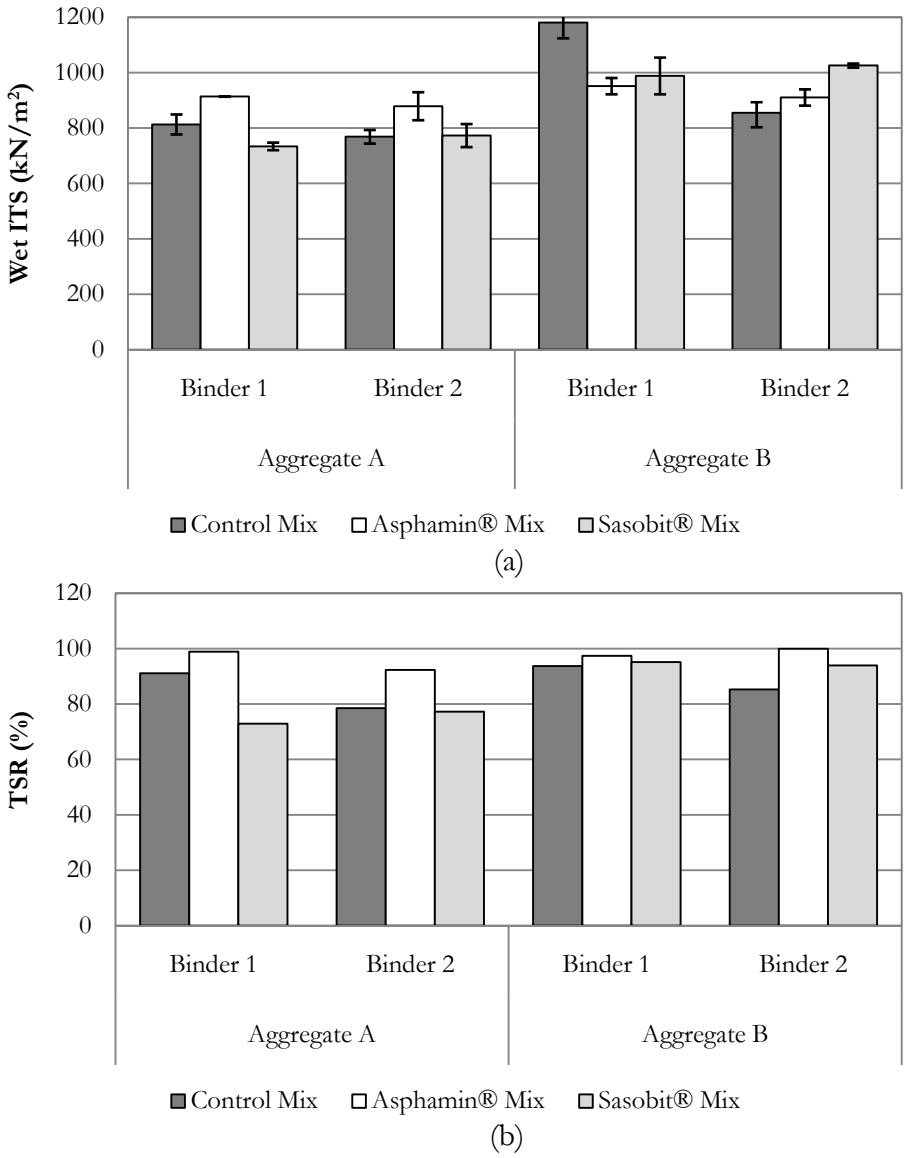

Figure 5-28: Moisture susceptibility of aged samples: (a) Wet ITS and (b) TSR

5.2.3 Rutting Test

Rutting is the formation of depressions along the pavement's wheel path as a result of traffic loads. Figure 5-29 shows the rutting depths of the mixes in unaged as well as aged conditions. From the statistical analysis of the APA rutting depths, it was observed that the unaged mixes containing Sasobit® had significantly lower rut values than the other mixes. This observation is consistent with the study on binder properties, where the addition of

Sasobit® significantly increases the binder complex modulus and the resistance to permanent deformation. Thus, it can be concluded that the addition of Sasobit® improves the rutting resistance of the unaged mixtures tested in this study.

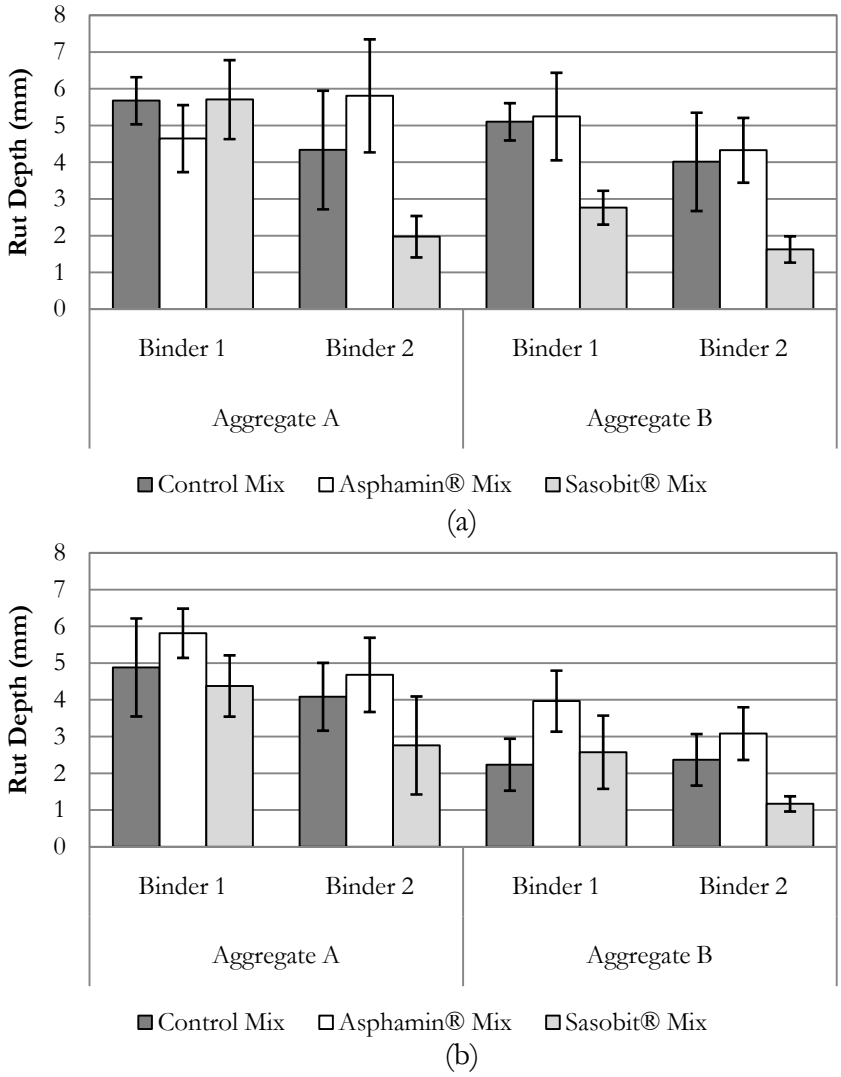

Figure 5-29: APA rutting depths of samples (after 8050 cycles): (a) Unaged samples and (b) Aged samples

When the rutting depths of the aged samples were compared, mixes containing Sasobit® had significantly lower rutting depths compared to mixes containing Asphamin®. In addition, mixes containing both the warm asphalt additives were significantly similar to

the control mixes. Thus, it can be concluded that the reduction of mixing and compaction temperatures of mixes containing the warm asphalt additives does not have any negative effect on the rutting resistance of the mixes tested in this study.

The binder sources used in this study did not have any significant effect on the rutting depths of the unaged or aged mixes. However, aged mixes prepared with Aggregate B seemed to have significantly lower rutting depths compared to the aged mixes prepared with Aggregate A. This could be due to the higher number of fractured faces in Aggregate B, which facilitate better interlocking thereby reducing the rutting in the mixtures.

5.2.4 Aging Characteristics of WMA

Since warm asphalt is a relatively new technology, there are no pavements that have been paved for several years using these technologies, and thus, the aging characteristics of warm mix asphalt are not known in great detail. Therefore, in this study, the mixture properties of unaged warm mix asphalt samples were compared to laboratory aged warm mix asphalt samples. From the comparison, it was observed that the wet ITS values of the unaged and aged mixes were significantly similar (Figure 5-30). Thus, the warm asphalt additives do not seem to affect the wet ITS of the mixes tested in this study as they age.

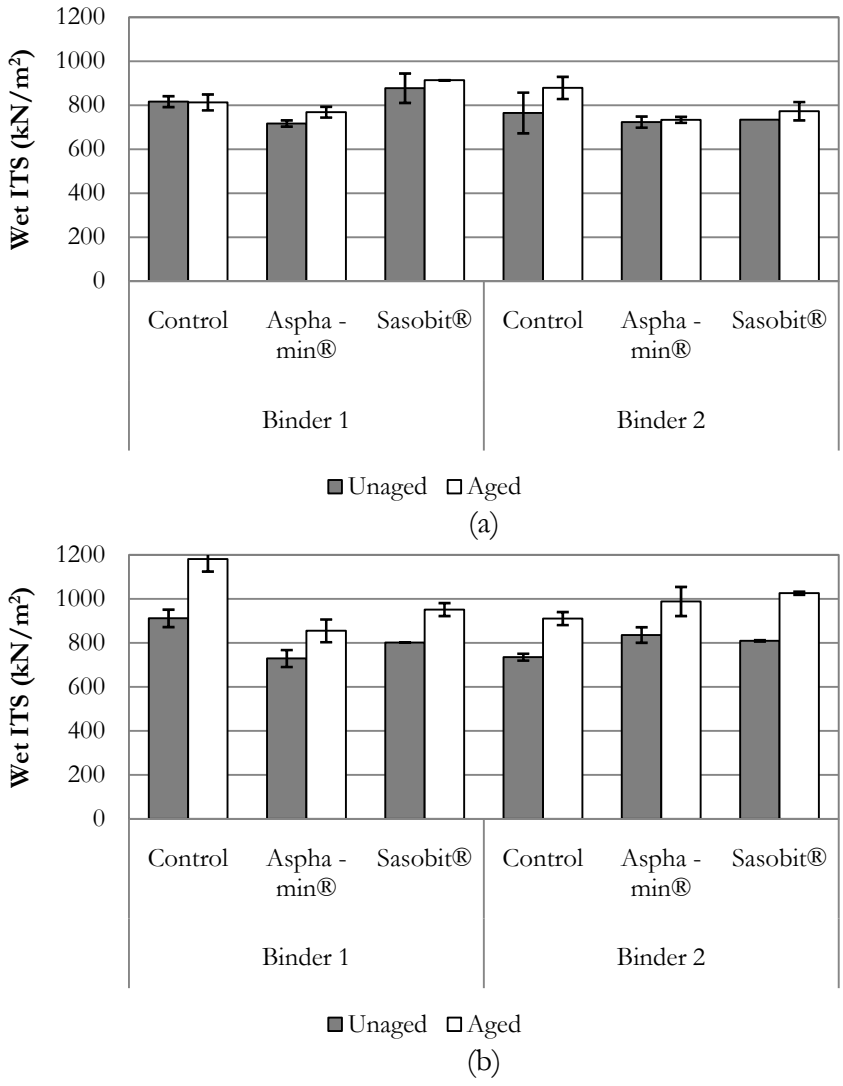

Figure 5-30: Comparison of wet ITS for unaged and aged samples: (a) Aggregate A and (b) Aggregate B

Figure 5-31 shows the TSR values of the unaged and aged mixes. It can be observed that the mixes containing the warm asphalt additives had lower TSR values after aging compared to the control mixtures after aging (with the exception of mixes containing binder 1 and Sasobit®).

