2012

Development and improvement of warm-mix asphalt technology

Shu Wei Goh
Michigan Technological University

Follow this and additional works at: https://digitalcommons.mtu.edu/etds

Part of the Civil and Environmental Engineering Commons

DEVELOPMENT AND IMPROVEMENT OF WARM-MIX ASPHALT TECHNOLOGY

By

Shu Wei Goh

A DISSERTATION

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

In Civil Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2012

This dissertation has been approved in partial fulfillment of the requirements for the Degree of DOCTOR OF PHILOSOPHY in Civil Engineering.

Department of Civil and Environmental Engineering

Advisor: *Zhanping You*

Committee Member: *George R. Dewey*

Committee Member: *Jacob E. Hiller*

Committee Member: *Jianping Dong*

Committee Member: *Amlan Mukherjee*

Committee Member: *Karl Peterson*

Department Chair: *David Hand*

Table of Contents

List of Figures

List of Tables

Acknowledgments

The author would like to thank Zhanping You for his constant guidance for this study. The author would like to thank the committee members George Dewey, Jianping Dong, Amlan Mukherjee, Karl Peterson and Jacob Hiller who make the defense of this dissertation possible. The author would also like to thank Jim Vivian and Ed Tulppo who has been very helpful in keeping the asphalt lab active. Also, thanks to David Porter, Damian Wallner, Su Ting Lau, Moua Lee, Kari Klaboe, Ryan Brennan, Joshua Marschke and Sarah Shann for their helps in mixing, compacting and testing the asphalt mixture samples. The research projects cannot be complete without the significant contribution of them.

Abstract

Traditionally, asphalt mixtures were produced at high temperatures (between 150°C to 180°C) and therefore often referred to as Hot Mix Asphalt (HMA). Recently, a new technology named Warm Mix Asphalt (WMA) was developed in Europe that allows HMA to be produced at a lower temperature. Over years of research efforts, a few WMA technologies were introduced including the foaming method using Aspha-min® and Advera® WMA; organic additives such as Sasobit® and Asphaltan B®; and chemical packages such as Evotherm® and Cecabase RT®. Benefits were found when lower temperatures were used to produce asphalt mixtures, especially when it comes to environmental and energy savings. Even though WMA has shown promising results in energy savings and emission reduction, however, only limited studies and laboratory tests have been conducted to date. The objectives of this project are to 1) develop a mix design framework for WMA by evaluating its mechanical properties; 2) evaluate performance of WMA containing high percentages of recycled asphalt material; and 3) evaluate the moisture sensitivity in WMA.

The test results show that most of the WMA has higher fatigue life and TSR which indicated WMA has better fatigue cracking and moisture damage resistant; however, the rutting potential of most of the WMA tested were higher than the control HMA. A recommended WMA mix design framework was developed as well. The WMA design framework was presented in this study to provide contractors, and government agencies successfully design WMA.

Mixtures containing high RAP and RAS were studied as well and the overall results show that WMA technology allows the mixture containing high RAP content and RAS to be produced at lower temperature (up to 35°C lower) without significantly affect the performance of asphalt mixture in terms of rutting, fatigue and moisture susceptibility.

Lastly, the study also found that by introducing the hydrated lime in the WMA, all mixtures modified by the hydrated lime passed the minimum requirement of 0.80. This indicated that, the moisture susceptibility of the WMA can be improved by adding the hydrated lime.

Chapter 1: Introduction

Hot Mix Asphalt (HMA) has been traditionally produced at a discharge temperature of between 280°F (138°C) and 320° F (160°C), resulting in high energy (fuel) costs and production of greenhouse gases. The asphalt industry has talked about energy savings and environmental benefits in cold or warm asphalt processes [3]. Additionally, environmental awareness has been increasing rapidly over the past years, and comprehensive measures like air pollution reduction targets set by the European Union with the Kyoto Protocol have encouraged efforts to reduce pollution [4]. The hot-mix asphalt industry is constantly exploring technological improvements that will enhance the material's performance, increase construction efficiency, conserve resources, and improve environmental stewardship.

Warm Mix Asphalt (WMA), a new paving technology that originated in Europe, reported by Harrison and Christodulaki [3] at the First International Conference of Asphalt Pavement (Sydney), is one of those efforts. WMA is produced at temperatures in the range of 30 to 100°F lower than typical hot-mix asphalt (HMA). The goal for Warm Mix Asphalt (WMA) is to use existing HMA plants and specifications to produce quality dense graded mixtures at significantly lower temperatures. Europeans are using WMA technologies that allow the mixture to be placed at temperatures as low as 250°F (121°C). It is reported that energy savings on the order of 30%, with a corresponding reduction in CO_2 emissions of 30%, are realized when WMA was used compared to conventional HMA. By adjusting the burner tuning to allow WMA process to operate at a lower setting, these energy savings and emission reduction could be greater. In addition, a lower temperature used during the production also accounted for the reduction in energy usage to mix the material, as well as to transport the material through the plant [5]. Figure 1.1 shows the typical mixing temperatures for asphalt mixtures.

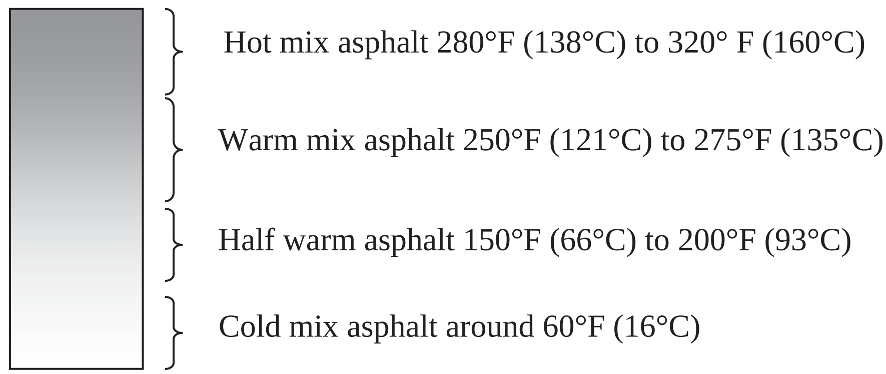


Figure 1.1 Typical Mixing Temperature Range for Asphalt Mixtures

1.1: Warm Mix Asphalt Technology

The technique of WMA was first invented by Professor Csanyi at Iowa State University in 1956 [6]. He found out that the foaming asphalt could be possible for use as soil binder. This invention was then modified by adding cold water instead of steam in asphalt, and it was patented by Mobil Oil Australia in 1968 [6]. This invention was later licensed to Conoco Inc. to promote foamed asphalt in United States, and further develop the product as a base stabilizer for both laboratory and field evaluation [7,8].

Since 1970s, researchers have been trying to investigate a new method to reduce asphalt mixture production temperature [9]. This method was later termed as Warm Mix Asphalt (WMA). Currently, several kinds of WMA technologies were developed and used in USA, and European countries [5,10]. As of today, three main types of WMA technologies were identified: foaming effect, organic additive and chemical package. The first type of WMA technology creates foaming effect during the mixing process to increase workability of asphalt mixture. This foaming effect can be achieved by the production process modification, or insert a small amount of water to the asphalt mixture during the production using a hydrophilic material [5]. The water creates a volume expansion of the binder that results in asphalt foam and allows increased workability and aggregate coating at lower temperature [11].

The organic additive for WMA is often referred to as wax or “asphalt flow improver” as this additive reduces the asphalt viscosity at certain temperatures (i.e. slightly above the melting point of that certain organic additive), allowing the asphalt mixture to be mixed and placed at lower temperatures [9,12,13]. It is necessary to ensure the selected organic material has a melting point above the expected service temperature to avoid permanent deformation [14].

The chemical package used for WMA is the technology developed in the United States that using different kinds of chemical additives. These chemical packages usually include anti-striping agents and compaction aids and they were designed to enhance coating, adhesion, and workability of the asphalt mixture [14,15]. Some of the chemical packages also serve as the emulsification agent [16-18]. Water in this emulsion flashes off as steam when mixing with aggregate and enhances the coating of aggregate by the asphalt. Examples of WMA technologies are summarized in Table 1.1.

Table 1.1 Examples of Existing and Potential Warm Mix Technologies

Foaming Additive		
WMA Technology	**Company**	**Recommended Additive/ Usage**
Aspha-min®	Eurovia and MHI	0.3% by total mass of mixture
ADVERA® WMA	PQ Corporation	0.25% by total mass of mixture
WAM-Foam®	Kolo Veidekke Shell Bitument	No additive. It is a two component binder system that introduces a soft and hard foamed binder at different stages during plant production.
LEA®	LEA-CO	0.2-0.5% by weight of binder
LEAB®	BAM	0.1% by weight of binder
Organic Additives		
WMA Technology	**Company**	**Recommended Additive/ Usage**
Sasobit®	Sasol	0.8-3.0% by weight of asphalt
Asphaltan-B®	Romonta	2.5% by weight of asphalt
Licomont BS 100®	Clariant	3% by weight of asphalt mixture
Chemical Package		
WMA Technology	**Company**	**Recommended Additive/ Usage**
CECABASE RT®	Arkema Group	0.2-0.4% by weight of asphalt
Evotherm®	Meadwestvaco Asphalt Innovations	Generally pumped right off a tanker truck to the asphalt line using a single pair of heated valves and check valves to allows for recirculation
Rediset WMX®	Akzo Nobel	2% by weight of mixture

