RHEOLOGICAL PROPERTIES OF ASPHALT BINDERS, PERFORMANCE AND SUSTAINABILITY OF WARM-MIX ASPHALT INCORPORATING SASOBIT®

by

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Thesis submitted in fulfillment of the requirements

for the Degree of

Doctor of Philosophyof Science

September 2013

ACKNOWLEDGEMENTS

In the name of God

I would like to express my utmost sincere thanks to my supervisor, Professor Meor Othman Bin Hamzah for his endless guidance, motivation and supports. Thank you for always providing me hope and encouragement during my hard times. I am most grateful for that. He has supported me financially since the first day, until the time you are reading this thesis.

Thanks to my co-supervisor, Associate Professor Ahmad Shukri Bin Yahaya for his guidance, suggestions and willingness to help me in any way he can.

I am also grateful to Professor Serji Amirkhanian, Clemson University, USA, Professor Zhanping You, Michigan Technological University, USA and Dr. Kunawee Kantpong, Asian Institute of Thechnology, Thailand, for their guidance and recommendations.

I am also indebted to the technicians of Highway Engineering Laboratory, Universiti Sains Malaysia, Mr. Mohd Fouzi Bin Ali and Mr. Zulhairi Bin Ariffin for their excellent support, co-operation and guidance throughout my laboratory works.

My appreciation also goes to Universiti Sains Malaysia for providing me with laboratory facilities and financial supports.

My thanks also go to all my Malaysian friends, Zulkurnain Bin Shahadan, Zul Fahmi Bin Mohamed Jaafar, Mohamad Yusri Bin Aman,Shu Wei Goh, Noorhaliza Binti Abdullah and Marliana Azura Binti Ahmad. A special thank to Mohd Rosli Bin Hassan who was my best friend, sharing all my happiness and hardship throughout my journey.

Special thanks to my parents, Haney Jamshidi and Zinat Sadat Mirkazemi, who always support me with their love, guidance and prayers.

This thesis is dedicated to all Malaysians because of their hospitality during my stay in this country. The publications from this thesis are also dedicated to all the people. I hope this thesis could be considered as a small step taken in sustainable development for greener future of our globe.

"The future belongs to those who believe in the beauty of their dreams."

(Eleanor Roosevelt)

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LIST OF ABREVIATIONS

A	Aging
AECH	Annual Energy Consumption per Household
AI	Aging Index
ANOVA	Analysis of Variance
APA	Asphalt Pavement Analyzer
APLF	Accelerated Pavement Loading Facility
ARRB	Australia Road Research Board
ASTM	American Society Testing Manual
AC	Aging Condition
BBR	Bending Beam Rheometer
BSM	Benzene Soluble Matter
BT	Asphalt Binder Type
CEI	Compaction Energy Index
CGN	Compaction Gyration Number
CO	Carbon Monoxide
CS	Creep Stiffness
DSR	Dynamic Shear Rheometer
DTT	Direct Tensile Tester
ECEC	Ecological Cumulative Exergy Consumption
EPP	Environmental Polluting Potentials
EVA	Ethylene-Vynyl-Acetate
FWD	Falling Weight Deflectometer
GHG	Greenhouse Gas
GLM	General Linear Model
HMA	Hot Mixture Asphalt
HWTT	Homburg Wheel Tracking Test
ICEC	Industrial Cumulative Exergy Consumption
ITS	Indirect Tensile Strength
LEED	Leadership in Energy and Environmental Design
LCA	Life Cycle Assessment
LTA	Long-Term-Aging
MMLS3	Model Mobile Load Simulator Third Scale
MOT	Ontario’s Ministry of Transportation
MSCR	Multiple Stress Creep Recovery
NSW	New South Wales
MT	Mixing Temperature
OAC	Optimum Asphalt Content
PAV	Pressure Aging Vessel
PG	Performance Grade
PMB	Polymer-Modified -Binder
POF	Photochemical Ozone Formation
PWD	Public Work Department
RAP	Reclaimed Asphalt Pavement
RAS	Recycled Asphalt Shingle
RCA	Recycled Coal Ash
RSM	Response Surface Methodology
RTA	Roads and Traffic Authority

RTFO	Rolling Thin Film Oven
RV	Rotational Viscometer
S	Sasobit®
SBS	Styrene-Butadiene-Styrene
SBR	Styrene-Butadiene-Rubber
SMA	Stone Matrix Asphalt
SST	Shear Superpave™ Tester
STA	Short-Term-Aging
T	Test Temperature
TDI	Traffic Densifications Index
TNF	Threshold of non-Newtonian Flow
TSR	Tensile Strength Ratio
UEGI	Unitless Energy Gradient Index
USEA	United States Energy Administration
UTM	Universal Testing Mashine
VFA	Voids Filled Asphalt
VMA	Voids Mineral Aggregate
VTM	Voids in Total Mixture
VOC	Volatile Organic Compounds
WMA	Warm Mixture Asphalt

LIST OF SYMBOLS

f	Recovered Angle
C	Specific Heat Capacity Coefficient
C_{PnT}	Unitless Specific Heat Capacity Coefficient of the Aggregate at the Target Temperature
C_{PT1}	Unitless Specific Heat Capacity Coefficient of the Aggregate at the Initial Temperature
C_{PT2}	Specific Heat Capacity Coefficient of the aggregate at the target temperature
C*	Specific Heat Capacity Coefficient for the selected temperature range
$\Delta\boldsymbol{\theta}$	Difference between the Ambient and Mixing Temperatures
E^0	Relative Energy for Mixing
E	Energy Required for Heating the Aggregate and Sasobit®-Modified Asphalt Binder
E_0	energy required to heat the mixture components of the control sample
G*/sin δ	Superpave™ Rutting Factor
G*sin δ	Superpave™ Fatigue Factor
$[G*/\sin\delta]_C$	Superpave™ Rutting Factor of Control Asphalt Binders
$[G*/\sin\delta]_S$	Superpave™ Rutting Factor of Sasobit®-Modified Asphalt Binders
G*	Complex Shear Modulus
δ	Phase Angle
α	Thermal Diffusivity
FT_U	High Failure Temperatures of Unaged Asphalt Binder
ε	Cumulative Micro-Strain
FT_S	High Failure Temperatures of Short-term-aged Asphalt Binder
G’	Elastic Component orStorage Modulus
G’’	Viscous Component orLoss Modulus
L_1	Limestone Aggregate Extracted from Source 1
L_2	Limestone Aggregate Extracted from Source 2
L_3	Limestone Aggregate Extracted from Source 3
G_1	Granite Aggregate Extracted from Source 1
G_2	Granite Aggregate Extracted from Source 2
G_3	Granite Aggregate Extracted from Source 3
$\nabla\eta_S$	non-Dimensional Viscosity Index
η_S	Relative Viscosity
ν_0	Asphalt Binder Viscosity at Initial or Control Condition
H_T	Total heat energy that is absorbed by the asphalt binder to reach the balance temperature after compaction
H_{Agg}	Heat energy that is liberated by the aggregate particles
H_B	Heat energy required to heat the asphalt binder to the mixing point
J_{nr}	Creep Compliance
M_R	Resilient Modulus
NSRP	non-Dimensional Superpave™ Rutting Factor
Q	Sum of Heat Energy
Q_{Agg}	Amount of Required Heat Energy for Aggregate
Q_B	Amount of Required Heat Energy for Asphalt binder