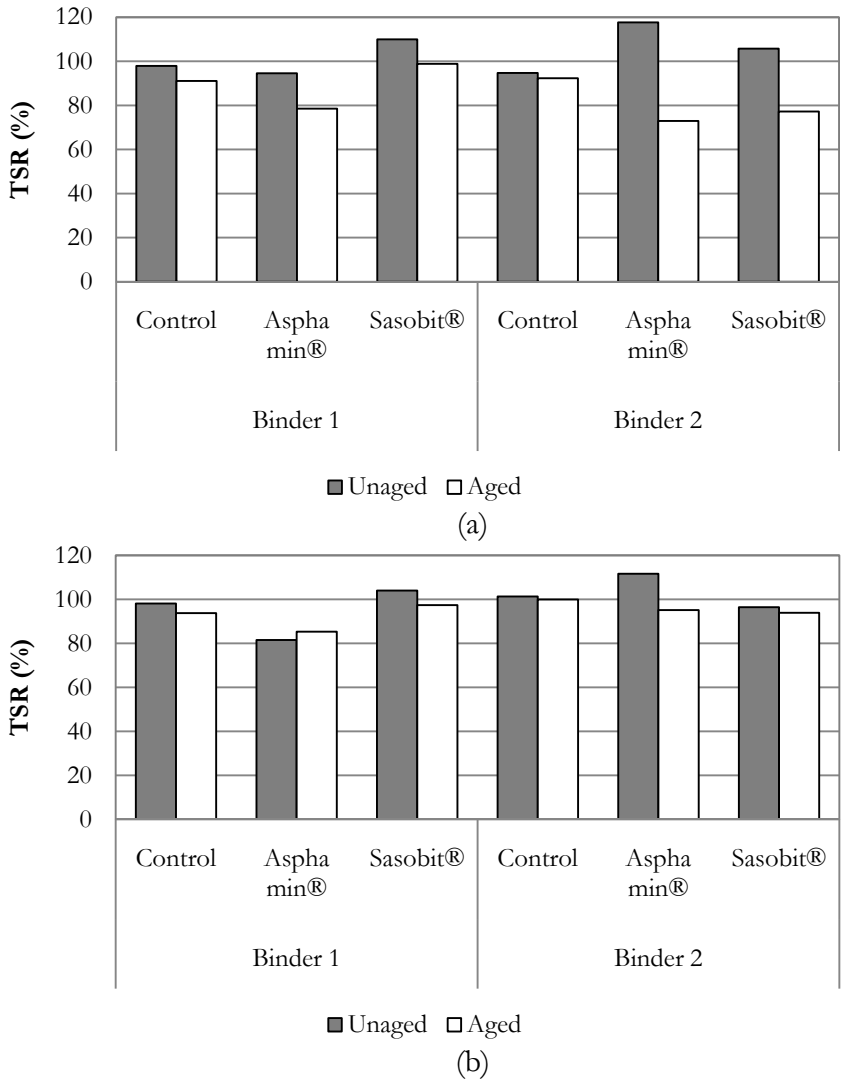

Figure 5-31: Comparison of TSR for unaged and aged samples: (a) Aggregate A and (b) Aggregate B

Similarly, the M_R values of the unaged and aged samples were compared, and in most cases it was observed that the aged mixes containing the warm asphalt additives had significantly higher M_R values compared to the unaged mixes. Figure 5-32 compares the M_R values of the unaged and aged samples measured at 5 °C. Similar trends were observed at other testing temperatures. It could be concluded that the aging of mixes containing the warm asphalt additives increases the resilient modulus of the mixes tested in this study. This could lead to an increase in cracking in the mixes containing the warm asphalt additives at

lower temperatures, and increased rutting resistance at higher temperatures, in spite of the binders undergoing reduced aging during the mixing and compaction process.

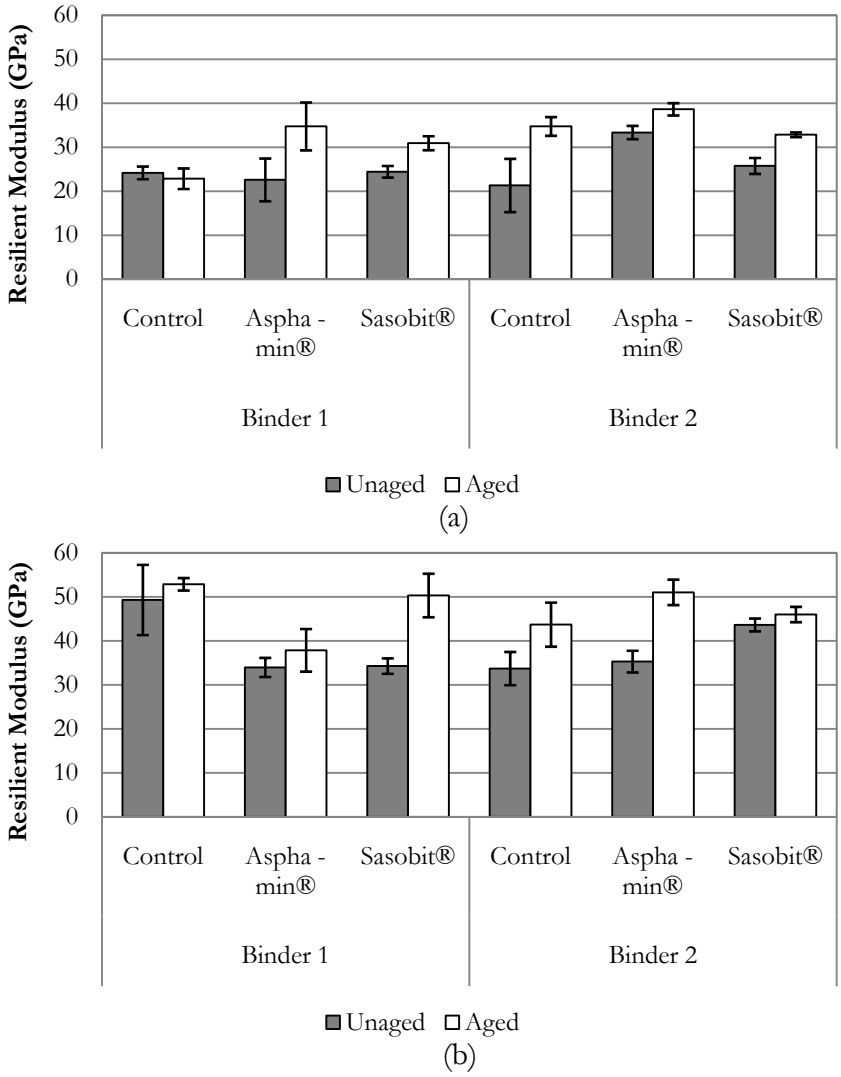

Figure 5-32: Comparison of M_R @ 5 °C for unaged and aged samples: (a) Aggregate A and (b) Aggregate B

Figure 5-33 compares the rut depths of the unaged and aged samples. From the graphs, no general trends were observed about the effects of the warm asphalt additives on the rutting resistance of the mixes as they aged. However, for most mixes, the rutting depths of the aged mixes were significantly similar or lower compared to the unaged mixes.

Additionally, it was observed that mixes prepared with Aggregate B seemed to rut significantly less after aging compared to unaged samples due to a higher fracture face count.

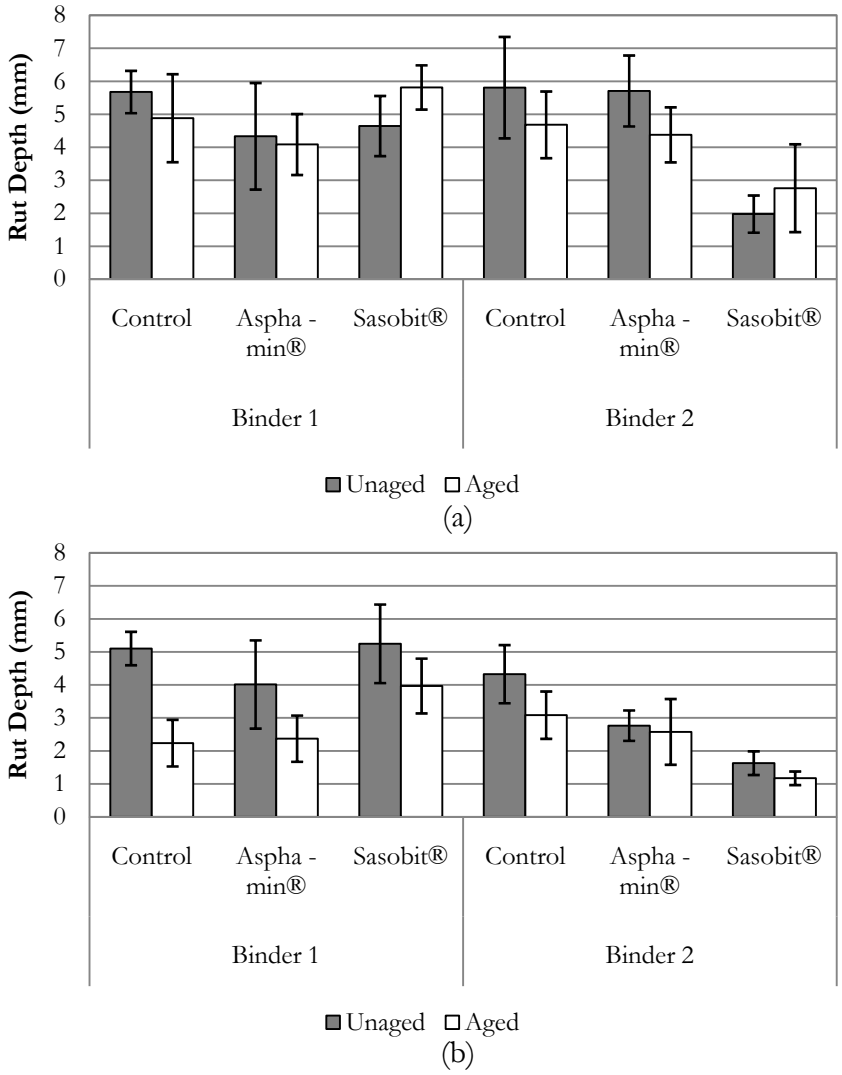

Figure 5-33: Comparison of APA rut depths (after 8050 cycles) of unaged and aged samples: (a) Aggregate A and (b) Aggregate B

5.3 Summary of the Results

In summary, the results of this research indicated that different warm asphalt additives affect the properties of the asphalt binders differently. It was observed in this research that the addition of Sasobit® significantly decreased the viscosity of the binders

used in this study, but the addition of Asphamin® had no significant effect on the viscosities of the binders. In fact, between 60 to 90 minutes after adding the additives, binders containing Asphamin® showed higher viscosities compared to control binders. Even at mid-temperatures, the warm asphalt additives affected the properties of various binders differently, depending on the binder source. In general, it was observed that the addition of the warm asphalt additives increased the complex modulus of the binders at 64 °C (147 °F), and the viscosity at 60 °C (140 °F). The binders containing the warm asphalt additives also had better response to creep and creep recovery tests, as they showed lesser permanent deformation compared to the control binders.