1.2: Benefits of Warm Mix Asphalt

The benefits of Warm Mix Asphalt (WMA) in terms of environmental aspects have been continuously identified by United States and European countries. Past research indicated that emissions and energy consumption (fuel) were reduced significantly when WMA was used [1-5]. Some other potential benefits included cold weather paving, reduced thermal segregation of material, extended paving window, improved workability, earlier traffic opening after construction, reduced worker exposure to asphalt fumes and slowed binder aging potential [19-21]. The benefits of this research are as follows:

1.2.1: Improved Mobility

Identifying the use of WMA technology on asphalt pavement will allow for the development of alternative mixture designs and surface treatments that have more environmental benefits. These improvements in asphalt pavement construction can be specified as part of publicly funded roads to ensure the highest possible quality in transportation construction for the State

1.2.2: Emission Reduction

Asphalt mixing is an energy intensive process compared with other industrial activities. The energy consumed during the mixing process was as much as 60 percent of the total energy required for the construction and maintenance of a given road over an average service life of 30 years [22]. The use of WMA techniques allow for the reduction in required mixing energy and eventually allow for significant savings in energy costs [23]. The use of additives in these WMA processes allowed the production temperatures to be 50°F to 100°F lower than the average HMA production temperatures [24]. According to previous studies, this correlates to burner fuel savings with WMA processes ranging from 20 to 35 percent [5]. These energy savings and emissions reductions could be greater if burners tuning was adjusted to provide the burners used in the WMA process to operate at lower settings. In addition, a lower temperature used during the production also accounted for the reduction in electrical usage to mix the material, as well as to transport the material through the plant [5]. Figure 1.2 shows the emission reduction results from WMA European Practice Report conducted by WMA Technical Working Group (WMA TWG) [5].

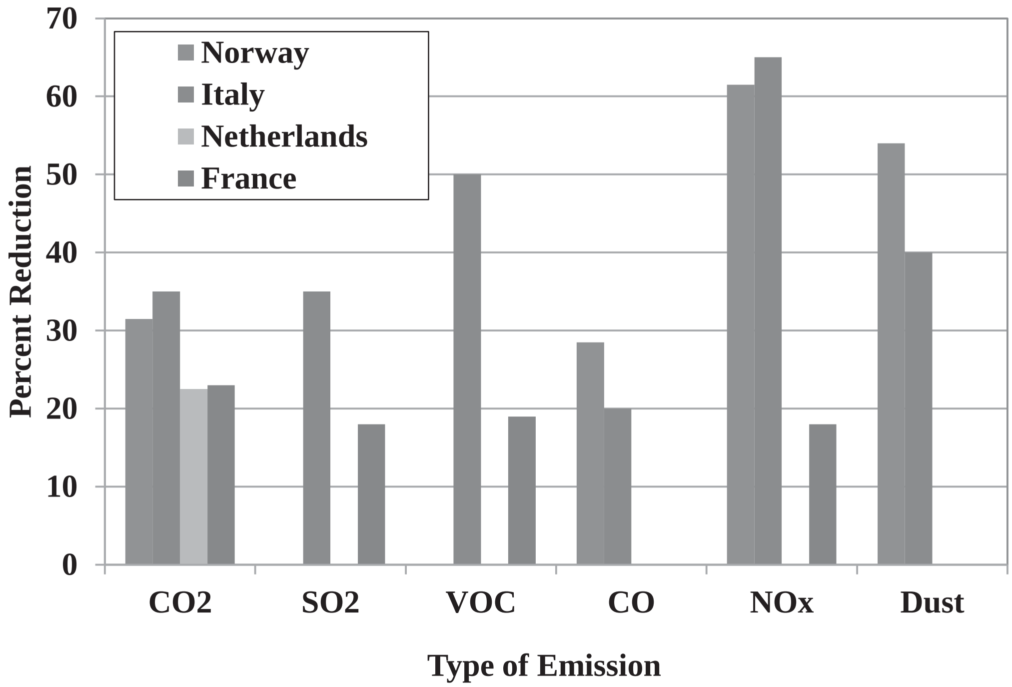


Figure 1.2 Reported Reduction in Plant Emission with the use of WMA for Selected EU Nations(data by WMA Technical Working Group [5])

1.2.3: Better Health to Contractors, Engineers, and Public

Hot asphalt fumes generated during asphalt mixing processes contain polycyclic aromatic hydrocarbon (PAH) compounds [22]. PAH compounds are of concern regarding exposure to workers because some of these compounds have been identified as carcinogenic, mutagenic and teratogenic. Presently, the most common asphalt mixing process is Hot Mix Asphalt (HMA), which can also allow for PAH emissions during the required warming and drying of aggregate steps [22]. The use of recycled asphalt in these processes can lead to further asphalt related emissions, and studies focus on this topic have indicated that a distinct relationship exists between production temperatures and asphalt fume generation [5]. The use of Warm Mix Asphalt processes can effectively reduce the production of these fumes, thus reducing exposure to workers. Monitoring of worker exposure to aerosol/fumes and PAHs within asphalt mixing plants showed a viable reduction in exposure as compared to the HMA processes. Data collected by the German Bitumen Forum indicated that WMA had a reduction of 30 to 50 percent in PAHs [25]. Aside from reducing exposure to these aerosols/fumes and PAHs, the lower mix temperatures utilized Warm Mix Asphalt processes seem to foster a more desirable work environment, potentially aiding in worker retention [5]. Therefore, the use of WMA will benefit many people including paving crews, contractors, MDOT engineers, and the public.

1.2.4: Early Traffic Opening

By producing the asphalt mixture at lower temperature (using WMA technology), the cool down time for asphalt mixture is lesser because it is closer to air ambient temperature. This allows WMA to have an early traffic opening and reduce traffic congestion. A study on field performance of WMA was conducted at the NCAT test track [26]. The results indicated that both HMA and WMA field sections showed excellent rutting performance after the application of 515,333 equivalent single axle loads (ESALs) over a 43-day period. One of the WMA sections was also evaluated for early opening to traffic and showed good performance.

1.2.5: Extends Paving Window

In cold region, the concern of paving hot mix asphalt (HMA) in cold weather often arises during fall, winter and spring seasons. Issues such as mixing temperature and placing the HMA are of special concern due to the colder environment. Previous study indicated that the use of WMA can improve colder weather paving [7]. Many advantages were found, particularly for cold weather condition when WMA is produced at regular HMA temperatures. These include extend paving season, longer haul distances, and less restriction and potentially more paving hours in nonattainment areas [7,27]. In the past, the research team evaluated the WMA using Sasobit® for cold region [28], the findings from the study show that WMA extend the paving time by 27 minutes which will allow a longer hauling distance during the construction for ambient air temperature of 7.7ºC (per Weather condition at Iron Mountain, Michigan on September 2007).

1.3: Problem Statement

WMA is a relatively new technology. Although it shows a significant promise in energy savings and emissions reduction, there have been only a few laboratory experiments conducted. Further detailed studies and tests are needed to evaluate the performance of WMA in terms of mixture volumetric design and asphalt binder properties. Based on the literature reviews, the following represent the challenges when considering WMA performance, design and construction issues compared to traditional HMA:

1. Since WMA is a new technology, it is important to ensure the overall performance of WMA is similar or better than HMA. Furthermore, a new/ modified mix design procedure is needed for WMA which will be compatible with traditional HMA design as well.
2. The current major problem of WMA is the moisture damage that is caused by the water trapped inside the aggregate. Moisture damage occurs when aggregates are not thoroughly dry during the low temperature mixing process.

3. WMA shows a lower air void level compared to HMA during Superpave gyratory compaction, which indicates WMA may have lower optimum binder content. The reduced optimum binder content could lead to an extra economic saving during the production; however, these lower optimum binder contents might affect the durability of an asphalt mixture as well (i.e. cracking, oxidative aging and moisture susceptibility).
4. Will WMA provides economic savings in the long term pavement production? How much will environmental and energy benefits from WMA be long term compared to HMA?
5. Could WMA technologies be used for asphalt mixtures that contain recycled material? In the past, few or no tests were conducted to evaluate this issue.

1.4: Objectives

The main objective of this research was to

1. Develop a mix design framework for WMA by evaluating its mechanical properties.
2. Evaluate the performance of WMA containing a high percentage of recycled asphalt material.
3. Evaluate the moisture sensitivity in WMA

1.5: Scope

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

- Develop a mix design and laboratory analysis framework for WMA
    - This was done by using aggregate and asphalt sources from state of Michigan and five WMA technologies – Aspha-min®, Sasobit®, Cecabase RT®, Advera® and water-based forming method. A total of

864 samples were prepared for Dynamic Modulus (|E*|), APA Rutting, Flow Number (F_N), Four Point Beam Fatigue and Indirect Tensile Strength Testing (IDT) in this study to compare the properties of WMA with HMA.

  - The aging effects of WMA were evaluated. For WMA binders, a total 30 samples were prepared and evaluated with Complex Shear Modulus (|G*|), Rotational Viscosity (RV) at different aging states. For WMA mixtures, aging and reheating of WMA mixtures were evaluated using |E*| and F_N.
  - A critical performance testing was selected to validate the performance of WMA and a recommended WMA mix design framework was developed based on the literature reviews and results from laboratory testing

- Evaluate the performance of WMA containing a high percentage of recycled asphalt material
  - High percentage of Recycle Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS) was used in this study. A total 468 mixtures that contained 50% and 75% RAP, and 5% and 10% RAS were tested and evaluated using compaction energy, volumetric properties – void in mineral (VMA) and void filled with asphalt (VFA). The mixture performance testing including |E*|, F_N, APA rutting and IDT.