Q_T	Total Amount of Required Heat Energy for Aggregate and Asphalt Binder
T_R	Torsional Recovery
U	Heat as Function of Coordination and Time
ω	Average Angular Recovery Speed
ώ	Average Angular Recovery Acceleration
$\frac{\partial U}{\partial T}$	Ratio of gradient of heat and time
$[\nabla M_R]_A$	Rate of Aging Effect on Resilient Modulus due to Long-term Aging Condition at 25℃
$[\nabla M_R]_T$	Rate of Test Temperature Effect on Resilient Modulus
$[\nabla M_R]_C$	Rate of Synergistic Effects of Reduced Construction Temperatures and Sasobit®Contents as Compared to HMA in terms of Resilient Modulus
ΔM_R	Difference in Resilient Modulus
∇M_R	Resilient ModulusGradient

ABSTRAK

CIRI RHEOLOGI PENGIKAT ASFALT, PRESTASI CAMPURAN DAN KELESTARIAN ASFALT SUAM YANG MENGANDUNGI SASOBIT®

Pembinaan turapan memerlukan sejumlah besar bahan sumber asli yang tidak boleh diperbaharui. Bahan sumber asli ini memerlukan kos yang tinggi dan semakin berkurangan dengan cepat terutamanya bitumen. Oleh itu, teknologi baru dengan kos yang lebih efektif diperlukan dalam pembinaan turapan untuk mengurangkan pengunaan sumber asli, seperti bahan dan tenaga yang tidak boleh diperbaharui. Salah satu teknologi baru ini adalahcampuran asfalt suam (WMA).Salah satu bahan tambah yang digunakan untuk menghasilkan WMA adalah sejenis lilin sintetik yang dinamakan Sasobit®. Keputusan keseluruhan ujian rheologi pengikat menunjukkan bahawa kandungan Sasobit® dan jenis pengikat asfalt mempunyai kesan yang ketara keatas parameter reologi pengikat asfalt dari segi kelikatan, G*/sin δ, G*sin δ, aliran asfalt, J_{nr}, peratus pemulihan. Keputusan Tugas 1 juga menunjukkan bahawa indeks kelikatan tidak berdimensi ($\nabla\eta_S$), faktor pengeluman tidak berdimensi Superpave™ (NSRP) dan ambang aliran bukan Newtonian (TNF) adalah parameter yang berguna untuk menerangkan perubahan sifat-sifat reologi pengikat asfalt terubahsuai Sasobit® yang dipengaruhi oleh keadaan yang berbeza seperti pengusiaan, suhu ujian dan kadar ricih. Sebagai contoh, analisis menunjukkan kelikatan relatif sampel pengikat berkurang sebanyak 7% bagi setiap 1% penambahan kandungan Sasobit®. Hasil keputusan daripada prestasi campuran menunjukkan bahawa prestasi sampel Sasobit®-WMA dari segi kekuatan tegangan tidak langsung, modulus kebingkasan, kekukuhan rayapan dan terikan micro tengam ketara kepada kandungan Sasobit®,

suhu ujian dan suhu penurapan. Sebagai contoh bagi analisis keperluan bahan api, untuk menaikkan suhu daripada suhu ambien ke suhu pencampuran, berdasarkan pada nilai C, agregat granit dari suatu sumber memerlukan 87% lebih tenaga haba atau bahan api yang lebih daripada sumber agregat granit yang lain. Walaupun jenis agregat yang sama dibekalkan dari sumber yang berbeza dan mempunyai sifat-sifat serupa seperti graviti tentu, namun, pekali muatan haba tentu (C) boleh menjadi sangat berbeza. Analisis keputusan menunjukkan bahawa dengan peningkatan nilai muatan haba tentu dalam kajian mikro agregat, keperluan bahan api dan pelepasan gas rumah hijau (GHG) HMA dan Sasobit®-WMA campuran meningkat dengan ketara Walaupun ia adalah daripada jenis agregat yang sama. Oleh itu, satu ukuran dicadangkan iaitu sebahagian kecil daripada agregat dengan nilai muatan haba tentu yang tinggi digantikan dengan agregat jenis yang sama tetapi dengan nilai muatan haba tentu yang rendah. Keputusan analisis jelas menunjukkan bahawa keperluan bahan api dan pelepasan GHG campuran agregat baru berkurangan secara mendadak dengan penambahan jumlah agregat muatan haba tentu rendah bagi setiap jenis pengikat, jenis pencampuran dan suhu pencampuran. Ia boleh menjadi satu justifikasi yang baik untuk mengubah suai kaedah pemilihan juzuk asfalt campuran untuk mengambil kira nilai muatan haba tentu sebagai penunjuk untuk mengukur potensi pencemaran alam sekitar (EPP) bagi bahan untuk pembinaan turapan asfalt. Dalam hal ini, pengambil kiraan nilai muatan haba tentu agregat boleh dicadangkan untuk ditambah ke dalam kaedah rekabentuk campuran Superpave™. Pengubahsuaian ini akan membawa kepada penghasilan HMA dan WMA yang mesra alam dan memenuhi kehendak yang ditetapkan oleh jurutera turapan, pihak berkuasa dalam sektor tenaga dan pembuat dasar alam sekitar.