Tests on binders aged in the laboratory and binders extracted from freshly mixed and aged mixtures indicated that the WMA binders extracted from WMA mixtures had significantly lower viscosities and $G^* / \sin \delta$ compared to binders extracted from HMA and binders aged in the RTFO at 163 °C (325 °F), indicating that the lower mixing and compaction temperatures reduce the aging of the binders.

The study on the mixtures indicated that the warm asphalt additives did not have any significant effects on the wet ITS of the mixes, however, the warm asphalt additives improved the TSR of the mixes significantly compared to the control mixes, in case of unaged mixtures. It was also observed that the addition of Asphamin® reduces the M_R values of the mixes significantly, indicating that the mixes containing Asphamin® tend to get softer. When the rut depths were compared, it was observed that the mixes containing Sasobit® had the lowest rut depths, indicating that the mixes containing Sasobit® improve the rutting resistance of the mixes.

When the laboratory oven aged mixes were compared, it was observed that the warm asphalt additives had no significant effects on the M_R values of the aged mixes. However, it was observed that the aged mixes had significantly higher M_R values compared to the unaged mixes, irrespective of the warm asphalt additive. It was also observed that the mixes containing Sasobit® had significantly lower TSR values and rut depths compared to mixes containing Asphamin®; however, mixes containing both the warm asphalt additives were significantly similar to the control mixes.

Chapter VI

6. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Conclusions

Based on this study on three binder, two aggregate sources, and three warm asphalt treatments (control, Asphamin® and Sasobit®), the following can be concluded.

- Asphamin® does not significantly affect the viscosity of the binders at 135 °C (275 °F) and 120 °C (248 °F), however, after 60 to 90 minutes of adding the additive to the binder, the viscosity of the binders is significantly higher than the base binder. This increase in viscosity is attributed to the addition of fine solid material to the binder, which acts like a filler. With time, the increase in the viscosity is more due to the decrease in foaming. Sasobit® significantly lowers the viscosity of the binders at these temperatures. The decrease in the viscosity of the binders is attributed to the dissolution of the wax in the binder, which 'dilutes' the binders.
- The addition of warm asphalt additives significantly increases the viscosities of the binders at 60 °C (140 °F). While the increase in the viscosity due to Asphamin® could be because of the filling effect of the additive, Sasobit® is an aliphatic hydrocarbon which re-crystallizes in the binders at mid-range temperatures, increasing the viscosity and stiffness of the binders.
- The addition of the warm asphalt additives increases the $G^* / \sin \delta$ of certain binders. In this study, while the addition of Asphamin® significantly increased

the G* / sin δ of Binder 2, the addition of Sasobit® significantly increased the G* / sin δ of Binders 2 and 3. Thus, the binder source also has an influence on the properties of the WMA binders.

- In the studied frequency ranges of 0.01 to 100 Hz, Sasobit® increased the stiffness of the binders at 60 °C (140 °F) and at any given frequency. The addition of Asphamin® also increased the stiffness of the binders, but not as much as Sasobit®.
- Binders containing Sasobit® showed lower compliance compared to the base binders which means that they are stiffer and more resistant to deformation at mid-range temperatures. Also, after the stress was removed, the binders with Sasobit® showed lower permanent deformation when compared to the base binders. Binders containing Asphamin® also showed lower compliance values compared to the base binders in most cases, however, no trend was observed regarding the recovery of the binders when the stress was removed.
- The warm asphalt additives did not have any significant effect on the complex modulus, G*, of the binders between 25 °C (77 °F) and 80 °C (176 °F). However, binders with Sasobit® seemed to show lower phase angles compared to the base binders, especially at lower temperatures, which suggests improved elasticity of the binders containing Sasobit® at lower temperatures.
- After RTFO aging, it was observed that reducing the RTFO temperatures significantly reduced the aging index of the binders. Also, it was observed that the binders containing Asphamin® had significantly higher viscosities compared to the unmodified binders, and binders containing Sasobit® had significantly

lower viscosities compared to the unmodified binders after RTFO aging at different temperatures.

- Using FTIR and GPC, it was observed that binders containing the warm asphalt additives did not age significantly compared to control binders and, therefore, the increase in the viscosity of the binders containing Asphamin® after RTFO aging was a result of the subsidence of the foaming effect, and the mineral filling effect of the zeolite.
- For binders containing warm asphalt additives, G*/sin δ values were significantly similar when aged in the RTFO at 163 °C (325 °F) and the lower temperature. However, irrespective of the binder source, it was observed that binders containing the warm asphalt additives had higher rutting parameters (G*/sin δ) compared to unmodified binders, which shows better resistance to rutting.
- The addition of Asphamin® and Sasobit® did not seem to influence the fatigue resistance of the binders as the G*sin δ values for binders with and without the warm asphalt additives were significantly similar. The RTFO temperature also did not have any significant effect on the G*sin δ values of the binders.
- Binders containing Asphamin® and Sasobit® had significantly higher creep stiffness values compared to unmodified binders. The RTFO temperature did not seem to have any significant effect on the stiffness values of the binders.
- Binders containing Sasobit® had significantly lower m-values compared to the unmodified binders. Binders containing Asphamin® had significantly lower m-values compared to unmodified binders only when aged in the RTFO at 163 °C

(325 °F). Thus, it was observed that reducing the aging temperature improves the resistance of the binders to thermal cracking in the presence of Asphamin®.

- While the RTFO aging temperature did not have a significant effect on the stiffness values of the binders, it was observed that the m-values were significantly higher for the binders aged at the lower temperature. This means that a reduction in mixing and compaction temperature of the binders can increase the resistance of the binders to thermal cracking at low temperatures. However, it was observed that the binders containing Sasobit® showed increased tendencies to low temperature cracking as they aged.
- From the DSC heat cycles between -100 °C and 150 °C (-148 and 300 °F), it was observed that binders containing Sasobit® had significantly higher glass transition temperatures, and in binders containing Sasobit® the wax starts melting around 80 °C (176 °F), and completely melts out around 100 °C (212 °F).
- Tests on binders aged in the laboratory and binders extracted from freshly mixed and aged mixtures indicated that the WMA binders extracted from WMA mixtures had significantly lower viscosities and G* / sin δ compared to binders extracted from HMA and binders aged in the RTFO at 163 °C (325 °F), indicating that the lower mixing and compaction temperatures reduce the aging of the binders.
- While Sasobit® had no significant effect on the M_R values of the unaged mixes, unaged mixes containing Asphamin® had significantly lower M_R values compared to the control mixes at 25 and 40 °C (77 and 104 °F). In addition, adding the warm asphalt additives had no significant effect on the M_R values of

aged mixes compared to the unaged control mixes. Also, aged mixes containing warm asphalt additives had significantly higher M_R values compared to the unaged mixes at all testing temperatures. Thus, it could be concluded that the aging of mixes with the warm asphalt additives significantly increased the stiffness of the mixes compared to the control mixes.

- The warm asphalt additives seem to improve the moisture susceptibility of the mixes, as they seem to increase the TSR values of the unaged mixes. After aging, the warm asphalt additives did not significantly reduce the wet ITS of the mixes compared to the aged control mixes. However, it was observed that the aged mixes with Sasobit® had significantly lower TSR values compared to aged mixes with Asphamin®. Also, the warm asphalt additives seemed to affect the TSR of the mixes as they age (unaged versus aged mixes).
- Addition of Sasobit® significantly lowered the rut depths of the unaged and aged mixes compared to the other mixes. Thus, the reduction in the mixing and compaction temperatures does not seem to negatively affect the rutting resistance of the mixtures containing Sasobit®.

6.2 Recommendations for Future Research

Since warm asphalt technology is relatively new, there are still several aspects about the technology that need to be evaluated in great detail before it is implemented. While earlier studies and this study have addressed several aspects of warm mix asphalt binders and mixtures, there are still several unknown parameters. It is recommended that the following topics be investigated to add on to the findings of this research.

- Evaluating the fatigue properties of warm asphalt mixtures.
- Evaluating the performance of warm mix asphalt binders and mixtures modified with polymers like crumb rubber and styrene butadiene styrene (SBS).
- Evaluating the performance of warm mix asphalt containing recycled pavement material and rejuvenating agents.
- Evaluating the performance of SMA and OGFC mixtures containing the warm asphalt additives.
- Life cycle cost analysis of WMA pavements versus HMA pavements.