- Evaluate the moisture sensitivity in WMA
  - Moisture was added to the HMA and WMA based on coarse aggregate surface saturated dry (SSD) condition.
  - A total 54 samples were prepared and tested with Tensile Strength Ratio.

- Hydrated lime was used as anti-stripping agent to evaluate if it can improve the moisture susceptibility of the SSD conditioned HMA and WMA.

Chapter 2: WMA Technologies

2.1: WMA using Foaming Effect

The WMA using foaming effect is one of the most commonly used WMA technologies in the United States due to its cost-effectiveness. There are no extra additives required using this technology, and the water is easier to handle and obtain [29]. The concept behind the foamed WMA is that the water turns to steam dispersed throughout the asphalt, and then the steam expands the volume of the binder providing a corresponding temporary reduction in viscosity. Currently, there are two commonly known techniques of producing foamed WMA: foaming admixture and free water system [14,30].

2.1.1: Foaming Technique 1: Foaming Admixture

A number of current WMA technologies use foaming admixture techniques to produce WMA. Two types of foaming admixture techniques will be discussed in this section: hydrophilic materials and damp aggregate.

2.1.1.1: Hydrophilic Materials

A number of current WMA technologies use hydrophilic materials to produce foamed asphalt binder. Hydrophilic materials such as synthetic zeolite are framework silicates that have large vacant spaces in their structure that allow space for large cations such as sodium potassium, barium and calcium, and even relatively large molecules and cation groups such as water. When the hydrophilic materials interact with hot asphalt binder, they will gradually release water and turns into steam at atmospheric pressure, expanding its volume and creating the foaming effect in the asphalt binder microscopically [11,14,31]. Technologies that use hydrophilic materials as foaming technique include Aspha-min® and ADVERA® WMA.

2.1.1.2: Damp Aggregate

WMA using damp aggregate as a foaming method have been used by many contractors especially in Europe[19,23,32]. Low Energy Asphalt (LEA) is one of the well-known technologies that used damp aggregate as a foaming admixture. LEA is the patented manufacturing process by Low Energy Asphalt Company (LEA-CO) that produced WMA at about as 95°C, the process relies on the foaming capacity of hot asphalt in the presence of the natural humidity of cold or warm aggregate [19,21,33]. In the LEA WMA process, there are five phases produce WMA [23]:

Phase 1: Heat the coarse aggregate to about or more than 266°F (130°C), and then mix and coat with hot asphalt at approximately 338°F (170°C) based on asphalt binder grade.

Phase 2: All the coarse aggregate should be fully coated by all the asphalt and have a thick film of asphalt.

Phase 3: Wet and cold fine aggregates were added, and moisture from fine aggregate should trigger asphalt foaming.

Phase 4: Foamed asphalt encapsulates fine aggregates.

Phase 5: Thermal equilibrium reached. All aggregate should be coated uniformly.

2.1.2: Foaming Technique 2: Free Water System

As more WMA trial sections were planned, more manufactures start developing their own WMA technologies. Free water systems were developed by those manufactures for asphalt plants to produce large scale WMA. The free water system used either a single nozzle or a series of nozzles to inject a small amount of water to produce foamed asphalt [34-39]. The concept behind the free water system is that water would expand by a factor of approximately 1,700 when it turns to steam [40]. This expansion of water inside the asphalt will result in a reduction of viscosity, allowing a lower temperature for aggregate coating and mixture compaction.

An example for such a free water system 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 pre-coated aggregates. 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). For a batch plant, a foaming nozzle and expansion chamber was needed to foam the hard binder. Other WMA technologies using free water system include Accu-Shear Dual Warm-Mix Additive system from Double Barrel Green System from Astec Industries[41,42], Standsteel – Figure 2.1 [37] and Aquablack WMA from Maxam Equipment Inc. – Figure 2.2 [43].

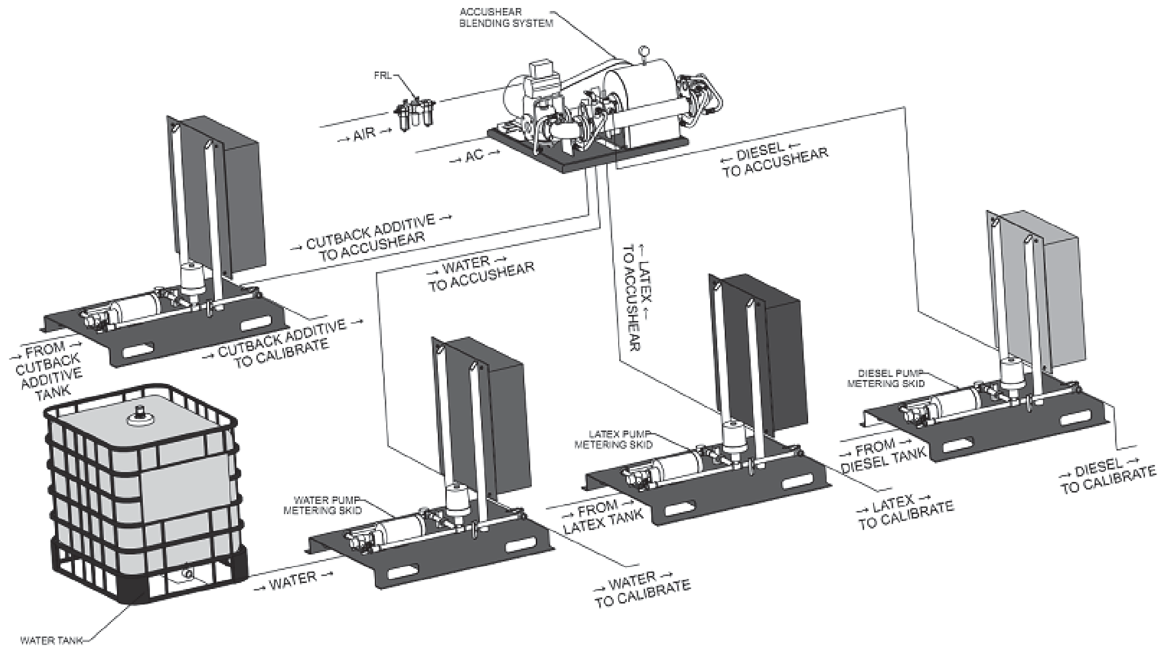


Figure 2.1 Accu-Shear Dual Warm-Mix Additive system[1] (from Standsteel [37])

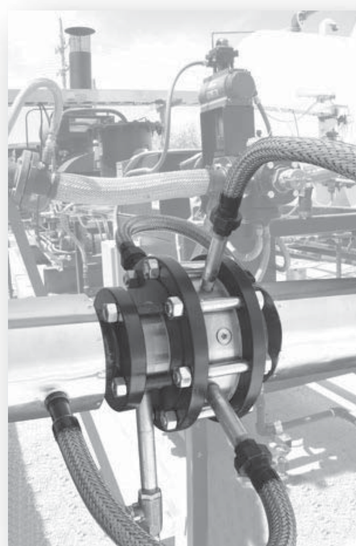


Figure 2.2 Aquablack WMA[2] (from Maxam Equipment Inc. [43])

[1] Image obtained from Standsteel with Permission – Please refer to Appendix 1
[2] Image obtained from Maxam Equipment Inc. – Please refer to Appendix 1

2.1.3: Laboratory Evaluation of WMA Using Foaming Technique

In this project, both WMA techniques using foamed admixture and free water system were evaluated. For foamed admixture, Aspha-min® and ADVERA® WMA were selected; and for free water system, WMA foamed by inject a small amount of water was produced under a laboratory setup. In this, various laboratory tests were performed to validate the performance of WMA designed with foaming method. The results and findings will be discussed in the following case studies.

2.1.4: Case Study 1: WMA using Aspha-Min®

Development of Aspha-min® dates back more than 10 years to when the European Union set industry targets to reduce CO_2 emissions by 15%. Aspha-min® (a.ka. zeolite) is a product of Eurovia Services GmbH, Germany. Aspha-min® has been used in Europe for several years, and U.S. has been using it in paving projects as well as a paving demonstration at the 2004 World of Asphalt [7,17,44].

Figure 2.3 Granular form of Asphalt-min®

Aspha-min® is a manufactured natrium-aluminum silicate, or better known zeolite which has been hydro-thermally crystallized. Most zeolites are characterized by their ability to lose and absorb water without damaging their crystal structure. It contains approximately 21% water by weight and is released in the temperature range of 85-180°C(185-360°F). Eurovia recommends adding Aspha-min® to an asphalt mixture at a rate of0.3% by mass of the mix or 6lb per ton, which enables approximately a 30°C (54°F) reduction in production and placement temperatures. Eurovia indicates that 50°Freduction in temperature equates to a 30% reduction in fuel energy consumption. In the asphalt plant, the zeolite can be added directly into the pugmill in a batch plant, through the RAP collar, or pneumatically fed into a drum plant using a specially built feeder.

2.1.4.1: Material Preparation and Experimental Design

This case study involves both asphalt binder and mixture test. For the asphalt binder test, two types of binder were used to evaluate the effects of Aspha-min® on binder properties, including PG 64-28 (was also used in preparing a mixture for the volumetric analysis) and PG52-34. For the PG64-28 binder, control binder and binders with 0.3% and 0.5% Aspha-min® based on the total weight of the binder were used. The PG64-28 control and WMA binders with un-aged conditions, after short-term aging process, and after long-term aging process were tested by Dynamic Modulus Rheometer (DSR), respectively. Viscosity and creep stiffness for both binders were also evaluated through the rotational viscosity test and Bending Beam Rheometer (BBR) test, respectively. For PG52-34, a control binder and a binder with 0.3%, 0.4% and 0.5% Aspha-min® based on the total weight of the binder were used. Viscosity and dynamic shear modulus (G*) for all the PG52-34 control and WMA binders at the un-aged condition was evaluated through viscometer and DSR as appropriate. The main purpose for the binder test was to evaluate the effects of Aspha-min® on binder properties. Hence, the amount of Aspha-min® used in this study was not based on the recommended value by Eurovia [45].