ABSTRACT

RHEOLOGICAL PROPERTIES OF ASPHALT BINDERS, PERFORMANCE AND SUSTAINABILITY OF WARM MIXTURES ASPHALT INCORPORATING SASOBIT®

Pavement construction consumes a significant amount of depleting non-renewable natural resources, including asphalt binder and aggregate and energy. Therefore, new and cost-effective technologies in the pavement construction are required to be fewer dependants on the non-renewable natural sources, such as energy and materials. One of such technologies is warm mixture asphalt (WMA). One of additives used to produce WMA is a type of synthetic wax called Sasobit®. In this thesis, overall results of rheological binder tests indicated that Sasobit® content and asphalt binder type had significant effects on rheological parameters of asphalt binders in terms of viscosity, G*/sin δ, G*sin δ, asphalt flow, J_{nr}, percent recovery. The results also indicated that non-dimensional viscosity index ($\nabla\eta_S$), non-dimensional Superpave™ rutting factor (NSRP) and threshold of non-Newtonian flow (TNF) were useful parameters to explain the changes of rheological properties of Sasobit®-modified asphalt binders influenced by different conditions such as aging, test temperature and shear rate. For example, analysis of $\nabla\eta_S$ indicated the relative viscosity of the binder sample reduces by 7% for every 1% Sasobit® content added. At higher temperatures ranging from 150°C to 160°C, the value of $\nabla\eta_S$ reduces to 4.1%. The general outputs of mixture performance tests showed that performance of Sasobit®-WMA samples in terms of indirect tensile strength, resilient modulus, creep stiffness and cumulative micro-strains depended on Sasobit® content, construction and testing temperatures. Although aggregate supplied from different sources can be the same type with similiar properties such as specific gravity, their specific heat capacity coefficient (C) can be very different. The analyses showed that fuel requirement and greenhouse gas emission (GHG) of HMA and Sasobit®-WMA increased

significantly as the specific heat capacity of aggregate increased. However, they were the same type. For instance, the analysis of fuel requirements, to raise the temperature from ambient to mixing temperature, based on C indicated that granite aggregate from a source needs 87% more heat energy or more fuel than the other source of granite aggregate. Therefore, it was suggested that a fraction of aggregate with high specific heat capacityvalue was replaced with the same type aggregate but with lower specific heat capacity value. The results of analyses clearly showed that fuel requirements and GHG emissions of WMA and HMA prepared using these new aggregate blends decreased dramatically as amount of low specific heat capacity aggregate increased for each binder type, mix type and mixing temperature. It can be a good justification to modify the methods of asphalt mixture constituent selection to incorporate specific heat capacity cofficient as an indicator to measure environmental polluting potentials (EPP) of materials to construct asphalt pavements. In this regard, a part that considers the specific heat capacity cofficient of aggregate was proposed to add in Superpave™ mixture design method. This modification would lead to produce the most environmental friendly HMA and WMA meeting the requirements prescribed by pavement engineers, authorities in energy sectors and environmental policy makers.

CHAPTER 1

INTRODUCTION

1.1 Preamble

Asphalt mixture production depends on energy resources in two ways, namely energy required to produce asphalt binders in oil refineries; and carbon-based energy carriers that are used as industrial fuels in asphalt mixing plants. In addition, asphalt production was the second most energy-intensive manufacturing industry in the United States (Zapata and Gambatese, 2005).

From the commercial viewpoint, oil refineries prefer to produce higher-value-added products rather than asphalt binder, which was once regarded as a waste material from “the bottom of the barrel”. Furthermore, the price of crude oil, which is the major source of asphalt binder and industrial fuels, has significantly increased in recent years. This has led to an increase in the total price of asphalt mixtures, which are among the materials most consumed in transportation infrastructure construction and maintenance. For example, the price of asphalt mixture increased from $68 per ton in 2004 to $104 per ton in 2007, an increase of 53% over a 3-year span (Hassan, 2009). In addition, to combat global warming and promoting sustainable practices, the industries in the world, including asphalt pavement manufacturers, have made persistent efforts to reduce greenhouse gas (GHG) emissions and fossil fuel consumption. The asphalt industry meets these challenges by promoting the following three strategies: development of inexhaustible and non-polluting new energy sources, use of renewable natural resources and synthetic adhesive binders as replacements for asphalt binders and development of new technologies to produce asphalt mixtures suitable for use at lower construction temperatures without sacrificing mixture properties.

The first and second strategies require a new infrastructure for the production and distribution of new energy sources and synthetic binders and reduction of mixture production costs. In addition, the benefits of developing new, non-polluting energy sources and synthetic binders on a large industrial scale will not be realized until a much later date. The third alternative strategy, development of new technologies to produce asphalt mixtures suitable for use at lower construction temperatures, may impact the industry within a short period of time. One such technology is warm-mixture asphalt (WMA), whose permits the reduction of emissions and energy consumption by decreasing the production temperatures by 30°C to 50°C in comparison with the traditional hot-mixture asphalt (HMA) (Peinado et al., 2011). The sustainability of WMA technology is highlighted by the fact that each 10°C reduction in the mixture production temperature decreases fuel oil consumption by 1 liter and CO_2 emission by 1 kg per ton, according to estimation of World Bank (Hanz and Bahia, 2011). Ideally, the performance of WMA should be the same as that of HMA, both structurally and functionally.

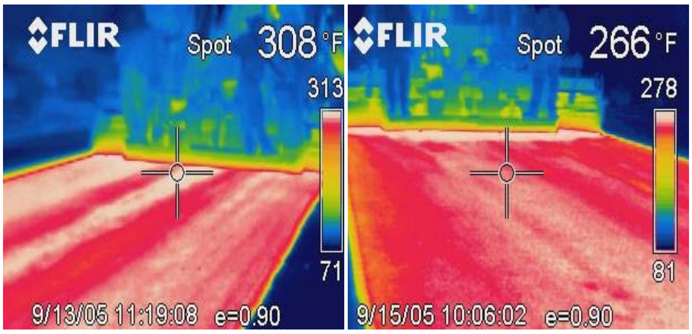
There are many asphalt binder and mixture additives that are available to produce WMA. This technology reduces greenhouse gas emission and energy consumption by lowering the production and paving temperatures of asphalt mixtures(Kristjonesdottir et al., 2007). Using WMA, suitable binder viscosities can be attained at lower temperatures than using conventional HMA. This results in reducing energy consumption, emissions, fumes and, odor at asphalt mixing plants and paving sites (Hurley and Prowell, 2005). For example, Plate 1.1 and Plate 1.2 show that the fumes reduced during mixture production and lying down, respectively. Plate 1.3 presents the difference in temperature contour between HMA and WMA mats using thermal camera. The reduced energy consumption associated with WMA also reduces the construction costs of asphalt pavement.