APPENDICES

Appendix A: Binder Test Results

Table A-1: Viscosity results for unaged Binder 1 at 135 °C

Time (min)	Additive	μ Trial 1 (cP)	μ Trial 2 (cP)	μ Trial 3 (cP)	Mean / *SD (cP)*
-	NIL	435	435	435	**434.17**
		435	432.5	432.5	
		435	435	432.5	*1.25*
30	Asphamin®	435	442.5	442.5	**439.17**
		435	442.5	440	
		432.5	442.5	440	*3.95*
60	Asphamin®	440	427.5	427.5	**431.67**
		440	427.5	427.5	
		440	427.5	427.5	*6.25*
90	Asphamin®	485	442.5	457.5	**461.11**
		485	442.5	455	
		485	442.5	455	*18.84*
30	Sasobit®	370	400	377.5	**382.22**
		370	400	377.5	
		370	397.5	377.5	*13.14*
60	Sasobit®	372.5	397.5	377.5	**382.50**
		372.5	397.5	377.5	
		372.5	397.5	377.5	*11.46*
90	Sasobit®	382.5	397.5	372.5	**384.17**
		382.5	397.5	372.5	
		382.5	**397.5**	**372.5**	***10.90***

Note: 'NIL': No warm asphalt additive
'SD': Standard Deviation

Table A-2: Viscosity results of unaged Binder 1 at 120 °C

Time (min)	Additive	μ Trial 1 (cP)	μ Trial 2 (cP)	μ Trial 3 (cP)	Mean / *SD (cP)*
-	NIL	982.5	980	980	**981.11**
		982.5	980	980	
		982.5	982.5	980	*1.32*
30	Asphamin®	997	1002	1053	**1016.22**
		995	1002	1050	
		997	1000	1050	*26.20*
60	Asphamin®	987.5	987.5	1010	**995.00**
		987.5	987.5	1010	
		987.5	987.5	1010	*11.25*
90	Asphamin®	1008	995	1035	**1012.67**
		1008	995	1035	
		1008	995	1035	*17.67*
30	Sasobit®	825	820	830	**825.00**
		825	820	832.5	
		825	822.5	825	*4.15*
60	Sasobit®	820	817.5	820	**819.17**
		820	817.5	820	
		820	817.5	820	*1.25*
90	Sasobit®	827.5	835	832.5	**831.39**
		827.5	835	832.5	
		827.5	835	830	*3.33*

Note: 'NIL': No warm asphalt additive
'SD': Standard Deviation

Table A-3: Viscosity results for unaged Binder 2 at 135 °C

Time (min)	Additive	μ Trial 1 (cP)	μ Trial 2 (cP)	μ Trial 3 (cP)	Mean / *SD (cP)*
-	NIL	642.5	647.5	660	**649.44**
		642.5	647.5	657.5	
		642.5	647.5	657.5	*7.05*
30	Asphamin®	657.5	695	680	**678.06**
		655	695	680	
		665	695	680	*15.80*
60	Asphamin®	665	667.5	670	**667.50**
		665	667.5	670	
		665	667.5	670	*2.17*
90	Asphamin®	682.5	680	697.5	**686.39**
		685	680	697.5	
		682.5	677.5	695	*8.01*
30	Sasobit®	600	587.5	587.5	**592.22**
		600	590	587.5	
		600	590	587.5	*5.92*
60	Sasobit®	582.5	587.5	600	**590.00**
		582.5	587.5	600	
		582.5	587.5	600	*7.81*
90	Sasobit®	585	605	605	**598.33**
		585	605	605	
		585	605	605	*10.00*

Note: 'NIL': No warm asphalt additive
'SD': Standard Deviation

Table A-4: Viscosity results of unaged Binder 2 at 120 °C

Time (min)	Additive	µ Trial 1 (cP)	µ Trial 2 (cP)	µ Trial 3 (cP)	Mean / *SD (cP)*
-	NIL	1575	1567	1567	**1570.33**
		1575	1567	1570	
		1575	1570	1567	*3.71*
30	Asphamin®	1667	1630	1685	**1658.44**
		1663	1628	1685	
		1660	1625	1683	*24.91*
60	Asphamin®	1663	1602	1655	**1640.33**
		1660	1605	1658	
		1660	1602	1658	*28.09*
90	Asphamin®	1750	1700	1747	**1732.22**
		1750	1700	1747	
		1747	1702	1747	*23.71*
30	Sasobit®	1305	1258	1258	**1273.89**
		1305	1260	1258	
		1305	1258	1258	*23.34*
60	Sasobit®	1283	1268	1275	**1275.11**
		1283	1268	1275	
		1283	1268	1273	*6.55*
90	Sasobit®	1313	1275	1278	**1289.33**
		1315	1275	1280	
		1313	1275	1280	*18.36*

Note: 'NIL': No warm asphalt additive
'SD': Standard Deviation

Table A-5: Viscosity results for unaged Binder 3 at 135 °C

Time (min)	Additive	μ Trial 1 (cP)	μ Trial 2 (cP)	μ Trial 3 (cP)	Mean / *SD (cP)*
-	NIL	417.5	422.5	420	**420.00**
		417.5	422.5	420	
		417.5	422.5	420	*2.17*
30	Asphamin®	415	415	415	**414.72**
		415	415	415	
		415	415	412.5	*0.83*
60	Asphamin®	430	432.5	430	**429.72**
		430	427.5	430	
		430	430	427.5	*1.50*
90	Asphamin®	435	432.5	432.5	**433.06**
		435	432.5	432.5	
		435	432.5	430	*1.67*
30	Sasobit®	360	360	360	**360.00**
		360	360	360	
		360	360	360	*0.00*
60	Sasobit®	362.5	362.5	362.5	**362.22**
		362.5	362.5	362.5	
		362.5	362.5	360	*0.83*
90	Sasobit®	365	365	367.5	**365.83**
		365	365	367.5	
		365	367.5	365	*1.25*

Note: 'NIL': No warm asphalt additive
'SD': Standard Deviation

Table A-6: Viscosity results of unaged Binder 2 at 120 °C

Time (min)	Additive	μ Trial 1 (cP)	μ Trial 2 (cP)	μ Trial 3 (cP)	Mean / *SD (cP)*
-	NIL	937.5	937.5	935	**936.11**
		935	937.5	935	
		935	937.5	935	*1.32*
30	Asphamin®	960	960	957.5	**957.50**
		957.5	957.5	955	
		957.5	957.5	955	*1.77*
60	Asphamin®	977.5	977.5	977.5	**977.78**
		980	977.5	977.5	
		980	977.5	975	*1.50*
90	Asphamin®	1002	1000	1000	**1000.44**
		1000	1000	1002	
		1000	1000	1000	*0.88*
30	Sasobit®	840	842.5	845	**842.78**
		840	842.5	845	
		842.5	842.5	845	*1.95*
60	Sasobit®	855	855	857.5	**856.39**
		855	857.5	857.5	
		855	857.5	857.5	*1.32*
90	Sasobit®	855	855	855	**855.83**
		855	855	857.5	
		855	857.5	857.5	*1.25*

Note: 'NIL': No warm asphalt additive
'SD': Standard Deviation

Table A-7: G*/ sin δ values of the unaged binders with and without the warm asphalt additives

Additive	Binder	G*/ sin δ @ 64 °C (MPa)			
		Trial 1	Trial 2	Mean	SD
-	1	1555	1855	**1705**	*212.13*
-	2	1895	1876	**1885.5**	*13.44*
-	3	1190	1150	**1170**	*28.28*
Asphamin®	1	1632	1554	**1593**	*55.15*
Asphamin®	2	2946	2862	**2904**	*59.40*
Asphamin®	3	1250	1260	**1255**	*7.07*
Sasobit®	1	2011	2174	**2092.5**	*115.26*
Sasobit®	2	2862	2929	**2895.5**	*47.38*
Sasobit®	3	1830	1900	**1865**	*49.50*

Table A-8: Results of tests on RTFO / PAV aged binder

RTFO @ 163 °C										
	#	Binder 1	Binder 1 + a	Binder 1 + s	Binder 2	Binder 2 + a	Binder 2 + s	Binder 3	Binder 3 + a	Binder 3 + s
G*/sinδ	**1**	3250	3880	4300	5950	7290	9310	3730	3510	4050
	2	3300	3710	4630	5790	7130	8330	3830	3160	3880
	μ	**3275**	**3795**	**4465**	**5870**	**7210**	**8820**	**3780**	**3335**	**3965**
	σ	*35*	*120*	*233*	*113*	*113*	*693*	*71*	*247*	*120*
G*sinδ (x1000)	**1**	2080	2830	3090	1850	2150	4290	1460	1020	2090
	2	2890	2880	3540	1350	1800	3880	1940	1970	1790
	μ	**2485**	**2855**	**3315**	**1600**	**1975**	**4085**	**1700**	**1495**	**1940**
	σ	*573*	*35*	*318*	*354*	*247*	*290*	*339*	*672*	*212*
Stiffness	**1**	244	247	250	146	189	188	114	128	138
	2	216	246	243	148	178	161	116	122	149
	3	204	238	241	161	187		120	125	147
	μ	**221.3**	**243.7**	**244.7**	**151.7**	**184.7**	**174.5**	**116.7**	**125.0**	**144.7**
	σ	*20.53*	*4.93*	*4.73*	*8.14*	*5.86*	*19.09*	*3.06*	*3.00*	*5.86*
m-Value	**1**	0.331	0.301	0.274	0.344	0.347	0.32	0.326	0.308	0.274
	2	0.306	0.295	0.277	0.345	0.353	0.328	0.317	0.306	0.275
	3	0.305	0.301	0.282	0.351	0.354		0.316	0.306	0.278
	μ	**0.314**	**0.299**	**0.278**	**0.347**	**0.351**	**0.324**	**0.320**	**0.307**	**0.276**
	σ	*0.015*	*0.003*	*0.004*	*0.004*	*0.004*	*0.006*	*0.006*	*0.001*	*0.002*
Viscosity (After RTFO)	**1**	715	875	647.5	1313	1424	1162	745	706	543
	2	745	822.5	662.5	1400	1446	1237	750	705	550
	3	760	875	677.5	-	1527	-	-	723	555
	μ	**740**	**857.5**	**662.5**	**1356**	**1465**	**1199**	**747.5**	**711.5**	**549.2**
	σ	*22.91*	*30.31*	*15.00*	*61.75*	*54.31*	*53.03*	*3.54*	*10.25*	*6.29*

Note: 'a' : Asphamin®
's' : Sasobit®

Table A-9: Results of tests on RTFO / PAV aged binder

RTFO @ 130 / 140°C										
	#	Binder 1	Binder 1 + a	Binder 1 + s	Binder 2	Binder 2 + a	Binder 2 + s	Binder 3	Binder 3 + a	Binder 3 + s
G*/sinδ	**1**	1990	2080	2550	3400	5190	4450	1430	1760	2200
	2	1900	2290	2510	3400	4300	4710	1460	1710	2110
	μ	**1945**	**2185**	**2530**	**3400**	**4745**	**4580**	**1445**	**1735**	**2155**
	σ	*64*	*148*	*28*	*0*	*629*	*184*	*21*	*35*	*64*
G*sinδ (x1000)	**1**	3580	1860	3060	2140	2500	2450	1420	1260	1120
	2	2980	2280	3340	2120	1940	2560	1130	960	920
	μ	**3280**	**2070**	**3200**	**2130**	**2220**	**2505**	**1275**	**1110**	**1020**
	σ	*424*	*297*	*198*	*14*	*396*	*78*	*205*	*212*	*141*
Stiffness	**1**	175	204	224	147	166	171	108	117	132
	2	187	216	225	145	166	173	109	126	132
	3	-	-	-	155	155	177	107	131	131
	μ	**181**	**210**	**224.5**	**149**	**162.3**	**173.7**	**108**	**124.7**	**131.7**
	σ	*8.49*	*8.49*	*0.71*	*5.29*	*6.35*	*3.06*	*1*	*7.1*	*0.56*
m-Value	**1**	0.319	0.330	0.298	0.381	0.362	0.329	0.332	0.321	0.287
	2	0.331	0.321	0.291	0.382	0.375	0.322	0.328	0.319	0.291
	3	-	-	-	0.378	0.380	0.325	0.322	0.323	0.290
	μ	**0.325**	**0.326**	**0.295**	**0.380**	**0.372**	**0.325**	**0.327**	**0.321**	**0.289**
	σ	*0.008*	*0.006*	*0.005*	*0.002*	*0.009*	*0.004*	*0.005*	*0.002*	*0.002*
Viscosity (After RTFO)	**1**	533	570	473	885	1053	791	480	525	499
	2	532	566	475	895	1063	806	486	529	485
	3	530	586	480	919	1097	827	490	538	483
	μ	**528**	**574**	**476**	**900**	**1071**	**808**	**485**	**531**	**489**
	σ	*4.88*	*10.55*	*3.82*	*17.56*	*23.07*	*18.17*	*5.02*	*6.37*	*9*