For the asphalt mixture preparation, the mixture design used in this study was based on specifications for a local asphalt mixture used in Michigan, USA. The nominal maximum aggregate size is 12.5mm, and the designed traffic level is less than 3 million ESALs based on the current Superpave™ asphalt mixture design procedure [46-48]. A PG64-28 binder (as mentioned previously) was used for both control and WMA mixtures. For control mixture, the sample was batched and mixed using a bucket mixer in the lab. The mixtures were then heated in an oven for two hours (short-term aging) until the control mixtures reached the compaction temperature (142°C). The Superpave™ specification [46-48] was followed in the mix preparation. For the WMA mixture, samples were batched and mixed in the lab using the same aggregate and binder as the control mixture. Aspha-min® was added at the rate of 0.3% and 0.5% based on the mixture weight during the mixing process. Both WMA mixtures with 0.3% and 0.5% Aspha-min® were mixed at 110°C and 130°C and compacted at 100°C and 120°C, respectively. All the mixtures (HMA and WMA) were compacted to the air void of 4% following the Superpave™ specification[46-48].

For the performance test, the control mixture and WMA mixture were evaluated through the Indirect Tensile (IDT) resilient modulus test, the Asphalt Pavement Analyzer (APA) rutting test, and the dynamic modulus (|E*|) test. The test results were compared and also used in evaluating the pavement permanent deformation using the Mechanistic-Empirical Pavement Design Guide (MEPDG) analysis.

2.1.4.2: Rotational Viscosity Testing

Previously, it was mentioned that most of the WMA reduced mixing and compacting temperature by lowering the binder viscosity. The viscosity test in this study was performed at six different temperatures (80°C, 100°C, 130°C, 135°C, 150°C, and 175°C)

For the PG64-28, three types of binder (i.e., control, 0.3% and 0.5% Aspha-min®) were chosen to run the rotational viscosity test. The test results are shown in

Figure 2.4. On the other hand, four types of PG52-34 binders (i.e., control, 0.3%, 0.4% and 0.5% Aspha-min®) were used in the viscosity test. The results are shown in Figure 2.5.

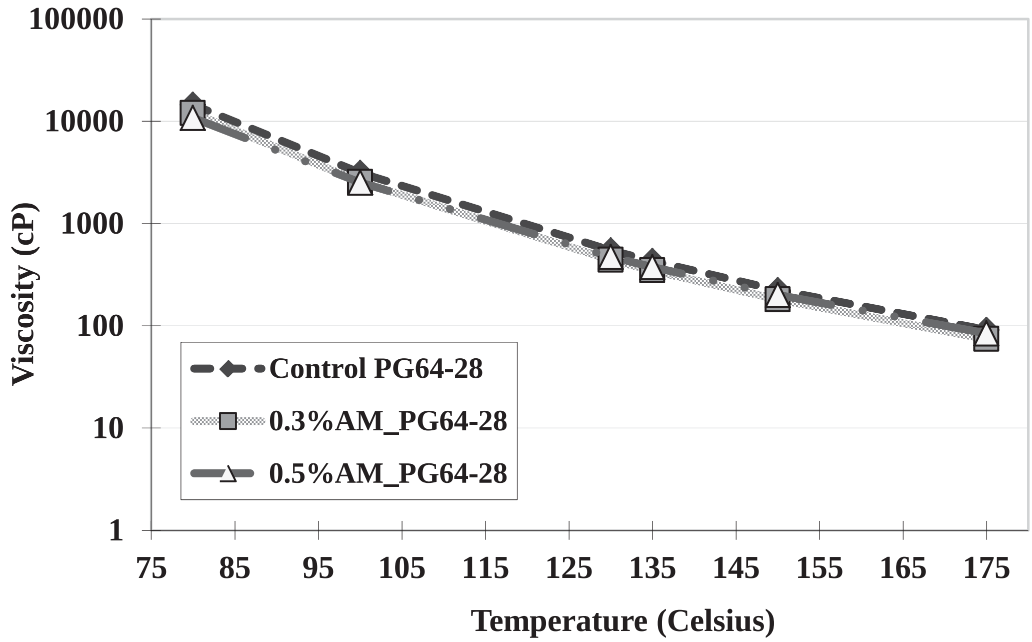


Figure 2.4 Comparing Viscosity Test Results for PG64-28 Control and WMA binders

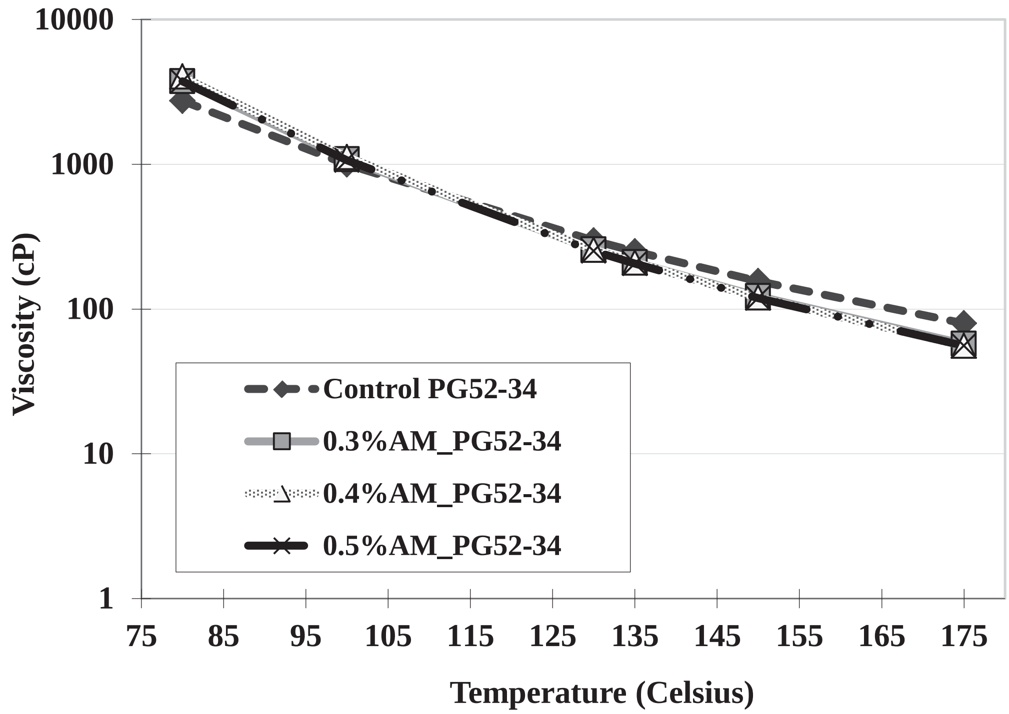


Figure 2.5 Comparing Viscosity Test Results for PG52-34 Control and WMA Binders

From Figure 2.4 and Figure 2.5, it is observed that the additional Aspha-min® does not have much effect on the viscosity of the binder. The mixing and compacting temperatures are located at 0.17+/-0.02 Pa·s and 0.28+/-0.03Pa·s, respectively. For PG64-28, the mixing and compacting temperatures increase when more Aspha-min® was used (i.e. 0.5%). However, the results of PG52-34 did not show a similar trend as PG64-28. Hence, the preliminary study of viscosity concluded that the reduction of viscosity is not affected with the amount of Aspha-min® added based on the rotational viscosity test.

In order to determine whether the Aspha-min® significantly affects the binder, a statistical method and paired t-test with 95% confidence level was performed. For the PG64-22 binder, the 95% confidence interval for the mean difference between the control binder and the binder with 0.3% Aspha-min® is found in a small range (-0.090, 0.693), and the range for control binder and the binder with 0.5% Aspha-min® is found within (-2.80, 9.10). For the PG52-34 binder, the 95% confident interval for the mean difference between Control PG52-34 and 0.3%AM_PG52-31, Control PG52-34 and 0.4%AM_PG52-34, and Control PG52-34 and 0.3%AM_PG52-34 are located in the range of (-0.0057, 0.0752), (-0.0008, 0.0683), and (-0.0139, 0.0939), respectively. Therefore, even though the Aspha-min® slightly reduced the viscosity of the binder, the statistical test results indicate that the additional 0.3% to 0.5% Aspha-min® did not significantly affect the viscosity.

Typically, mixing and compacting temperatures are evaluated from a viscosity-temperature graph. However, it is not feasible to follow the traditional rule in this case. Eurovia[45,49] indicates that the Aspha-min® is added during the mixing process so that it can release the water spray and allow a lower mixing temperature. Adding the Aspha-min® into the binder may change the binder's characteristic, and it is inappropriate to predict the mixing and compacting temperature through the viscosity- temperature chart.

2.1.4.3: Dynamic Shear Modulus (|G*|) Testing

The Dynamic Shear Rheometer (DSR) test was performed to evaluate the effect of rheological properties for the additional Aspha-min® in the binder. As indicated previously, PG64-28 and PG52-34 were used. For binder PG64-28, un-aged binder, binder after short-term aging process, and binder after long-term aging process were used in the DSR tests. The short-term aging process is known as the asphalt binder condition after pavement construction and is simulated using the Rolling Thin Film Oven (RTFO) in the lab. The long-term aging process was prepared through a Pressure Aging Vessel (PAV). The PAV is used to simulate in-service oxidative aging of asphalt binder by exposure to elevated temperatures in a pressurized environment in the laboratory. For binder PG52-34, only DSR results for un-aged binder are presented at this time.