(a)HMA (b)WMA

Plate 1.1Asphalt Mixing Plants (Shell, 2011)

(a)HMA (b)WMA

Plate 1.2A Mat of Asphalt Mixture (Kristjonesdottir, 2006)



(a)HMA (b)WMA

Plate 1.3A Thermal Picture of Mat of Asphalt Mixture (Kristjonesdottir, 2006)

Apart from the clear advantageous such as reduced emissions in asphalt mixing plants and paving sites, there are several other advantageous using WMA like quicker turnover to traffic, longer hauling distances and extended paving window(Rubio et al., 2012). There are different processes to produce WMA as follows (Rubio et al., 2012, Hurley and Prowell, 2005, D'Angelo et al., 2008):

- Foaming processes (subdivided into water-containing and water-based processes) such as Aspha-Min®, Advera®, Double Barrel Green, Evotherm®, Ultrafoam GX, LT Asphalt, WAM Foam, Low Energy Asphalt (LEA®) and LEAB®.
- Addition of organic additives, that is Fischer-Tropsch synthesis wax, fatty acid amides and Montan wax, such as Sasobit®, Asphaltan B, Licomont BS and Ecoflex.
- Addition of chemical additives that is usually emulsification agents or polymers such as Cecabase®, Rediset®, Revix® and Iterlow T.

Since WMA technology reduces the temperatures of mixtures construction depend on different mechanisms, then the amount of additive recommended by manufacturers for WMA production can be varied as presented in Table 1.1. Accordingly, the engineering properties of WMA can be different. Therefore, it is difficult to compare the performance of WMA based on amounts of WMA additives recommended by WMA producers.

Table 1.1:Recommended Amount of WMA Additives(Rubio et al., 2012, D'Angelo et al., 2008, Hurley and Prowell, 2005)

Name of Additive	Value (%)	By Mass of	
		Binder	Mixture
Asphaltan (B)	2-4	✓	
Sasobit®	0.8-4	✓	
Evotherm®	0.3	✓	
Licomont®	3	✓	
Aspha-Min®	0.3		✓
LEA®	0.2-0.5	✓	
LRAB®	0.1	✓	
Advera®	0.25	✓	
Cecabase®	0.3-0.5	✓	
Rediset®	2	✓	

Consequently, the selection of appropriate WMA process and the content should be made carefully. Meanwhile, the findings from the rheological binder tests and WMA performance can provide a comprehensive database to provide useful guidelines to select suitable asphalt binder, aggregate types and appropriate amounts of different WMA additives. The database can be also helpful for asphalt pavement material researchers and those interested to develop new WMA additives and to improve the performance of existing WMA additives.

1.2 Problem Statement

Many WMA additives have been tried and are commercially available in the market. It is therefore necessary to formulate parameters that enable asphalt technologists to evaluate the performance of asphalt binders and mixtures blended with WMA additives. The parameters should be sensitive to variations in aging condition, test temperature and additive content. The parameters can be formulated based on unit percentage of WMA additive incorporated in asphalt binder or mixture under various conditions including binder type and source. The candidate parameter is also expected to be sensitive to sweep temperature and reflects the rheological trends of modified warm binders and engineering properties of mixture. These trends can be used to quantify the effects of aging and WMA additive contents on the properties of binders and mixtures. Currently, detailed information on such parameters is not available in the literature. In addition, because of the complex behaviours of WMA, it is necessary to understand the relationship between binders containing various WMA additive and mixture engineering properties at different aging conditions and test temperatures. Meanwhile, one of the major objectives of WMA technology is to produce sustainable mixture. Therefore, sustainability of mixture constituents including aggregate particle and binder should be analyzed in terms of outputs that are tangible for researchers, environmental policy makers and paving project managers, namely fuel consumption and GHG emissions. It should be noted that correlations between asphalt mixture constituents and fuel consumption as well as GHG for WMA production still remain unclear.

1.3 Objectives

The specific objectives of this research are as follows:

1. To estimate the correlations between different Sasobit® contents and binder rheological properties and to develop rheological-based parameters that characterizes their rheological properties at high and intermediate temperatures.
2. To evaluate the effects of different Sasobit®contents on the engineering properties of WMA and to establish the correlations between the rheological characteristics of binders containing Sasobit® and engineering properties of Sasobit®-WMA.

3. To obtain the correlation between mixture constituent properties and Sasobit®content in terms of fuel consumption and GHG emission for Sasobit®-WMA production.

1.4 Significance of Study

WMA technology is relatively new and requires more researches. The performance of WMA can be very different because of various mechanisms of WMA additives in reducing asphalt mixture construction temperatures, differences in binder source, binder type, aggregate type, gradation, environmental factors, that is temperature and humidity, traffic loading, construction method, equipment and performance criteria of mixtures prescribed by construction standards in each country.

Therefore, it is necessary to investigate the feasibility of WMA additives in WMA production using local materials complying with the construction standard. The rheological properties and mixture performance tests can provide good references to characterize the effects of each WMA additive for the selection of the best WMA additive for each pavement project. The results from this study can be used as a guide to select the appropriate amount of WMA additive for each binder type produced in Malaysia. The results of WMA performance tests can also provide useful information on WMA mixture design and performance at different aging conditions and testing temperatures.

The correlation between rheological properties of binders and mixtures incorporating WMA additives may show good relationship between structural response of asphalt mixture and binder characteristics at each aging conditions. These correlations play as guides for binder researchers and engineers to design

WMA recipe by selecting the appropriate amount of WMA additive, binder type and construction temperature without any negative influence on the WMA engineering properties.

The results of this research can also show the effects of aggregate source, aggregate type and asphalt binder type on fuel consumption and GHG emissions in an asphalt mixing plant. In other words, the appropriate aggregate source and binder type can be selected by environmental policy makers and managers in paving projects using an integrated system proposed to produce more sustainable HMA and WMA. Although the environmental policy makers have been assessing the environmental loads of different pavement alternatives, including cement concrete, asphalt concrete and concrete block pavements, in their life cycles, the effects of source of materials on fuel consumption and GHG emission during pavement construction have not been investigated in details. The proposed integrated system highlights the role of environmental policy makers more than before via analysis of GHG emissions in asphalt mixing plants. Management of fuel consumption in the asphalt mixing plant is another aspect that can be adopted by paving project managers using the proposed integrated system. It is obvious that lower fuel consumption leads to the reduction in total cost of a paving project as well as the produced emissions. Therefore, the results of this research are useful for asphalt binder researchers, paving engineers, environmental policy makers and paving projects managers.

1.5 Scope and Limitation of Research

The asphalt binders were tested based on Superpave™ specification and its recommended criteria at high and intermediate temperatures, while the rheological properties at low temperatures was not investigated. Two binder types were used in this research. The effects of asphalt binder source on rheological properties of asphalt and performance of mixtures were neglected. The heat energy was computed based on a basic thermodynamic equation, while fuel consumption and GHG emissions were calculated using conversion factors.