Note: 'a' : Asphamin®
's' : Sasobit®

Table A-10: Results of tests on extracted binders

		Binder 1	Binder 1+a	Binder 1+s	Binder 2	Binder 2+a	Binder 2+s
G*/sinδ	**1**	4780	3430	3340	7000	6310	6000
	2	4580	3340	3310	6850	6180	6450
	μ	**4680**	**3385**	**3325**	**6925**	**6245**	**6225**
	σ	*141*	*64*	*21*	*106*	*92*	*318*
G*sinδ (x1000)	**1**	2420	1150	1460	2000	1980	1340
	2	1130	1280	1890	1730	1440	1320
	μ	**1775**	**1215**	**1675**	**1865**	**1710**	**1330**
	σ	*912*	*91*	*304*	*190*	*381*	*14*
Stiffness	**1**	172	-	159	127	117	126
	2	184	149	146	130	122	128
	3	187	141	171	134	128	128
	μ	**181.00**	**145.00**	**158.67**	**130.33**	**122.33**	**127.33**
	σ	*7.93*	*5.65*	*12.50*	*3.51*	*5.50*	*1.15*
m-Value	**1**	0.34	-	0.34	0.381	0.404	0.375
	2	0.345	0.378	0.338	0.377	0.4	0.383
	3	0.342	0.375	0.345	0.372	0.392	0.379
	μ	**0.342**	**0.377**	**0.341**	**0.377**	**0.399**	**0.379**
	σ	*0.003*	*0.002*	*0.004*	*0.005*	*0.006*	*0.004*
Viscosity (After Short term aging)	**1**	742	630	575	1237	1138	1063
	2	748	643	578	1245	1150	1084
	3	748	630	578	1242	1163	1094
	μ	**746**	**634**	**576**	**1241**	**1150**	**1080**
	σ	*3.36*	*7.21*	*1.92*	*4.35*	*12.50*	*15.82*

Note: 'a' : Asphamin®
's' : Sasobit®

Table A-11: FTIR peaks for binders with and without the warm asphalt additives at 1030 cm^{-1}

Sample			Run 1			Run 2			Run 3		
			Base Line Value	Peak Value	Net Peak Value	Base Line Value	Peak Value	Net Peak Value	Base Line Value	Peak Value	Net Peak Value
Original Binder	Binder 1	-	.005	.020	**.015**	.010	.021	**.011**	.009	.021	**.012**
		a	.005	.027	**.022**	.004	.030	**.026**	.005	.029	**.024**
		s	.005	.015	**.010**	.006	.017	**.011**	.013	.023	**.010**
	Binder 2	-	.006	.017	**.011**	.005	.017	**.012**	.008	.016	**.008**
		a	.005	.023	**.018**	.007	.026	**.019**	.009	.024	**.015**
		s	.008	.020	**.012**	.012	.022	**.010**	.006	.016	**.010**
	Binder 3	-	.005	.011	**.006**	.009	.016	**.007**	.015	.020	**.005**
		a	.003	.010	**.007**	.017	.026	**.009**	.016	.030	**.014**
		s	.006	.010	**.004**	.011	.016	**.005**	.015	.020	**.005**
RTFO Aged Binder	Binder 1	-	.006	.016	**.010**	.017	.028	**.011**	.013	.024	**.011**
		a	.014	.041	**.027**	.006	.024	**.018**	.005	.031	**.026**
		s	.000	.010	**.010**	.010	.021	**.011**	.024	.034	**.010**
	Binder 2	-	.003	.019	**.016**	.008	.026	**.018**	.008	.023	**.015**
		a	.007	.026	**.019**	.007	.027	**.020**	.012	.039	**.027**
		s	.006	.015	**.009**	.019	.029	**.010**	.006	.016	**.010**
	Binder 3	-	.004	.011	**.007**	.008	.015	**.007**	.012	.018	**.006**
		a	.004	.014	**.010**	.012	.029	**.017**	.011	.023	**.012**
		s	.010	.014	**.004**	.009	.014	**.005**	.014	.020	**.006**
PAV Aged Binder	Binder 1	-	.007	.024	**.017**	.017	.034	**.017**	.013	.030	**.017**
		a	.009	.037	**.028**	.012	.027	**.015**	.006	.029	**.023**
		s	.004	.021	**.017**	.014	.031	**.017**	.012	.027	**.015**
	Binder 2	-	.007	.025	**.018**	.006	.025	**.019**	.020	.037	**.017**
		a	.004	.032	**.028**	.006	.032	**.026**	.009	.037	**.028**
		s	.004	.020	**.016**	.007	.025	**.018**	.008	.023	**.015**
	Binder 3	-	.006	.014	**.008**	.015	.022	**.007**	.016	.023	**.007**
		a	.005	.020	**.015**	.010	.022	**.012**	.007	.027	**.020**
		s	.011	.018	**.007**	.008	.019	**.011**	.016	.023	**.007**

Note: '-': No warm asphalt additive
'a' : Asphamin®
's' : Sasobit®

Table A-12: FTIR peaks for binders with and without the warm asphalt additives at 1700 cm^{-1}

Sample			Run 1			Run 2			Run 3		
			Base Line Value	Peak Value	Net Peak Value	Base Line Value	Peak Value	Net Peak Value	Base Line Value	Peak Value	Net Peak Value
Original Binder	Binder 1	-	.004	.011	**.007**	.002	.007	**.005**	.005	.011	**.006**
		a	-.003	.004	**.007**	.000	.006	**.006**	.002	.009	**.007**
		s	.002	.007	**.005**	.000	.005	**.005**	.002	.008	**.006**
	Binder 2	-	.001	.008	**.007**	.000	.008	**.008**	.001	.007	**.006**
		a	-.003	.005	**.008**	.000	.009	**.009**	-.003	.006	**.009**
		s	-.003	.005	**.008**	.000	.008	**.008**	.000	.006	**.006**
	Binder 3	-	-.003	.005	**.008**	.004	.013	**.009**	.003	.012	**.009**
		a	-.001	.007	**.008**	.004	.013	**.009**	.002	.011	**.009**
		s	-.005	.004	**.009**	.008	.016	**.008**	.004	.012	**.008**
RTFO Aged Binder	Binder 1	-	-.002	.006	**.008**	.010	.018	**.008**	.005	.013	**.008**
		a	.000	.008	**.008**	-.001	.008	**.009**	.002	.010	**.008**
		s	-.002	.004	**.006**	.005	.012	**.007**	.010	.019	**.009**
	Binder 2	-	.002	.014	**.012**	.001	.016	**.015**	.001	.015	**.014**
		a	.002	.013	**.011**	.001	.010	**.009**	.002	.015	**.013**
		s	.002	.010	**.008**	.006	.017	**.011**	.001	.011	**.010**
	Binder 3	-	-.002	.009	**.011**	.006	.016	**.010**	.003	.014	**.011**
		a	.000	.012	**.012**	.005	.016	**.011**	.007	.018	**.011**
		s	-.002	.009	**.011**	.002	.013	**.011**	.008	.018	**.010**
PAV Aged Binder	Binder 1	-	.000	.014	**.014**	.006	.020	**.014**	.006	.019	**.013**
		a	.002	.015	**.013**	.004	.013	**.009**	.004	.015	**.011**
		s	.000	.012	**.012**	.005	.017	**.012**	.005	.017	**.012**
	Binder 2	-	-.002	.013	**.015**	.003	.017	**.014**	.005	.020	**.015**
		a	.000	.014	**.014**	.002	.015	**.013**	.002	.017	**.015**
		s	-.001	.013	**.014**	.001	.017	**.016**	.008	.021	**.013**
	Binder 3	-	-.001	.018	**.019**	.003	.021	**.018**	.004	.022	**.018**
		a	-.003	.015	**.018**	.001	.019	**.018**	.002	.020	**.018**
		s	.001	.019	**.018**	.001	.018	**.017**	.012	.028	**.016**

Note: '-': No warm asphalt additive
'a' : Asphamin®
's' : Sasobit®

Table A-13: Gel permeation chromatography results (%LMS) for aged binders

	Binder	Additive	LMS 1	LMS 2	LMS 3	Mean	*SD*
RTFO @ 163 °C	1	-	14.44	16.38	16.02	**15.61**	*1.032*
		a	8.43	9.81	10.24	**9.49**	*0.946*
		s	11.94	11.17	13.15	**12.09**	*0.998*
	2	-	16.69	15.81	16.13	**16.21**	*0.445*
		a	17.45	14.18	16.92	**16.18**	*1.755*
		s	16.12	17.71	15.23	**16.35**	*1.256*
RTFO @ 130/140 °C	1	-	10.86	15.53	14.81	**13.73**	*2.514*
		a	9.75	9.54	12.64	**10.64**	*1.732*
		s	16.76	15.16	16.66	**16.19**	*0.896*
	2	-	12.64	13.67	15.11	**13.81**	*1.241*
		a	13.39	13.53	9.32	**12.08**	*2.391*
		s	13.94	14.03	12.06	**13.34**	*1.112*
Extracted Binder	1	-	8.43	14.66	12.76	**11.95**	*3.193*
		a	15.86	13.5	11.46	**13.61**	*2.202*
		s	13.64	16.33	12.13	**14.03**	*2.127*
	2	-	14.07	14.8	12.62	**13.83**	*1.110*
		a	15.25	15.68	11.72	**14.22**	*2.173*
		s	14	11.86	14.29	**13.38**	*1.327*
PAV (RTFO @ 163 °C)	1	-	15.76	13.84	15.12	**14.91**	*0.978*
		a	13.06	13.89	12.11	**13.02**	*0.891*
		s	11	13.24	13.23	**12.49**	*1.290*
	2	-	17.67	16.21	16.43	**16.77**	*0.787*
		a	16.49	13.59	17.12	**15.73**	*1.883*
		s	18.67	14.96	17.11	**16.91**	*1.863*
PAV (RTFO @ 130/140 °C)	1	-	13.28	13.72	14.66	**13.89**	*0.705*
		a	15.28	12.74	10.12	**12.71**	*2.580*
		s	14.52	15.97	16.93	**15.81**	*1.213*
	2	-	14.93	13.94	13.37	**14.08**	*0.789*
		a	11.85	14.05	12.78	**12.89**	*1.104*
		s	14.32	15.17	12.35	**13.95**	*1.447*
Extracted Binder	1	-	13.81	11.51	11.01	**12.11**	*1.493*
		a	16.67	11.11	14	**13.93**	*2.781*
		s	14.47	14.85	13.76	**14.36**	*0.553*
	2	-	13.23	15.78	15.21	**14.74**	*1.338*
		a	14.66	17.17	15.66	**15.83**	*1.264*
		s	14.52	15.16	14.6	**14.76**	*0.349*

Note: '-': No warm asphalt additive
'a' : Asphamin®
's' : Sasobit®
'SD': Standard Deviation

Table A-14: Glass transition temperatures of binders with and without warm asphalt additives

Sample		Tg 1 (°C)	Tg 2 (°C)	Mean (°C)	*SD (°C)*
Binder 1	-	10.27	9.18	**9.73**	*0.771*
	a	10.85	10.11	**10.48**	*0.523*
	s	13.68	13.23	**13.46**	*0.318*
Binder 2	-	16.32	16.75	**16.54**	*0.304*
	a	16.01	16.53	**16.27**	*0.368*
	s	20.54	21.12	**20.83**	*0.410*
Binder 3	-	3.11	3.17	**3.14**	*0.042*
	a	3.26	3.75	**3.51**	*0.346*
	s	4.53	4.53	**4.53**	*0.000*

Note: '-': No warm asphalt additive
'a' : Asphamin®
's' : Sasobit®
'SD': Standard Deviation

Appendix B: Mixture Test Results

In this study, each of the mixes was given a unique code containing 3 parts. The first part is the aggregate (A or B); the second part represents the binder source; (I or II), and the third part represents the warm asphalt additive (C for control, a or s). For example, AIIs denotes a mixture prepared with aggregate A, binder II, and Sasobit® as the warm asphalt additive.