Table 2.1 shows the results of the DSR test for the PG64-28 and PG52-34 with and without the Aspha-min® additive. It is observed that the additional Aspha-min® lowers the value of G*/sin(δ) for both PG52-34 and PG64-28 binders. In addition, PG64-28 binder with the addition of 0.3% and 0.5% Aspha-min® failed to meet Superpave™ specification requirement (i.e., minimum 1.00KPa). This also indicates that the binder may bump down by one performance grade after adding the Aspha-min®, which confirmed the findings in the literature [7,17]; the additional Aspha-min® may decrease the production temperature by bumping one grade down on high temperature.

For the DSR results of PG64-28 binder after the short-term aging process, as expected, value of G*/sin(δ) appears to be larger than the binder with additional Aspha-min®. The temperature used in the RTFO aging process was 163°C for all binders even though the mixing temperature of binder with Aspha-min® was lower during the mixing process. The G*/sin(δ) for the control binder is 2.62KPa and for additional 0.3% and 0.5% Aspha-min® were 2.05KPa and 2.03KPa respectively. Again, the PG64-28 binder with the additional Aspha-min® does not qualify for Superpave™ binder specification where the minimum requirement value after the short-term aging process is 2.20KPa. Both results from DSR test for un-aged and short-term aging processes have shown that the additional Aspha-min® increases the rutting potential.

For the DSR test results on the PG64-28 binder after long-term aging, G*·sin(δ) for the control binder is 2064.3KPa while the binders with the addition 0.3% and 0.5% of Aspha-min® are 2639.2KPa and 2813.8KPa respectively. This indicates that the additional Aspha-min® shows a higher potential in fatigue distress. However, the results still fall under the limitation of Superpave™ specification of maximum 5000KPa.

The aging factor was found based on this test as well. The aging factor was determined based on the ratio between G*/sin(δ) of un-aged and short term aging[13].

Due to the limited availability of current test results, only the aging factor of PG64-28 was evaluated. Table 2.2 shows the aging factor for control and WMA binders. This finding indicated that the additional Aspha-min® increased the binder's aging factor (i.e. an increase of 0.01 and 0.38 by adding 0.3% Aspha-min® and 0.5% Aspha-min®, respectively). Generally, a lower aging factor indicated better pavement life because pavement aged slower over its serviceability [13]. Thus, this finding concluded that WMA has a shorter pavement life compared to the HMA.

Table 2.1 Dynamic Shear Modulus Test Results for High and Low Temperatures

	G*/sin(δ) (kPa)				G*·sin(δ) (kPa)
	High Temperature[1]				Low Temperature[2]
	Un-aged binder[3]		Binder after RTFO aging[4]		Binder after PAV aging[5]
Asphalt Binder	52°C	64°C	52°C	64°C	22°C
Control PG52-34	1.23	-	-	-	-
0.3%AM_PG52-34	1.06	-	-	-	-
0.4%AM_PG52-34	1.07	-	-	-	-
0.5%AM_PG52-34	1.01	-	-	-	-
Control PG64-28	-	1.18	-	2.62	2064.30
0.3%AM_PG64-28	-	0.92	-	2.05	2639.20
0.5%AM_PG64-28	-	0.78	-	2.03	2813.80

[1] High temperature testing is designed to evaluate the rutting potential

[2] Low temperature testing is designed to evaluate the fatigue cracking potential

[3] Asphalt with original condition that didn't go through any aging process, or tank asphalt

[4] Asphalt that went through short-term aging process using Rolling Thin Film Oven (RTFO)

[5] Asphalt that went through RTFO and long-term aging process using Paving Aging Vessel (PAV)

Table 2.2 Aging factor (the ratio of G*/sin(δ) RTFO to G*/sin(δ) original) between original and short-term aged binder for the control mix and warm mix asphalt

Asphalt binder	Aging factor
Control PG64-28	**2.22**
0.3%AM_PG64-28	**2.23**
0.5%AM_PG64-28	**2.60**

2.1.4.4: Binder Creep Stiffness using Bending Beam Rheometer (BBR)

The Bending Beam Rheometer (BBR) test was performed to evaluate the creep stiffness of the binder by applying a constant creeping load. All the binders went through the short-term aging process (RTFO) and long-term aging process (PAV) prior to this test.

The results obtained from the BBR test showed that the average of three replicates of creep stiffness and m-value for PG64-28 control binder was 210.5MPa and 0.315 respectively. For binder with additional Aspha-min®, the average three replicates of creep stiffness for binder with 0.3% and 0.5% Aspha-min® is 193.75MPa and 191.83MPa, respectively. In addition, the m-value for binder with 0.3% Aspha-min® was 0.317 and 0.321 for binder with 0.5% Aspha-min®. It is noteworthy that the additional Aspha-min® slightly decreases the value of the flexural creep stiffness of the binder in terms of the m-value and average stiffness. Based on the statistical analysis using the paired t-test, the 95% confidence interval for the mean difference of creep stiffness between the control binder and the binder with 0.3% and 0.5% Aspha-min® is found to be(7.61, 24.06) and (12.18, 25.15) respectively. This indicates that the additional Aspha-min® significantly reduces the creep stiffness of the binder, and thus the binder with Aspha-min® is likely to be less susceptible to thermal cracking.

2.1.4.5: Resilient Modulus using Indirect Tensile Testing (IDT)

The Indirect Tensile Test (IDT) was performed to examine the resilient modulus (M_R) for both control and WMA mixtures based on the AASHTO TP 31 specification. Tests were performed at four temperatures: 4°C, 21.1°C, 37.8°C and 54.4°C. Figure 2.8 shows the IDT results tested at 4°C, 21.1°C, 37.8°C, and 54.4°C. Observation of Figure 2.8 shows the M_R tested at high temperatures (i.e., 37.8°C and 54.4°C) increased slightly for both 0.3% and 0.5% Aspha-min® additives when compared to the control mixture. The difference of M_R is not significant at lower temperatures (e.g., 4°C and 21.1°C) based on statistical analysis. In order to determine whether the Aspha-min® significantly affects the M_R, a statistical method, paired t-test, with 95% confidence level was performed. Based on the statistical analysis, the M_R of WMA compacted at 120°C is significantly higher than the control mixture, and there is no significant difference between the control mixture and WMA compacted at 100°C. In addition, the amount of Aspha-min® added does not show significant effects on the M_R based on the statistical analysis.

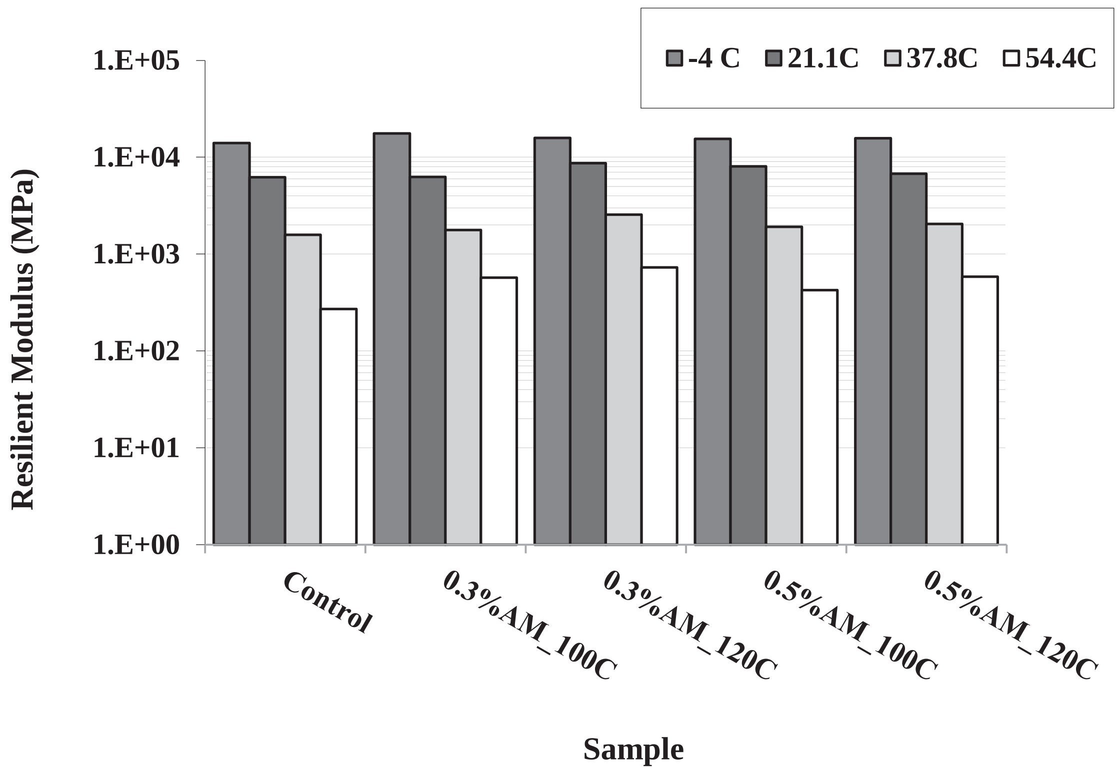


Figure 2.6 Resilient Modulus tested at 4°C, 21.1°C, 37.8°C and 54.4°C for control mixture compacted at 140°C and WMA mixture compacted at 100°C and 120°C

In the tests shown here, the temperature did affect the modulus when tested at high temperatures (i.e., 37.8°C and 54.4°C). It was observed that the M_R increases when the compacting temperature increases. This agrees with the finding from the NCAT research that two parameters (i.e., air void content and temperature) affect the M_R values [17]. The IDT results tested at high temperatures show that the WMA compacted at 120°C has a slightly higher M_R when compared to the WMA compacted at 100°C. The reason being that at high temperatures (i.e. 37.8°C and 54.4°C), the asphalt is very soft and tends to flow. The M_R is mainly affected by the aggregate skeleton filled with viscous asphalt. The specimens compacted at 120°C may have a better aggregate skeleton to resist load compared with the specimens compacted at 100°C. A stronger aggregate skeleton or aggregate-aggregate contact in the asphalt mixture may increase the asphalt mixture modulus because of the better capability of the loads from one aggregate to another aggregate [50-52]. Therefore, for specimens with both 0.3% and 0.5% Aspha-min® additives, the specimens compacted at 120°C show a higher resilient modulus than the specimens compacted at 100°C. When a paired t-test was applied for the dataset of both 0.3% and 0.5% additives tested at the four temperatures, it was found that there is no significant difference at a 95% confidence level in the M_R between the two compaction temperatures.