1.6 Organizationof Thesis

This thesis is organized in the following manner:

- Chapter one provides an overview of the thesis, including the preamble of study and its objectives.
- Chapter Two covers literature review of previous research finding spertaining to WMA technology, use of Sasobit® to modify binder and mixtures and experiences gained from field investigations of warm asphalt pavements using Sasobit®.
- Chapter Three describes the material properties of aggregates and binders. This chapter also explains the binder rheological tests, mixture performance tests and experimental plan designed for this research.
- Chapter Four presents the results of rheological tests conducted on the binders modified by different Sasobit® contents and the detailed discussion and analysis of the data.
- Chapter Five discusses the laboratory performance of the WMA incorporating the different amounts of Sasobit® in terms of indirect tensile strength, resilient modulus and dynamic creep at different temperatures. This chapter also correlates the rheological characteristics of Sasobit®-modified binders and engineering properties of Sasobit®-WMA.

- Chapter Six deliberates the effects of the aggregate source and type on fuel requirements and GHG emissions. This chapter also proposes the methodology to select the aggregate materials and binder based on the results in chapters four and five to obtain more sustainable HMA and WMA.
- Chapter Seven explans the conclusions and the recommendations for further research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a summary of more than 100 credible studies including scientific papers, technical reports and theses, that had been conducted on both warm asphalt binders and warm mixtures incorporating Sasobit® over the last decade and to draw general conclusions regarding the present state of knowledge of warm asphalt binder rheology and mixture performance. The chapter is presented in three companion sections. The section one addresses the rheological characteristics of binders containing Sasobit®, while the second and third section discuss the laboratory and field performances, respectively, of mixtures containing Sasobit®. Figure2.1shows the flowchart of discussion in this chapter.

2.2 Background

Wax additives for asphalt have two substantially different functions that are based on the physical phase of the asphalt binder. The first function of the wax can be observed when the asphalt binder is in the liquid phase at temperatures higher than 100°C. Above this temperature, the wax reduces the binder viscosity. The second function of the wax can be observed at intermediate and low temperature ranges, when the asphalt binder is in the colloid or the solid phase, which asphalt binder viscosity increases. Although lower and higher viscosity values at elevated and intermediate temperatures, respectively, are more desirable in terms of lowering construction temperatures and improving plastic deformation (rutting) resistance, these objectives conflict with to the objective of minimizing fatigue and low-temperature cracking.

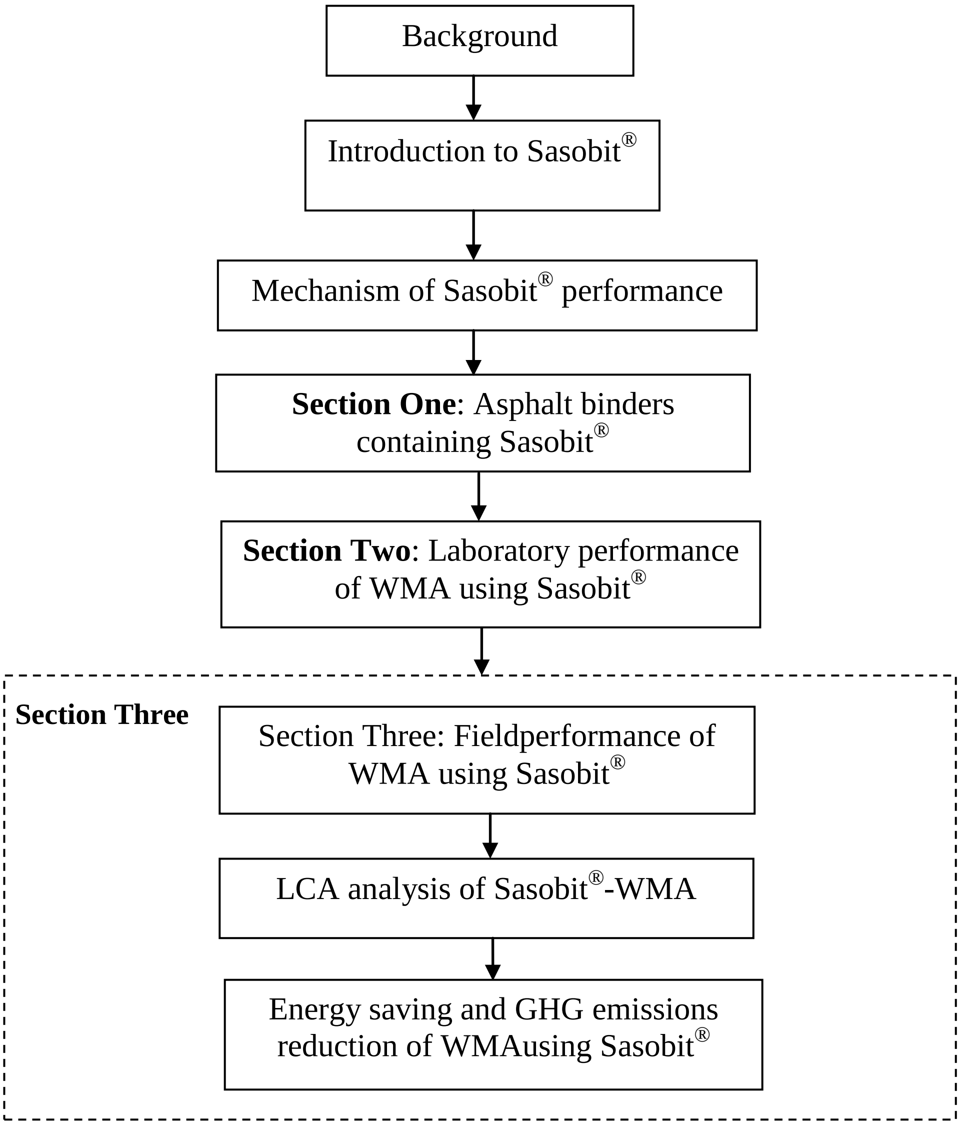


Figure 2.1: The Flowchart of Discussion and Analysis in Chapter 2

The effect of wax depends on the chemical compositions and the rheological characteristics of the asphalt binder, the composition crystallinity of the wax, the application temperature range and the amount of wax (Edwards and Isacsson, 2005a). In some countries such as Germany, France and China, the amount of wax in the asphalt binder is restricted, based on the assumption that melting waxes at elevated temperatures may decrease the mixture's resistance to rutting and that wax crystallization can lead to mixture cracking at low temperatures (Lu and Redelius, 2007). Although waxy asphalt may cause damage in asphalt pavements, the potential of some synthetic commercial waxes such as Sasobit® to improve mixture properties and achieve better performance at reduced construction temperatures offers a practical option to lessen energy consumption and increase sustainability in asphalt pavement technology.