Table B-1: Mix design results for control mixes

Mix Name	Optimum AC (%)	VMA (%)	VFA (%)
AIC	5.8	17.5	76
AIIC	5.8	17.3	77
BIC	4.6	15.1	74
BIIC	4.6	15.0	73

Note: Based on NCAT recommendations, these mix design results were used for warm asphalt mixes also.

Table B-2: Indirect tensile strengths of mixes

	Mix	Dry Strength		Mean	SD	Wet Strength		Mean	SD	TSR
Unaged Samples	AIC	133	109	**120.8**	*17.27*	121	116	**118.4**	*3.61*	**98.0**
	AIIC	105	115	**110.0**	*6.49*	105	103	**104.0**	*2.04*	**94.6**
	AIa	109	122	**115.7**	*9.56*	120	134	**127.3**	*9.69*	**110.0**
	AIIa	111	123	**117.1**	*8.25*	120	101	**110.9**	*13.44*	**94.7**
	AIs	96	82	**89.1**	*9.47*	102	107	**104.9**	*3.66*	**117.7**
	AIIs	104	98	**100.7**	*4.33*	107	107	**106.5**	*0.00*	**105.8**
	BIC	130	139	**134.6**	*5.86*	136	128	**132.2**	*5.77*	**98.2**
	BIIC	131	128	**129.7**	*1.71*	102	110	**105.7**	*5.59*	**81.5**
	BIa	111	113	**111.7**	*1.49*	116	116	**116.2**	*0.04*	**104.0**
	BIIa	109	101	**105.2**	*5.95*	105	108	**106.6**	*2.26*	**101.3**
	BIs	103	114	**108.6**	*7.93*	125	118	**121.2**	*5.14*	**111.6**
	BIIs	120	123	**121.6**	*2.07*	118	117	**117.3**	*0.45*	**96.4**
Aged Samples	AIC	131	128	**129.3**	*2.35*	122	114	**117.9**	*5.23*	**91.1**
	AIIC	141	142	**141.9**	*0.72*	109	114	**111.5**	*3.56*	**78.5**
	AIa	140	128	**133.9**	*8.44*	133	132	**132.5**	*0.09*	**98.9**
	AIIa	141	135	**138.0**	*4.78*	122	133	**127.4**	*7.30*	**92.3**
	AIs	141	150	**145.9**	*6.41*	108	105	**106.4**	*1.98*	**72.9**
	AIIs	143	148	**145.1**	*3.47*	116	108	**112.1**	*6.05*	**77.2**
	BIC	191	174	**182.7**	*11.81*	165	177	**171.2**	*8.25*	**93.7**
	BIIC	153	138	**145.3**	*10.95*	119	129	**123.9**	*7.48*	**85.3**
	BIa	155	128	**141.6**	*19.44*	135	141	**137.9**	*4.29*	**97.4**
	BIIa	150	114	**132.1**	*25.39*	135	129	**132.0**	*4.29*	**100.0**
	BIs	156	146	**150.5**	*7.08*	136	150	**143.3**	*9.61*	**95.2**
	BIIs	160	157	**158.3**	*1.90*	149	148	**148.7**	*1.03*	**93.9**

Table B-3: Resilient modulus of mixes containing Aggregate A (@ 5 °C)

	Sample	AIC	AIIC	AIa	AIIa	AIs	AIIs
Unaged Samples	MR @ 5 °C	24181	21250	23894	18015	34258	27854
		22541	27214	22221	32686	30908	25260
		22758	24494	24104	17653	34581	23785
		24782	22782	24242	18279	34532	28122
		26470	30392	22652	32884	31691	26316
		24393	22358	24474	18577	34617	23633
		-	22996	26090	19054	34916	27369
		-	12845	26045	19287	31273	23538
		-	25235	25432	18486	33702	24730
		-	23099	25292	18350	34259	27118
		-	14437	-	-	31665	-
		-	24195	-	-	33949	-
	Mean	**24187.5**	**22608.1**	**24444.6**	**21327.1**	**33362.6**	**25772.5**
	SD	*1439.44*	*4854.17*	*1315.74*	*6056.89*	*1506.67*	*1806.7*
Aged Samples	**Sample**	**AIC**	**AIIC**	**AIa**	**AIIa**	**AIs**	**AIIs**
	MR @ 5 °C	22373	35854	29632	33250	40454	31937
		25603	30256	31591	38133	37383	33082
		19944	43419	31379	34456	37602	33513
		23117	35177	28390	35666	39971	32284
		25860	29921	32639	38504	37899	32874
		21407	39943	32885	34110	37502	32999
		19598	39393	29553	32115	40399	33395
		25017	28461	31438	35042	38669	32851
		21967	37504	-	33066	37529	-
		20738	27574	-	32056	40617	-
		26276	-	-	36568	38965	-
		22405	-	-	34026	36751	-
	Mean	**22858.8**	**34750.2**	**30938.4**	**34749.3**	**38645.1**	**32866.9**
	SD	*2333.77*	*5448.99*	*1588.86*	*2133.58*	*1397.24*	*529.804*

Table B-4: Resilient modulus of mixes containing Aggregate B (@ 5 °C)

	Sample	BIC	BIIC	BIa	BIIa	BIs	BIIs
Unaged Samples	MR @5 °C	51638	31824	36276	36509	38714	46649
		45388	35524	33762	30997	34602	42311
		48880	31642	35166	36541	33060	43740
		44916	36357	35377	30633	37967	44785
		45982	34295	30971	38244	34002	42941
		41751	31312	36626	30196	31752	43252
		61113	36715	34684	29215	38825	42401
		46419	34102	32538	37446	36088	43025
		41649	-	32615	-	32467	-
		65404	-	35539	-	37092	-
		-	-	32627	-	35722	-
		-	-	35188	-	33420	-
	Mean	**49314**	**33971**	**34281**	**33723**	**35309**	**43638**
	SD	*7985*	*2167*	*1753*	*3775*	*2460*	*1449*
Aged Samples	**Sample**	**BIC**	**BIIC**	**BIa**	**BIIa**	**BIs**	**BIIs**
	MR @ 5 °C	53021	42793	50038	41622	55163	44867
		54333	42906	54433	42277	48727	46848
		50523	31412	48664	41042	52735	46090
		52462	43009	47682	38134	53063	44976
		51694	41037	41752	42687	47650	44084
		54706	32685	50277	41375	51341	47221
		53951	40953	48899	51357	53819	49346
		52326	37910	59935	40264	46647	44577
		-	33040	51404	39642	52533	-
		-	32958	-	48273	53420	-
		-	-	-	43227	46990	-
		-	-	-	54554	50422	-
	Mean	**52877**	**37870**	**50343**	**43705**	**51043**	**46001**
	SD	*1417*	*4849*	*4947*	*5015*	*2901*	*1750*

Table B-5: Resilient modulus of mixes containing Aggregate A (@ 25 °C)

	Sample	AIC	AIIC	AIa	AIIa	AIs	AIIs
Unaged Samples	MR @ 25 °C	9217	9486	8668	6485	7880	8553
		10362	12045	12807	9019	8078	13224
		9828	8865	9494	6574	10392	7707
		10071	9447	8427	6632	7378	7972
		9004	13515	12334	9314	7790	12986
		9505	8533	9028	6683	9308	7254
		7793	8676	8731	6378	7329	7567
		8741	10372	8305	6056	7349	11522
		-	8380	9903	5880	8903	7753
		-	8627	9899	5864	7104	7966
		-	10002	-	-	8183	11665
		-	7815	-	-	8783	7301
	Mean	**9315.1**	**9646.9**	**9759.6**	**6888.5**	**8206.4**	**9289.2**
	SD	*821.1*	*1658*	*1588*	*1239*	*977.5*	*2330*
Aged Samples	**Sample**	**AIC**	**AIIC**	**AIa**	**AIIa**	**AIs**	**AIIs**
	MR @ 25 °C	16914	12168	10400	9902	13022	11478
		8779	9069	10720	11259	12063	11501
		9038	13787	10745	8704	12136	11968
		15783	12915	10933	10712	12434	11956
		8605	8655	10634	11505	11255	11871
		8801	14684	11275	9439	12147	12027
		8384	9873	10855	11012	12339	10633
		9195	9937	10650	10615	12145	11641
		-	9579	-	9465	12638	-
		-	9260	-	10916	11887	-
		-	-	-	11290	12099	-
		-	-	-	9375	11367	-
	Mean	**10687**	**10993**	**10777**	**10350**	**12128**	**11634**
	SD	*3516*	*2187*	*256.7*	*928.2*	*486.4*	*458.2*

Table B-6: Resilient modulus of mixes containing Aggregate B (@ 25 °C)