2.1.4.6: Permanent Deformation using Asphalt Pavement Analyzer (APA)

In the APA rutting test, control and WMA mixture with a binder grade of PG64-28 were used. This test was performed using the Asphalt Pavement Analyzer (APA) device based on AASHTO TP 63-03 at 64°C. The purpose of this test was to determine the rut resistance for WMA and compare the results with the control mixture. The results of the APA test are presented in Figure 2.7. Based on the results conducted, it was found that WMA has a lower rutting depth compared to the control mixture. For the general trend shown in Figure 2.11, the rut depth decreases when the compacting temperature increases. This is most likely due to the compactability of the sample during the compacting process. It is also found that the rut depth decreases for both 0.3% and 0.5% Aspha-min® compacted at 120°C, which was around 2mm to 2.5mm when compared to the control mixture.

The additional Aspha-min® reduced the permanent deformation with the APA test, which was also observed by Wasiuddin [13]. Theoretically, the rutting depth for WMA is higher than the control mixture due to lesser binder aging effect. However, the APA test results in this study show that WMA has a better rutting resistance. The initial finding indicated that segregations might happen at the high temperature (i.e. 142°C) during the compaction process and this affected the compactability of the mixture. It shall be noted that the APA samples were prepared with a gyratory compactor and then tested in the next a few days. Further investigation is ongoing to study the microstructure of the aggregate-aggregate interaction in a project funded by the National Science Foundation.

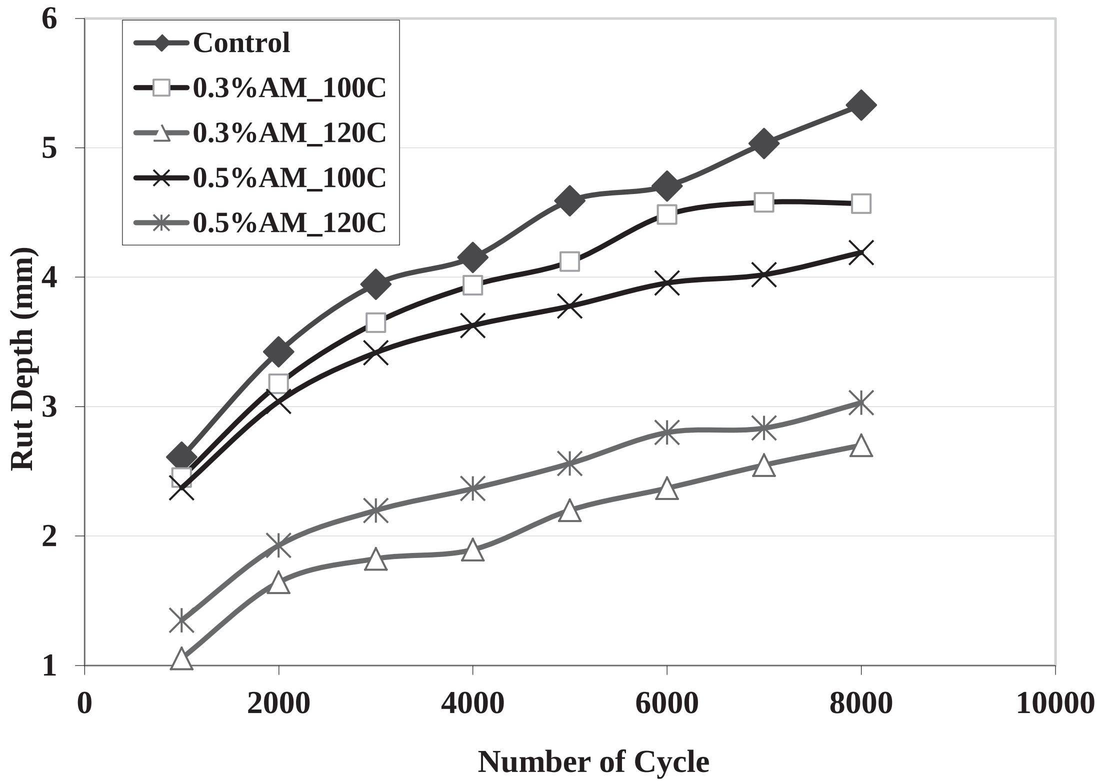


Figure 2.7 APA rutting test results for the control mixture and the WMA at 64°C

2.1.4.7: Dynamic Modulus (|E*|) Testing

Dynamic modulus (|E*|) is the modulus of a visco-elastic material. The |E*| of a visco-elastic test is a response developed under sinusoidal loading conditions[53]. Figure 2.8 shows the test set up, where the sample of an asphalt mix specimen is loaded under the compressive test. The applied stress and the resulting recoverable axial strain response of the specimen are measured and used to calculate the dynamic modulus and phase angle. The dynamic modulus is defined as the ratio of the amplitude stress (σ) and amplitude of the sinusoidal strain (ε) that results in a steady state response at the same time and frequency. The advantage of the |E*| is that it can be used in developing a series of prediction models through Mechanistic-Empirical Pavement Design Guide (MEPDG). |E*| tests were conducted according to AASHTO TP62-03.

The temperatures used were -5°C, 4°C, and 21.1°C. The frequencies used in this test ranged from 0.1Hz to 25Hz. As described previously, five types of mixtures were use in this test: a control mixture, WMA with 0.3% Aspha-min® mixture compacted at 100°C and 120°C, and WMA with 0.5% Aspha-min® mixture compacted at 100°C and 120°C. The recoverable axial micro-strain in this test was controlled within 50 and 100 micro strains so that the material is in a visco-elastic range [54].

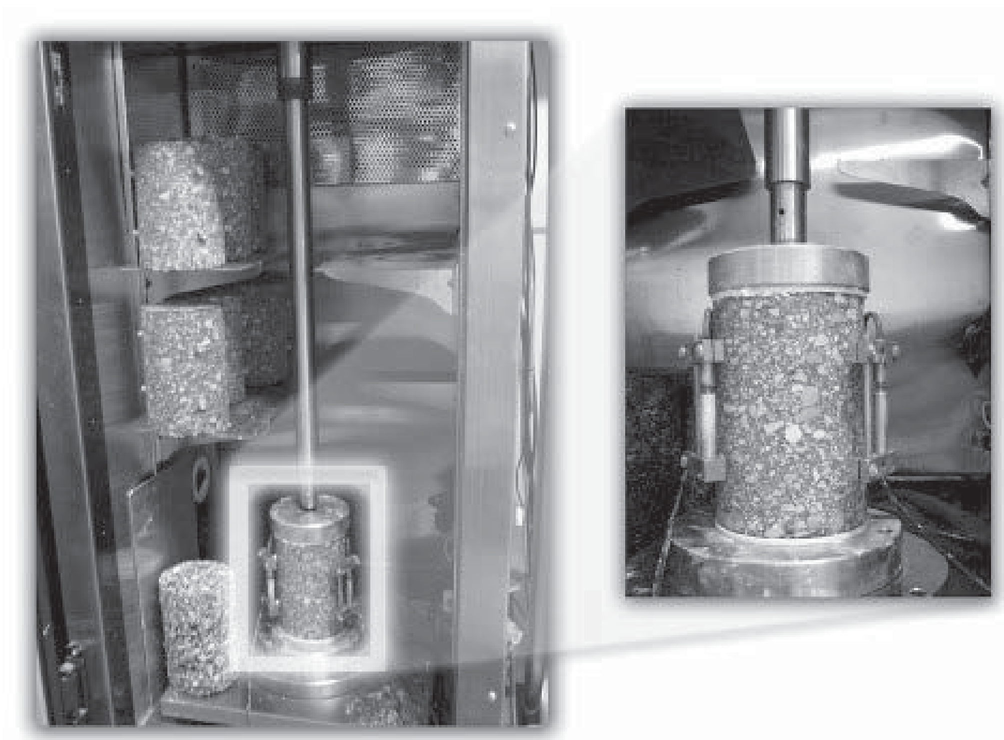


Figure 2.8 Dynamic Modulus Test Setup

Dynamic modulus values measured over a range of temperatures and frequencies of loading can be shifted into a master curve for analyzing the asphalt mixture's performance. The concept of a sigmoidal master curve is to "shift" the relative |E*| from different temperatures to the time of loading using the sigmoidal fitting model, so that the various curves can be aligned to form a single master curve. In this study, a sigmoidal master curve was constructed for the measured |E*| for both control and Aspha-min® mixtures, and are shown in Figure 2.9. During the formation of the sigmoidal master curve, -5°C was used as the reference temperature.