2.3 IntroductiontoSasobit®

Sasobit® is an organic warm binder additive that is registered by the Chemical Abstract Service (CAS) as number 8002-74-2 and whose chemical formula is C_nH_{2n+2} (Sasolwax, 2008). Sasobit® is produced by Sasol Wax in South Africa.

It is a long chain of aliphatic hydrocarbons produced by the gasification of coal, a process involving the treating of white-hot hard coal or coke with a blast of steam via the Fischer-Tropsch method (Damm, 2003).The manufacturer's description of the production process is as follows (Worrel and Choi, 2007):

"During the Fischer-Tropsch process, carbon monoxide is converted into a mixture of hydrocarbons having molecular chain lengths of 1 to 100 carbon atoms and greater. The beginning point for the process is a synthetic gas which is a mixture of carbon monoxide and hydrogen, produced by gasification of coal. The gas is manufactured in vast quantities for commercial use".

In 2003, Sasol Wax invested \$360 million to pipe natural gas from Mozambique to Sasolburg, South Africa, for the production of Sasobit®(Aurilio and Michael, 2008). It is essential in the preparation of hydrogen and as a fuel in the making of steel and in other industrial processes. The synthetic gas is reacted in the presence of an iron or cobalt catalyst; heat is created and products such as methane, synthetic gasoline, waxes and alcohols are made (Worrel and Choi, 2007). The chemical reaction is presented in Equation (2.1) (Sampath, 2010). The liquid products are separated and the Fischer-Tropsch waxes are collected.

$$(2n+1)H_2+nCO_2 \longrightarrow C_nH_{2n+2}+ nH_2O \qquad (2.1)$$

Sasobit® is available in 2, 5, 20 and 600 kg bags (Hurley, 2006, Hurley and Prowell, 2005). It can be added into asphalt binder without using a shear mixing apparatus, while adding Sasobit® into asphalt mixtures requires a few modifications to the mixing process (Perkins, 2009, Hurley, 2006, Hurley and Prowell, 2005, Hurley and Prowell, 2006, Kristjonesdottir et al., 2007). In Asia, Europe and, South Africa, Sasobit® has been added directly to the aggregate as solid pills (small pellets) or as a molten liquid (produced from flakes). Sasobit® has also been blended with hot asphalt binder at the terminal (no high-shear mixing required) and as pills blown directly into the mixing chamber in asphalt mixing plants in the United States (Hurley, 2006). Sasobit® can also be blended with hot binder manually and or mechanically; this blending method has no effect on the properties of the resultant Sasobit®-modified asphalt binder properties (Ji and Xu, 2010). Sasol Wax recommends the use of from 0.8% to 4% Sasobit® by mass of binder (Hurley and Prowell, 2005, Hurley, 2006, Hurley and Prowell, 2006). However, the addition of more than 4% of Sasobit® can lead to negative effects on the low-temperature properties of the asphalt binder(Edwards and Isacsson, 2005b).

2.4 Mechanismof Sasobit®Performance

Waxes are often classified into the following three general groups: including macro crystalline, microcrystalline and / or amorphous (noncrystalline) waxes(Edwards, 2005, Edwards and Isacsson, 2005b). In general, asphalt wax is microcrystalline may also be amorphous and different asphalts may contain larger or smaller amounts of wax (Edwards and Isacsson, 2005b). In addition, different wax types are produced, including artificial, partially artificial and natural waxes (Bueche,2011).

Microcrystalline wax mainly consists of naphthenes and isoparaffins. Sasobit® is a synthetic microcrystalline wax that differs from natural asphalt waxes in its longer chain length and its finer crystalline structure.The predominant chain length of the hydrocarbons in Sasobit® is in the range of 40 to 115 carbon atoms, while that of natural asphalt paraffin waxes is normally in the range 22 to 45 carbon atoms (Syroezhko et al., 2011). The wider range of chain lengths extends the plastic limit and increases the range of melting temperatures of asphalt binders (Wasiuddin et al., 2011a, Wasiuddin et al., 2011b). The longer chains also help to keep the wax in solution, thereby reducing the asphalt binder’s viscosity and the construction temperatures at which mixtures containing the Sasobit®-modified asphalt binder can be placed.The manufacturer states that the approximately melting point of Sasobit® is almost 100°C and that it is fully miscible in asphalt binder at temperatures higher than 116°C. Beyond Sasobit®’s melting point, the wax liquefies and significantly reduces asphalt binder viscosity, enablingasphalt mixture production temperatures to be decreased by 20°C to 30°C (D'Angelo et al., 2008, Rubio et al., 2012, Zhao and Guo, 2012).At temperatures below its melting point, Sasobit® forms a lattice structure in the asphalt binder and provides better stability according to reports on field trials (Hurley, 2006, Hurley and Prowell, 2005). In other words, Sasobit®-modified warm asphalt binder behaves as a Newtonian fluid at temperatures higher temperatures than Sasobit®'s melting point and as a non-Newtonian fluid at temperatures lower than the melting point. Sasobit®'s formation of a lattice structure prevents the movement of molecules in the modified binder, consequently increasing the viscosity at low and intermediate temperatures (Ji and Xu, 2010). Equation (2.2) is valid for Sasobit®'s rheological sweep temperature at a frequency of 1 Hz in complex shear modulus (G*) testing (Silva et al., 2010a):

$$G^* = \begin{cases} 10^6 \text{ Pa} & 30℃ \leq T \leq 95℃ \\ -38732T + 4 \times 10^6 & 95℃ \leq T \leq 120℃ \quad R^2 = 0.86 \\ 0.50 \text{ Pa} & 120℃ \leq T \leq 180℃ \end{cases} \tag{2.2}$$

T = temperature.

Equation (2.2) clearly shows that G* decreases significantly in the temperature range of 95°C to 120°C around the melting point of 100°C, while at temperatures below 95°C and above 120°C, G* is relatively constant. Using the Fischer-Tropsch process to produce Sasobit® maintains control over the chain length, avoids branching and produces a wax without the contaminants (such as sulfur) that are frequently found in other sources of natural hydrocarbon (Seller, 2009). In addition, the absence of double bonds along the molecular chain's backbone alleviates oxidative chain scission in Sasobit® and extends the service lives of asphalt mixtures containing this additive (Seller, 2009).