	Sample	BIC	BIIC	BIa	BIIa	BIs	BIIs
Unaged Samples	MR @ 25 °C	17056	13322	10592	9593	13350	11416
		14382	12209	10225	8088	13684	11403
		14640	17725	11634	13877	13325	11813
		15807	13154	11055	7259	13255	11238
		14767	12006	9467	13683	13843	11310
		15784	18347	11194	7336	13881	11601
		16010	12730	10956	7694	12147	11232
		14797	11630	9477	16676	12398	12033
		14621	11832	11609	-	11894	-
		15696	12058	10733	-	12821	-
		14690	-	10200	-	13769	-
		16860	-	11266	-	12694	-
	Mean	**15426**	**13501**	**10700.7**	**10525.8**	**13088.4**	**11505.8**
	SD	*910.9*	*2457*	*736.02*	*3678.2*	*686.51*	*289.09*
	Sample	**BIC'**	**BIIC'**	**BIa'**	**BIIa'**	**BIs'**	**BIIs'**
Aged Samples	MR @ 25 °C	18245	15827	15747	14168	18768	16829
		21740	17550	14828	15195	16978	20055
		18642	12382	15717	14403	19603	19746
		21377	12364	15661	13391	19000	17474
		17468	16910	15812	14784	16592	18893
		20645	11881	15359	14618	18959	16606
		21517	17375	14619	13710	18241	13434
		18240	15886	15534	14787	16427	-
		-	13078	-	14534	19254	-
		-	15893	-	13906	18430	-
		-	-	-	15238	16311	-
		-	-	-	14764	18410	-
	Mean	**19734**	**14914.6**	**15409.6**	**14458.2**	**18081.1**	**17576.7**
	SD	*1753*	*2241.3*	*449.57*	*570.56*	*1180.8*	*2282.3*

Table B-7: Resilient modulus of mixes containing Aggregate A (@ 40 °C)

	Sample	AIC	AIIC	AIa	AIIa	AIs	AIIs
Unaged Samples	MR @ 40 °C	1823	3621	1865	2631	1939	2700
		1893	4429	3327	2591	2570	2890
		1991	3767	2524	1838	2337	2743
		6515	3579	1861	2861	1844	3493
		3634	4149	3107	2492	2812	2124
		2208	3878	3655	1845	2036	2838
		2469	3443	1805	3499	2509	2160
		2611	3327	1687	3338	2089	2109
		-	2879	2206	1837	2421	2855
		-	3145	3044	3264	4021	3954
		-	3178	-	1733	-	-
		-	2742	-	0	-	-
	Mean	**2893**	**3511.42**	**2508.1**	**2539**	**2457.8**	**2786.6**
	SD	*1574.6*	*499.17*	*724.51*	*657.13*	*628.94*	*594.42*
Aged Samples	**Sample**	**AIC**	**AIIC**	**AIa**	**AIIa**	**AIs**	**AIIs**
	MR @ 40 °C	3579	2459	3504	3049	3668	3609
		3474	3465	2883	3333	3384	3423
		3423	2524	5533	2943	3732	3539
		-	3656	3304	2935	3655	3479
		-	2319	3831	3551	3660	3894
		-	3353	3023	2727	3893	3446
		-	2250	3501	3054	3752	3424
		-	3614	2488	3382	3574	3707
		-	3595	-	2668	3667	-
		-	3442	-	2977	3820	-
		-	-	-	3445	3689	-
		-	-	-	2607	3670	-
	Mean	**3492**	**3067.7**	**3508.38**	**3055.92**	**3680.33**	**3565.13**
	SD	*79.542*	*596.03*	*919.07*	*312.39*	*125.49*	*165.88*

Table B-8: Resilient modulus of mixes containing Aggregate B (@ 40 °C)

	Sample	BIC	BIIC	BIa	BIIa	BIs	BIIs
Unaged Samples	MR @ 40 °C	5903	4895	3135	2554	4417	3919
		4486	4337	5000	2731	4856	3147
		6116	4901	3654	2857	4892	4225
		4695	4446	3193	2875	4509	3266
		5459	4607	3478	2706	4751	3679
		5155	4470	3418	2410	5139	3846
		5209	5480	3305	2797	4532	3321
		5686	4829	3478	2632	4300	3894
		5224	4633	2642	-	4632	-
		4781	5853	2801	-	3981	-
		-	-	3521	-	4465	-
		-	-	-	-	-	-
	Mean	**5271.4**	**4845.1**	**3420.5**	**2695.3**	**4588.5**	**3662.1**
	SD	*530.1*	*481.3*	*608.5*	*158.4*	*316.5*	*379.7*
Aged Samples	**Sample**	**BIC**	**BIIC**	**BIa**	**BIIa**	**BIs**	**BIIs**
	MR @ 40 °C	7474	7003	5814	4596	5735	7949
		7946	6122	5520	5712	6560	8288
		6838	4439	5443	5138	7205	6369
		8298	6673	5870	4775	6226	7026
		7067	5660	4982	5192	6321	6691
		9146	4413	5231	4741	7444	6488
		8994	4477	5768	4915	6173	7980
		6817	4060	5488	5236	6360	6181
		-	4716	-	4809	7110	-
		-	4241	-	4475	5895	-
		-	-	-	5279	4999	-
		-	-	-	4950	-	-
	Mean	**7822.5**	**5180.4**	**5514.5**	**4984.8**	**6366.2**	**7121.5**
	SD	*928.7*	*1088*	*304.8*	*343.3*	*707.4*	*830.6*

Table B-9: APA rut depths (after 8050 cycles) of mixes containing Aggregate A

	Sample	AIC	AIIC	AIa	AIIa	AIs	AIIs
Unaged Samples	APA Rut Depths (mm)	5.790	6.172	4.520	4.200	4.490	2.530
		5.640	3.702	4.320	5.930	5.290	2.990
		5.380	3.134	5.940	5.710	5.080	2.210
		4.770	0.000	5.410	5.040	5.190	2.750
		6.200	0.000	4.680	7.290	4.590	1.880
		5.890	0.000	3.500	7.980	5.360	2.290
		5.560	0.000	3.140	7.810	5.130	1.660
		4.600	0.000	3.480	7.810	5.120	1.470
		6.580	0.000	5.550	4.390	6.780	1.480
		6.360	0.000	5.620	4.210	6.500	1.400
		0.000	0.000	4.680	4.060	7.860	1.370
		0.000	0.000	4.900	5.280	7.100	1.680
	Mean	**5.677**	**4.336**	**4.645**	**5.809**	**5.708**	**1.976**
	SD	*0.641*	*1.615*	*0.912*	*1.538*	*1.075*	*0.563*
	Sample	**AIC**	**AIIC**	**AIa**	**AIIa**	**AIs**	**AIIs**
Aged Samples	APA Rut Depths (mm)	4.890	5.020	6.590	4.570	3.840	4.400
		3.660	4.130	6.550	5.430	3.780	4.280
		5.990	5.140	6.710	5.700	3.400	4.020
		5.640	4.780	6.430	5.880	3.790	5.210
		5.620	3.340	5.290	3.700	5.380	1.990
		4.890	3.290	6.050	3.540	3.610	1.090
		2.840	2.640	4.500	3.320	3.940	1.660
		2.060	2.500	5.370	3.830	3.870	2.150
		6.130	4.590	5.330	5.740	4.770	1.760
		5.180	4.200	5.800	5.110	5.520	2.250
		5.690	4.930	5.690	0.000	4.870	2.220
		6.020	4.470	5.470	0.000	5.780	2.100
	Mean	**4.884**	**4.086**	**5.815**	**4.682**	**4.379**	**2.761**
	SD	*1.334*	*0.924*	*0.671*	*1.011*	*0.834*	*1.333*

Table B-10: APA rut depths (after 8050 cycles) of mixes containing Aggregate B

	Sample	BIC	BIIC	BIa	BIIa	BIs	BIIs
Unaged Samples	APA Rut Depths (mm)	4.963	5.380	6.630	4.810	3.590	1.830
		5.666	4.630	6.020	4.580	3.380	1.300
		4.681	4.930	6.650	4.810	2.690	0.960
		0.000	4.400	6.760	3.400	2.730	1.280
		0.000	5.980	4.230	3.440	2.740	1.890
		0.000	3.900	3.750	3.690	2.970	1.800
		0.000	5.050	3.370	2.920	2.220	1.980
		0.000	4.500	4.100	3.430	2.620	2.040
		0.000	2.080	5.210	5.130	2.060	1.460
		0.000	2.590	5.050	5.030	2.220	1.800
		0.000	2.240	5.130	5.380	2.910	1.960
		0.000	2.480	6.060	5.300	3.060	1.250
	Mean	**5.103**	**4.013**	**5.247**	**4.327**	**2.766**	**1.629**
	SD	*0.507*	*1.338*	*1.191*	*0.882*	*0.460*	*0.359*
Aged Samples	Sample	BIC	BIIC	BIa	BIIa	BIs	BIIs
	APA Rut Depths (mm)	2.680	2.340	3.620	3.560	2.120	1.380
		1.890	2.520	3.610	3.130	1.830	1.210
		2.850	1.690	3.450	2.640	1.340	1.010
		3.280	3.360	3.980	2.420	1.920	1.020
		1.610	1.540	5.540	2.540	1.840	0.990
		2.020	1.480	5.190	2.340	1.690	0.000
		1.510	2.280	0.000	2.490	2.440	1.010
		1.610	1.690	0.000	2.700	2.980	1.150
		3.280	2.620	3.580	2.990	3.310	1.280
		2.800	2.790	4.390	3.780	3.010	1.620
		2.030	2.440	2.950	3.740	3.680	1.040
		1.280	3.690	3.360	4.670	4.760	0.000
	Mean	**2.237**	**2.370**	**3.967**	**3.083**	**2.577**	**1.171**
	SD	*0.707*	*0.701*	*0.831*	*0.717*	*0.998*	*0.206*

Appendix C: Statistical Analysis Results

All the statistical analysis was performed at a level of significance (α) of 0.05. 'NS' denotes a non-significant difference between two sample means and 'S' denotes a significant difference between two sample means.