Thermal degradation of Sasobit® occurs at temperatures between 350°C and 520°C and follows a polynomial trend as indicated by Equation (2.3). The corresponding temperature at which thermal degradation of neat asphalt binder begins is 250°C (Sasolwax, 2008). Thus, Sasobit® is more thermally stable than asphalt binder.

$$\text{WL} = \begin{cases} 100\% & 50℃ \leq \text{T} \leq 350℃ \\ 0.0009\text{T}^2 - 1.34\text{T} + 472.36 & 350℃ \leq \text{T} \leq 550℃ \quad \text{R}^2 = 0.98 \end{cases} \tag{2.3}$$

where

WL = weight loss

T = temperature

A laboratory test was implemented to assess the oxidation potential ofSasobit® and SBS (Finaprene® 502), the most widely used asphalt binder additives (Sasolwax, 2008). The Sasobit®and SBS samples were irradiated with intensive ultraviolet (UV) light for 48 hours in the laboratory. The color of the SBS changed from white to yellow, indicating significant aging. Sasobit® showed no aging in the test.

2.5 Asphalt Binders Containing Sasobit®

2.5.1 Effects of Sasobit® on Asphalt Binder Rheological Characteristics

Sasobit® increasedthe complex shear modulus (G*)of asphalt binder at medium-sweep temperatures as well as the softening point and maximum force of ductility, while it decreased the non-recoverable compliance (J_{nr}), penetration number and Fraass breaking point irrespective of binder source (Syroezhko et al., 2011 , Wasiuddin et al., 2011a, Silva et al., 2010a, Xiao et al., 2011a, Xiao et al., 2012, Ran et al., 2010, Zaumanis, 2010, Biro et al., 2009a, FHWA., 2009, Tasdemir, 2009, Edwards et al., 2007, Edwards et al., 2006a, Silva et al., 2010b , Polacco et al., 2012, Cao and Ji, 2011).

The degree of change in the rheological and chemical properties of Sasobit®–modified asphalt binder, including the decrease in viscosity at high temperatures and the increase in rutting resistance or fatigue potential at intermediate and low temperatures, as well as aging, depended on the asphalt binder source and the amount of natural wax in the asphalt binder, in other words, the chemical structure of the asphalt binder (Ji and Xu, 2010, Wasiuddin et al., 2011a, Biro et al., 2009a, Tasdemir, 2009, Edwards et al., 2006b, Edwards et al., 2007, Edwards et al., 2006a, Arega et al., 2011, Liu et al., 2011, Wasiuddin et al., 2007a, Gandhi et al., 2009, Gandhi and Amirkhanian, 2007, Mogawer et al., 2009, Sampath, 2010). For example, a Fourier transform infrared (FTIR) spectroscopy analysis of an unaged asphalt binder showed that the carbonyl content decreased by 25.58% and 26.74% with the addition of 3% and 6% Sasobit®, respectively (Edwards et al., 2007). The results for the same binder type and aging state but from another source showed that the carbonyl content increased by 2.99% and 13.96% with the addition of 3% and 6% Sasobit®, respectively.

Seller,(2009) proved using epiflourescence microscopy imaging (EMI) that the average size and shape of crystals formed in the Sasobit®-modified asphalt binder depended on the Sasobit® content. For instance, crystals that appear in a modified binder containing 20% Sasobit® had an angular shape similar to a needle, while crystals in a warm binder containing 1% Sasobit® were less needle-like and rounder in shape.

2.5.2 Effects of Sasobit® on Rutting Performance of Asphalt Binder

The Rutting potential in asphalt binder is evaluated by different methods. The Superpave™ asphalt mixture design and analysis system defines and recommends minimum values for the rutting factor, G*/sin δ (where δ is the phase angle) which represents the high-temperature viscous component of overall binder stiffness (SP-1, 2003). G*/sin δ must be at least 1 kPa and 2.2 kPa for unaged and short-term-aged binders, respectively, to meet the Superpave™ binder test's criteria (SP-1, 2003). A higher G*/sin δ corresponds to better asphalt binder rutting resistance.

Another test method uses the zero shear viscosity (ZSV) concept. ZSV is theoretically the viscosity in shear deformation at a shear rate approaching zero (Biro et al., 2009b). Asphalt binder being a viscoelastic material, its behavior depends on time and temperature. The time includes both the time of testing and the time of loading. Time of testing can be simulated in the laboratory via synthetic aging, while the time of loading is simulated using a frequency sweep. Because G*/sin δ is determined at a constant frequency (1.59 Hz) in Superpave™ testing, the effects of loading time cannot be investigated in great detail. Furthermore, G*/sin δ does not reflect binder recovery, because it does not distinguish between total energy dissipated and energy dissipated in permanent flow (Bahia et al., 2001).

As expected, Sasobit® increasedG*/sin δ, increased ZSV and decreased the creep compliance of asphalt binder for a given aging state and binder type and source(Wasiuddin et al., 2011a, Xiao et al., 2011a, Xiao et al., 2012, Biro et al., 2009a, Edwards et al., 2007, Liu et al., 2011, Wasiuddin et al., 2007b, Biro et al., 2009b, Buss, 2011, Hossain et al., 2009, Cao and Ji, 2011). Sasobit® also increased

G*/sin δ and failure temperature and reduced creep compliance and phase angle more than other warm asphalt binder additives such as Rediset® and Cecabase® at each aging state (unaged and short-term-aged) and for each binder source (Xiao et al., 2011a, Xiao et al., 2012) .

Since ZSV is computed using different techniques, their values can be different. For example, the ZSV of Sasobit®-modified asphalt binder was 960 Pa.s based on Carreau's model, while it is 480 Pa.s for the same source of asphalt binder using the Cross/Sybliskis model (Biro et al., 2009b). It was also observed that the shear thinning for a Sasobit®-modified asphalt binder at 60°C was a pseudoplastic phenomenon (Biro et al., 2009a, Biro et al., 2009b).

2.5.3 Effects of Sasobit® on Stiffness of Asphalt Binder

Since Sasobit® increased G*, G*sin δ was expected to increase with increasing Sasobit® content. Therefore, to avoid intermediate temperature cracking due to high stiffness of binder, a value of G*sin δ less than 5 MPa is desirable, according to Superpave™ (SP-1, 2003). The degree of Sasobit® effect on G*sin δ depended on the binder type, the chemical properties of the binder and the Sasobit® content (Gandhi et al., 2009, Arega et al., 2011, Liu et al., 2011). Although asphalt binders containing Sasobit® age more slowly because they can be used at lower construction temperatures, Sasobit® content and binder type should be selected with care because stiffening effects due to aging associated with a high Sasobit® content can increase G*sin δ beyond 5 MPa.

2.5.4 Effects of Sasobit® on Low-Temperature Cracking Potential of Asphalt Binder

The advantageous effects of Sasobit® at high and intermediate temperatures can correspond to detrimental effects at low temperatures. In this regard, the following two phenomena should be evaluated for Sasobit®-modified asphalt binders: creep stiffness and physical hardening. Creep stiffness is evaluated using a bending beam rheometer (BBR) in Superpave™ testing. Physical hardening is a reversible procedure that can lead to changes in rheological characteristics without changing the chemical composition of the material (Lu and Isacsson, 2000). The physical hardening of asphalt can be due to molecular self-assembly and molecular agglomerations of crystalline phases at intermediate and low temperatures, respectively (Edwards et al., 2005, Claudy et al., 1992). Another possible cause is spinodal decomposition, a process by which a homogeneous liquid separates into two liquid phases as the material is cooled (Hilliard, 1970).

Sasobit® increased binder stiffness, indicating less resistance to low-temperature cracking for a given binder source (Edwards et al., 2006b, Liu et al., 2011, Hossain et al., 2011, Liu and Peng, 2012). The degree of increase in binder stiffness and decrease in physical hardening index (PHI) depended on the Sasobit® content and the binder source as presented in Table 2.2and Table 2.3. You et al., (2011) suggested that guidelines should be provided to select the maximum Sasobit® content in order to minimize the potential for low-temperature cracking in the asphalt mixture.

Li and Peng (2012) evaluated the effects of Sasobit® contents on the cracking temperatures of unaged and long-term-aged PG 58-28 binders using an asphalt binder cracking device. The results indicated that in general, the cracking temperatures of both unaged and long-term aged binders increased slightly as the Sasobit® content increased. In other words, binders containing higher Sasobit® contents were more susceptible to cracking at lower temperatures. However, within the range of Sasobit® contents investigated (0% to 3%), the increment of cracking temperatures for both unaged and long-term aged binders was not significant (-38.98ºC to -35.67ºC for unaged binders and -33.23ºC to -31.70ºC for long-term aged binders). The effects of asphalt binder type and source were not investigated.

Table 2.1:Percentage Change in Creep Stiffness and PHI(Edwards et al., 2006b)

Asphalt Source	Sasobit®Content (%)	Changes (%)	
		Stiffness at -20ºC	PHI
	0	-	-
1	3	+63	-6.8
	6	+101	-21
	0	-	
2	3	81	-37.5
	6	112	0
	0	-	-
3	3	+75	-6.12
	6	+114	-22.5

Table 2.2:Percentage Change in Low Temperature Cracking (You et al., 2011)

Sasobit® content (%)	Change (%)
1	5.31
2	8.5
3	12.76

2.5.5 Effects of Aging on Sasobit®-Modified Asphalt Binder

Aging and moisture damage are the main factors influencing the durability of asphalt pavements (Airey and Choi, 2002). Aging affects binder rheological properties throughout the life of the asphalt pavement. This effect is primarily due to two mechanisms. The first is the loss of volatile components and oxidation of the binder during mixing at the plant, mixture transportation and paving, which is called short-term aging (SP-1, 2003). The second is the progressive oxidation of the material in the field, namely long-term aging (SP-1, 2003, Shalaby, 2002). Resins, which have small molecular sizes (SMS), turns into asphaltenes, which have large molecular size (LMS), consequently increasing the viscosity and the elastic solid properties of the asphalt binder during aging (Rajan et al., 2010, Gao et al., 2006). In other words, the proportion of LMS increases while the proportion of SMS decreases with aging. Asphalt mixture properties are more strongly related to the proportion of LMS than to the proportions of SMS and medium molecular size (MMS) (Lee et al., 2011, Lee et al., 2009a, Doh et al., 2008, Wahhab et al., 1999, Kim and Burati Jr, 1993). Other factors that may lead to aging include molecular structuring over time (steric hardening) and actinic light (primarily ultraviolet radiation, particularly in arid conditions)(Airey, 2003). Aging depends on the asphalt binder content and properties, the type of aggregate and its particle size distribution, the mixture type, the void content in the mixture, time and the ambient temperature(Xiaohu and Isacsson, 2002). Additives may affect the rate and degree of short and long-term aging. Gandhi and Amirkhanian (2007) conducted a laboratory study to evaluate aging in Sasobit®-modified asphalt binders. They found that for each binder source considered, asphalt binder extracted from short-term-aged and long-term-aged Sasobit®- WMA samples showed less aging in terms of normalized viscosity,$G^*/\sin\delta$, $G^*\sin\delta$ and binder stiffness, compared to binder extracted from HMA samples. The reduced aging in the Sasobit®-modified asphalt binder is due to reduced volatilization and oxidation because of lower construction temperatures (Gandhi et al., 2009). Meanwhile, Sasobit®-modified asphalt binder exhibited lower rate of gain in amount of G* over time as compared to binder samples without Sasobit®, indicating lesser susceptibility to aging of asphalt binders blended with Sasobit®(Banerjee et al., 2012).

2.5.6 Effect of Sasobit® on Thermal Characteristics of Asphalt Binder

The thermal characteristics of Sasobit®-modified asphalt binders have been investigated by some researchers. The crystallization temperature of Sasobit®is 102.5°C (Seller, 2009), while the crystallization temperature of Sasobit®-modified asphalt binder decreases with decreasing Sasobit® content. For example, the crystallization temperatures of modified asphalt binder containing 20% and 1% Sasobit® are 95.9°C and 73.8°C, respectively.

Sasobit® increases the crystal starting and wax melt out temperatures, but has no effect on the glass transition temperature, according to laboratory research conducted by Edwards et al., (2006b). In another study, Gnadhi (2008) carried out a thermal analysis on Sasobit®-modified asphalt binders. The results showed two different trends with temperature. At low temperatures, adding Sasobit® increased the glass transition temperature of the modified asphalt binders compared to that of the control binder.

At higher temperatures (higher than 80°C), Sasobit® decreased heat flow for the warm binder samples, meaning that the wax melted at those temperatures. From Equation (2.2), a significant reduction in G* is also expected beyond 100°C because this temperature is approximately the melting point of Sasobit®.

Different methods of heating the asphalt binder samples can give different results for the crystallization temperature. Figure 2.2(a) and (b) illustrate the first and