Binder Test Results

Table C-1: Viscosity of binders 30 mins after adding warm asphalt additive (Irrespective of Binder Source)

	Viscosity at 135 °C			Viscosity at 120 °C		
	Control	**Asphamin®**	**Sasobit®**	**Control**	**Asphamin®**	**Sasobit®**
Control	-	-	-	-	-	-
Asphamin®	NS	-	-	NS	-	-
Sasobit®	S	S	-	S	S	-

Table C-2: Viscosity of binders 60 mins after adding warm asphalt additive (Irrespective of Binder Source)

	Viscosity at 135 °C			Viscosity at 120 °C		
	Control	**Asphamin®**	**Sasobit®**	**Control**	**Asphamin®**	**Sasobit®**
Control	-	-	-	-	-	-
Asphamin®	NS	-	-	NS	-	-
Sasobit®	S	S	-	S	S	-

Table C-3: Viscosity of binders 90 mins after adding warm asphalt additive (Irrespective of Binder Source)

	Viscosity at 135 °C			Viscosity at 120 °C		
	Control	Asphamin®	Sasobit®	Control	Asphamin®	Sasobit®
Control	-	-	-	-	-	-
Asphamin®	S	-	-	S	-	-
Sasobit®	S	S	-	S	S	-

Table C-4: Viscosity of binders 30 mins after adding warm asphalt additive (Irrespective of Binder Source)

	Viscosity at 135 °C			Viscosity at 120 °C		
	Binder I	Binder II	Binder III	Binder I	Binder II	Binder III
Binder I	-	-	-	-	-	-
Binder II	S	-	-	S	-	-
Binder III	NS	S	-	NS	S	-

Table C-5: Viscosity of binders 60 mins after adding warm asphalt additive (Irrespective of Binder Source)

	Viscosity at 135 °C			Viscosity at 120 °C		
	Binder I	Binder II	Binder III	Binder I	Binder II	Binder III
Binder I	-	-	-	-	-	-
Binder II	S	-	-	S	-	-
Binder III	NS	S	-	NS	S	-

Table C-6: Viscosity of binders 90 mins after adding warm asphalt additive (Irrespective of Binder Source)

	Viscosity at 135 °C			Viscosity at 120 °C		
	Binder I	Binder II	Binder III	Binder I	Binder II	Binder III
Binder I	-	-	-	-	-	-
Binder II	S	-	-	S	-	-
Binder III	NS	S	-	NS	S	-

Table C-7: G*/sin δ of binders after RTFO aging (Irrespective of Binder Source)

	RTFO Aging at 130/140 °C			RTFO Aging at 163 °C		
	Control	Asphamin®	Sasobit®	Control	Asphamin®	Sasobit®
Control	-	-	-	-	-	-
Asphamin®	S	-	-	NS	-	-
Sasobit®	S	NS	-	S	S	-

Table C-8: G*sin δ of binders after RTFO aging (Irrespective of Binder Source)

	RTFO Aging at 130/140 °C			RTFO Aging at 163 °C		
	Control	Asphamin®	Sasobit®	Control	Asphamin®	Sasobit®
Control	-	-	-	-	-	-
Asphamin®	NS	-	-	NS	-	-
Sasobit®	NS	NS	-	S	S	-

Table C-9: Creep stiffness of binders after RTFO aging (Irrespective of Binder Source)

	RTFO Aging at 130/140 °C			RTFO Aging at 163 °C		
	Control	Asphamin®	Sasobit®	Control	Asphamin®	Sasobit®
Control	-	-	-	-	-	-
Asphamin®	S	-	-	S	-	-
Sasobit®	S	S	-	S	NS	-

Table C-10: m-value of binders after RTFO aging (Irrespective of Binder Source)

	RTFO Aging at 130/140 °C			RTFO Aging at 163 °C		
	Control	Asphamin®	Sasobit®	Control	Asphamin®	Sasobit®
Control	-	-	-	-	-	-
Asphamin®	NS	-	-	S	-	-
Sasobit®	S	S	-	S	S	-

Table C-11: Viscosity of binders after RTFO at 130 / 140 °C (Irrespective of Binder Source)

	RTFO Aging at 130/140 °C			RTFO Aging at 163 °C		
	Control	Asphamin®	Sasobit®	Control	Asphamin®	Sasobit®
Control	-	-	-	-	-	-
Asphamin®	S	-	-	S	-	-
Sasobit®	S	S	-	S	S	-

Table C-12: G*/sin δ of binders after RTFO aging (Irrespective of Warm Asphalt Additive)

	RTFO Aging at 130/140 °C			RTFO Aging at 163 °C		
	Binder I	**Binder II**	**Binder III**	**Binder I**	**Binder II**	**Binder III**
Binder I	-	-	-	-	-	-
Binder II	S	-	-	S	-	-
Binder III	S	S	-	NS	S	-

Table C-13: G*sin δ of binders after RTFO aging (Irrespective of Warm Asphalt Additive)

	RTFO Aging at 130/140 °C			RTFO Aging at 163 °C		
	Binder I	**Binder II**	**Binder III**	**Binder I**	**Binder II**	**Binder III**
Binder I	-	-	-	-	-	-
Binder II	S	-	-	NS	-	-
Binder III	S	S	-	NS	NS	-

Table C-14: Creep stiffness of binders after RTFO aging (Irrespective of Warm Asphalt Additive)

	RTFO Aging at 130/140 °C			RTFO Aging at 163 °C		
	Binder I	**Binder II**	**Binder III**	**Binder I**	**Binder II**	**Binder III**
Binder I	-	-	-	-	-	-
Binder II	S	-	-	S	-	-
Binder III	S	S	-	S	S	-

Table C-15: m-value of binders after RTFO aging (Irrespective of Warm Asphalt Additive)

	RTFO Aging at 130/140 °C			RTFO Aging at 163 °C		
	Binder I	Binder II	Binder III	Binder I	Binder II	Binder III
Binder I	-	-	-	-	-	-
Binder II	S	-	-	S	-	-
Binder III	NS	S	-	NS	S	-

Table C-16: Viscosity of binders after RTFO aging (Irrespective of Warm Asphalt Additive)

	RTFO Aging at 130/140 °C			RTFO Aging at 163 °C		
	Binder I	Binder II	Binder III	Binder I	Binder II	Binder III
Binder I	-	-	-	-	-	-
Binder II	S	-	-	S	-	-
Binder III	NS	S	-	S	S	-

Table C-17: FTIR absorbance of original binders (Irrespective of Binder Source)

	Absorbance @ 1700 cm^{-1}			Absorbance @ 1030 cm^{-1}		
	Control	Asphamin®	Sasobit®	Control	Asphamin®	Sasobit®
Control	-	-	-	-	-	-
Asphamin®	NS	-	-	S	-	-
Sasobit®	NS	NS	-	NS	S	-

Table C-18: FTIR absorbance of RTFO aged binders (Irrespective of Binder Source)

	Absorbance @ 1700 cm^{-1}			Absorbance @ 1030 cm^{-1}		
	Control	Asphamin®	Sasobit®	Control	Asphamin®	Sasobit®
Control	-	-	-	-	-	-
Asphamin®	NS	-	-	S	-	-
Sasobit®	NS	NS	-	NS	S	-

Table C-19: FTIR absorbance of PAV aged binders (Irrespective of Binder Source)

	Absorbance @ 1700 cm^{-1}			Absorbance @ 1030 cm^{-1}		
	Control	Asphamin®	Sasobit®	Control	Asphamin®	Sasobit®
Control	-	-	-	-	-	-
Asphamin®	NS	-	-	S	-	-
Sasobit®	NS	NS	-	NS	S	-

Table C-20: FTIR absorbance of original binders (Irrespective of Warm Asphalt Additive)

	Absorbance @ 1700 cm^{-1}			Absorbance @ 1030 cm^{-1}		
	Binder I	Binder II	Binder III	Binder I	Binder II	Binder III
Binder I	-	-	-	-	-	-
Binder II	NS	-	-	NS	-	-
Binder III	NS	NS	-	NS	NS	-

Table C-21: FTIR absorbance of RTFO aged binders (Irrespective of Warm Asphalt Additive)

	Absorbance @ 1700 cm^{-1}			Absorbance @ 1030 cm^{-1}		
	Binder I	Binder II	Binder III	Binder I	Binder II	Binder III
Binder I	-	-	-	-	-	-
Binder II	NS	-	-	NS	-	-
Binder III	NS	NS	-	NS	NS	-

Table C-22: FTIR absorbance of PAV aged binders (Irrespective of Warm Asphalt Additive)

	Absorbance @ 1700 cm^{-1}			Absorbance @ 1030 cm^{-1}		
	Binder I	Binder II	Binder III	Binder I	Binder II	Binder III
Binder I	-	-	-	-	-	-
Binder II	NS	-	-	NS	-	-
Binder III	NS	NS	-	NS	NS	-

Table C-23: DSC Heat flow of binders (Irrespective of Binder Source)

	Control	Asphamin®	Sasobit®
Control	-	-	-
Asphamin®	NS	-	-
Sasobit®	S	S	-

Table C-24: DSC heat flow of binders (Irrespective of Warm Asphalt Additive)

	Binder I	Binder II	Binder III
Binder I	-	-	-
Binder II	S	-	-
Binder III	S	S	-

Table C-25: %LMS of binders (Irrespective of Binder Source)

	Control	Asphamin®	Sasobit®
Control	-	-	-
Asphamin®	NS	-	-
Sasobit®	NS	NS	-

Table C-26: % LMS of binders (Irrespective of Warm Asphalt Additive)

	Binder I	Binder II	Binder III
Binder I	-	-	-
Binder II	NS	-	-
Binder III	NS	NS	-

Mixture Test Results

Table C-27: Wet ITS of unaged samples (Irrespective of Aggregate and Binder Sources)

	Control	Asphamin®	Sasobit®
Control	-	-	-
Asphamin®	NS	-	-
Sasobit®	NS	NS	-

Table C-28: Wet ITS of aged samples (Irrespective of Aggregate and Binder Sources)

	Control	Asphamin®	Sasobit®
Control	-	-	-
Asphamin®	NS	-	-
Sasobit®	NS	NS	-

Table C-29: TSR of unaged samples (Irrespective of Aggregate and Binder Sources)

	Control	Asphamin®	Sasobit®
Control	-	-	-
Asphamin®	S	-	-
Sasobit®	S	NS	-

Table C-30: TSR of aged samples (Irrespective of Aggregate and Binder Sources)

	Control	Asphamin®	Sasobit®
Control	-	-	-
Asphamin®	NS	-	-
Sasobit®	NS	S	-

Table C-31: APA depths of unaged samples (Irrespective of Aggregate and Binder Sources)

	Control	Asphamin®	Sasobit®
Control	-	-	-
Asphamin®	NS	-	-
Sasobit®	S	S	-

Table C-32: APA depths of aged samples (Irrespective of Aggregate and Binder Sources)

	Control	Asphamin®	Sasobit®
Control	-	-	-
Asphamin®	NS	-	-
Sasobit®	NS	S	-

Table C-33: M_R at 5 °C for unaged samples (Irrespective of Aggregate and Binder Sources)

	Control	Asphamin®	Sasobit®
Control	-	-	-
Asphamin®	NS	-	-
Sasobit®	NS	NS	-

Table C-34: M_R at 25 °C for unaged samples (Irrespective of Aggregate and Binder Sources)

	Control	Asphamin®	Sasobit®
Control	-	-	-
Asphamin®	S	-	-
Sasobit®	NS	NS	-

Table C-35: M_R at 40 °C for unaged samples (Irrespective of Aggregate and Binder Sources)

	Control	Asphamin®	Sasobit®
Control	-	-	-
Asphamin®	S	-	-
Sasobit®	NS	NS	-

Table C-36: M_R at 5 °C for aged samples (Irrespective of Aggregate and Binder Sources)

	Control	Asphamin®	Sasobit®
Control	-	-	-
Asphamin®	NS	-	-
Sasobit®	NS	NS	-

Table C-37: M_R at 25 °C for aged samples (Irrespective of Aggregate and Binder Sources)

	Control	Asphamin®	Sasobit®
Control	-	-	-
Asphamin®	S	-	-
Sasobit®	NS	S	-

Table C-38: M_R at 40 °C for aged samples (Irrespective of Aggregate and Binder Sources)

	Control	Asphamin®	Sasobit®
Control	-	-	-
Asphamin®	NS	-	-
Sasobit®	NS	NS	-

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