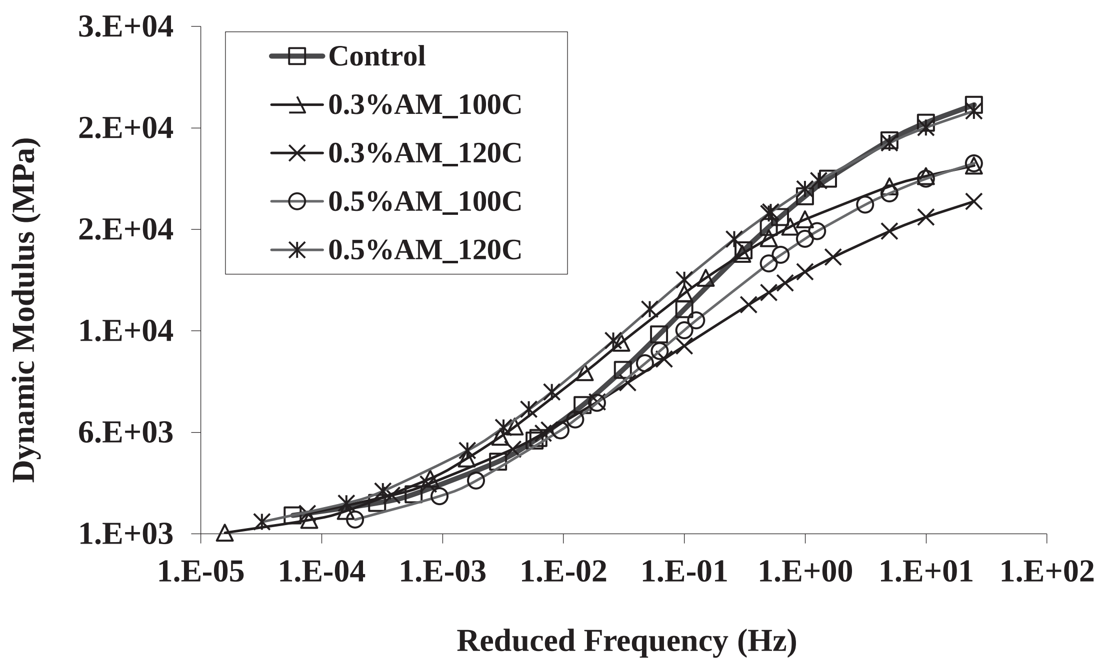


Figure 2.9 Sigmoidal Master Curve of Dynamic Modulus Test Results for Control and WMA Mixtures

Based on the test results, it is observed that the mixtures with the additional 0.5% Aspha-min® have a higher |E*| value overall when compared to the control mixture. A statistical method, paired t-test, with 95% confidence level was performed to evaluate the effect of Aspha-min®. Based on the statistical analysis, the |E*| for WMA made with 0.5% Aspha-min® is significantly higher than the control mixture. In addition, WMA compacted at 120°C has a higher |E*| based on the statistical analysis. A higher |E*| means the mixture has better performance in terms of rutting resistant [55]. Based on the |E*| test results, it can be concluded that the WMA has the same or better performance in pavement rutting resistant compare to HMA (i.e., the control mixture).

2.1.4.8: The Application of the Aspha-min® in the Mechanistic-Empirical Pavement Design

The mechanical properties of the WMA and control mixtures were evaluated. However, at this time, the field performance data was not available. Therefore, an alternative approach by using the Mechanistic-Empirical Design Guide (MEPDG) was used to assess the pavement distress level. The MEPDG was developed under the National Cooperative Highway Research Program (NCHRP) Project 1-37A and is designed to be adopted by the American Association of State Highway and Transportation Officials (AASHTO) for use as the future pavement design guide for public and private sectors. The development of the MEPDG is based on the collective experience of pavement experts, data from road tests, calculation of pavement response, and mechanistic and empirical pavement performance models[56,57]. The MEPDG is able to predict the development and propagation of various kinds of pavement distress, including rutting and fatigue cracking, using input data on asphalt mixture characteristics obtained from laboratory testing. There are three hierarchical levels in the MEPDG: Level 1, Level 2, and Level 3, with the accuracy of prediction increasing from Level 3 to Level 1 [58].

In this study, a Level 1 design was used with the measured dynamic modulus as shown in the previous section. The assumed values for creep compliance were used for all the WMA and control mixtures. The creep compliance will most dramatically impact the prediction of thermal cracking. This study focuses exclusively on the development and propagation of rutting. The design pavement life was set at 20 years. Since this study only focuses on comparing the performances between WMA made with Aspha-min® and traditional HMA (control), a reasonable layer of pavement thickness was used in the MEPDG analysis for both WMA and HMA.

The climatic data and traffic information were estimated for a local highway condition [50,59]. The traffic parameters included the initial two-way AADTT, number of lanes in design direction, percent of trucks in design direction, percent of trucks in design lane, operational speed (km/h), mean wheel location (distance from the lane marking), traffic wander standard deviation, design lane width, growth rate, and growth function. The vehicle distribution for different classes was identified for this study. After the MEPDG analysis for the defined pavement structure, the distress levels over 20 years were predicted using the built-in models. The rutting predicted using the MEPDG was used as the pavement distress for comparison in this study.

The pavement structure used in this study is illustrated in Figure 2.10, and the MEPDG analysis results are shown in Figure 2.11. The results indicated that the difference in predicted permanent deformation for both HMA and WMA is insignificant.

Even though previous discussions indicated that WMA has the same or better performance in terms of rutting resistant based on |E*| results, the different air void level and density of WMA used in MEPDG resulted in having a similar performance to HMA over a 20-year period. It should be noted that the long term field performance data will be more reliable.

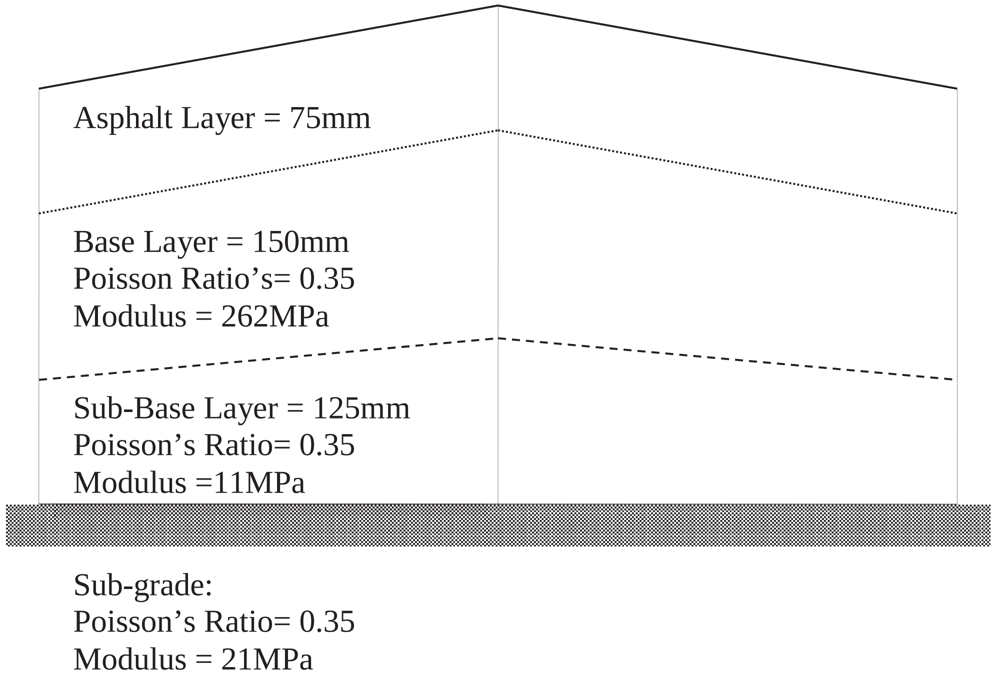


Figure 2.10 Pavement Structure for the Control and WMA in MEPDG Study

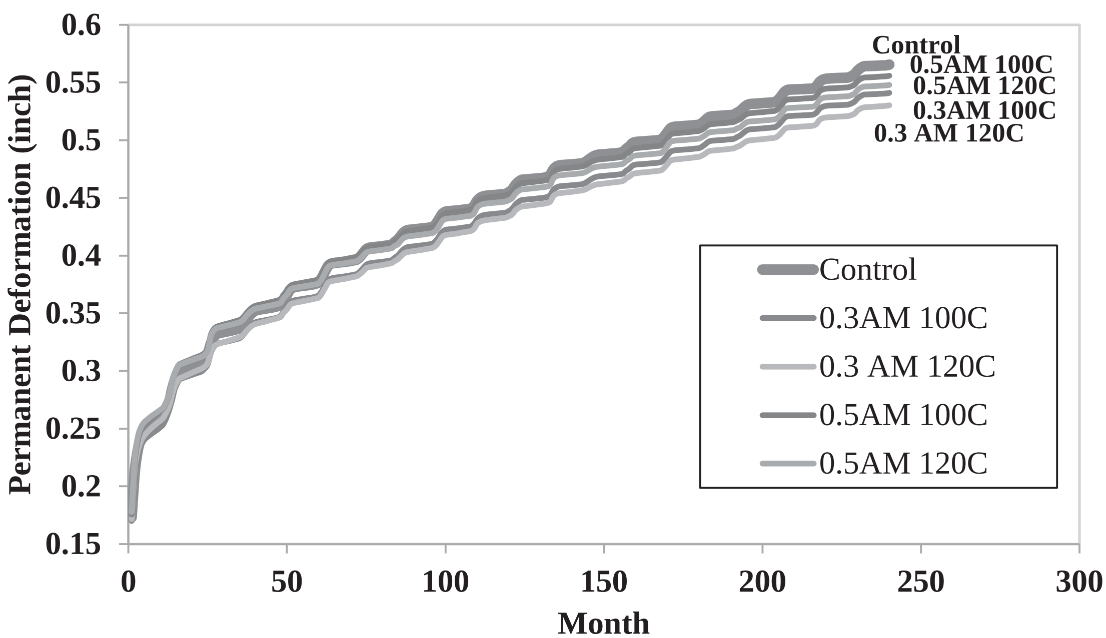


Figure 2.11 Predicted rutting depth over 20 years using MEPDG analysis

2.1.4.9: Summary

This case study presented laboratory results of WMA made with Aspha-min®, and an evaluation of pavement design using MEPDG:

1. Through the asphalt binder test, the additional Aspha-min® slightly decreases the binder's viscosity, and mixing and compacting temperature. However, the statistical analysis shows that this effect is not significant.
2. The additional Aspha-min® also shows a higher potential in rutting and fatigue cracking through the DSR test when compared to the control binder.
3. The BBR test results indicated that the additional Aspha-min® significantly reduces the binder's creep stiffness based on statistical analysis and thus the binder with Aspha-min® is likely to be less susceptible to thermal cracking.
4. For the resilient modulus under the indirect tensile test setup, there is no significant difference for resilient modulus at a lower temperature. However, WMA has a higher resilient modulus when compared to the control mixture, and this is probably due to the different aggregate skeletons in the control mixture compacted at a high temperature (142°C) and WMA produced at lower temperatures (both 100°C and 120°C).
5. Through the APA test, it is found that WMA appears to have higher rutting resistance and the rutting resistance increased when the compaction temperature for WMA increased. The initial finding indicated that segregations might happen at high temperature (i.e. 142°C) during the compaction process and this affected the compactability of the mixture.
6. WMA made with 0.5% Aspha-min® or compacted at 120°C had shown a higher performance overall for |E*| through the dynamic modulus test. It is noticeable that WMA compacted at 120°C has a higher |E*| when both results (WMA compacted at 100°C and 120°C) were compared.

7. In this study, the dynamic modulus |E*|from different temperatures and frequencies, mixture air void level, and density were used as an important input parameters for the MEPDG. The results indicated that the difference of predicted permanent deformation for both HMA and WMA is insignificant. Even though previous discussions indicated that WMA has a same or better performance in rutting resistant based on |E*| results, the different air void level and density of WMA used in MEPDG resulted in having similar performance to HMA over 20-year period.

2.1.5: Case Study 2: WMA using ADVERA® WMA

ADAVERA® WMA is similar to Aspha-min®, which is also an aluminosilicate or hydrated zeolite powder [60]. According to the manufacture of ADVERA® WMA, PQ Corporation indicated that ADVERA® WMA contains 18-21% of its mass as water (entrapped in its crystalline structure) and the water will be released at a temperature above 210°F. Figure 2.12 shows the ADVERA® WMA used in this project.

The ADVERA® WMA was recommended to be added at the rate of 0.25% by weight the mixture. In the asphalt plant, ADVERA® WMA can be introduced to the mixture through an existing port for fiber line. In order to have better dispersion of ADVERA® WMA, additional mixing box in the drum plant shown in Figure 2.13 was recommended.

Figure 2.12 ADVERA® WMA

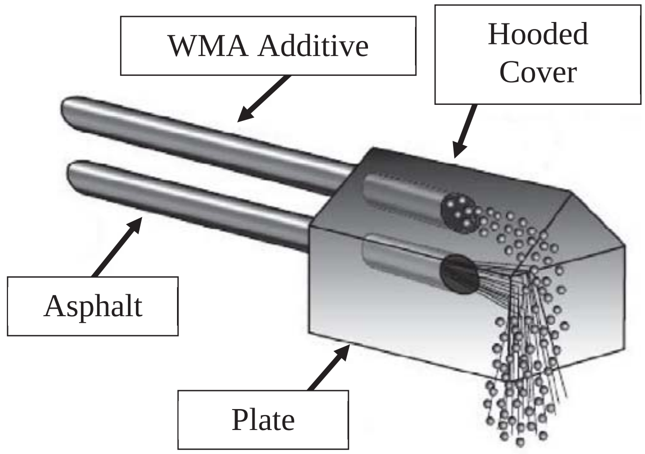


Figure 2.13 ADVERA® WMA Mixing Box (from PQ Corp[3])

2.1.5.1: Sample Preparation

In this case study, both asphalt and mixture test were involved. Past studies indicated that ADVERA® WMA would not affect asphalt binder properties [60]; however, the properties of asphalt would be different due to different production temperatures. Thus, in this case study, four types of binder at four aging conditions were used to evaluate their rheological properties and aging factors. Binder performance grade of PG 58-34 (also used in mixture testing) was used in this study, and they were aged at four different temperatures (i.e. 100°C, 115°C, 130°C, and 163°C) for 12 hours.

For asphalt mixture testing, the mixture design used in this study was based on specifications for a local asphalt mixture used in Michigan. The (nominal maximum aggregate size is 12.5m, and the designed traffic level is less than 3 million ESALs based on the current Superpave™ asphalt mixture design procedure [46-48]. A PG58-34 binder (as mentioned previously) was used for both control and WMA mixtures. For control mixture, the sample was batched and mixed using a bucket mixer in the lab. The mixtures were then heated in an oven for two hours (short-term aging) until the control

[3] Image obtained from PQ Corp with permission – please refer to Appendix 1

mixtures reached the compaction temperatures (153°C). The Superpave™ specification [46-48] was followed in the mix preparation. For the WMA mixture, samples were batched and mixed in the lab using the aggregate and binder same as the control mixture. ADVERA® WMA was added at the rate of 0.15%, 0.25% and 0.35% based on the mixture weight during the mixing process. All WMA mixtures were mixed at 100°C, 115°C and 130°C, and compacted at 100°C, 115°C and 130°C, respectively. All the mixtures (HMA and WMA) were compacted using the 86 gyration numbers.

Table 2.3 shows the volumetric properties and compaction energy index [61] measured after the compaction. Based on Table 2.3, it is shown that the WMA has an average air void levels ranged from 4.38% to 6.11%, and VMA ranged from 25.14 to 26.19. The initial hypothesis was when the compaction temperature increase, the air void level decreased and/ or the compaction energy index decrease. However, the testing results show that the compaction temperature does not affect the air void level and compaction energy index.

Table 2.3 Volumetric Properties of HMA and WMA made with Advera® WMA

Mixture Type	Average G_{mm}	Average G_{mb}	Average Air Void	VMA[1]	Compaction Energy Index
Control HMA	2.5730	2.4411	5.13%	25.37	61.62
0.15 Advera 130C	2.5487	2.4213	5.00%	25.67	73.70
0.25 Advera 130C	2.5632	2.4067	6.11%	25.17	105.07
0.35 Advera 130C	2.5542	2.4293	4.89%	25.55	71.82
0.15 Advera 115C	2.5556	2.4232	5.18%	26.13	82.12
0.25 Advera 115C	2.5526	2.4373	4.52%	25.14	69.54
0.35 Advera 115C	2.5523	2.4309	4.76%	26.16	62.23
0.15 Advera 100C	2.5746	2.4277	5.71%	25.85	79.47
0.25 Advera 100C	2.5407	2.4293	4.38%	26.19	61.90
0.35 Advera 100C	2.5557	2.4310	4.88%	25.64	60.38

[1] Void in Mineral Aggregate

For the performance test, the control and WMA mixtures were evaluated using dynamic modulus, tensile strength ratio, four point beam fatigue, flow number and asphalt pavement analyzer (APA) rutting tests. All testing were performed immediately after samples were produced and completed within two months to avoid aging of HMA and WMA.

2.1.5.2: Rheological Properties and Asphalt Aging Factor

The Dynamic Shear Rheometer (DSR) test was performed to evaluate the effect of rheological properties and aging factor. As indicated previously, a PG58-34 binder was used in this test, and it was tested at unaged and short-term aging condition. The short-term aging process is known as the asphalt binder condition after pavement construction and is simulated by heating in the oven for 12 hours. Additionally, four different temperatures were used for short-term aging in this case study, and they were 163°C for control, and 100°C, 115°C and 130°C for WMA.

Table 2.4 Complex Shear Modulus and Aging Factor for HMA and WMA

	Aging Temperature			
	Control	WMA		
	163°C	100°C	115°C	130°C
Unaged	1345.94	1287.61	1306.13	1345.94
Aged	2609.44	1630.01	1635.97	2609.44
Aging Factor	1.93875	1.03648	1.26592	1.25253

For DSR testing, temperature of 58C and frequency of 10 rad/s were used in this testing. Table 2.4 shows the testing results for DSR and the aging factor of WMA aged at different temperatures. Based on Table 2.4, it is observed that all the binders meet the Superpave™ specification requirement (i.e., minimum 1.00KPa). The aging factor was found based on this test as well. As indicated previously, the aging factor was determined based on the ratio between $G^*/\sin(\delta)$ of un-aged and short term aging[13]. This finding from Table 2.4 indicated binders aged at lower temperature (i.e. 100°C, 115°C and 130°C) have significantly lower aging factors compared to control 163°C. A lower aging factor due to lower production temperature could increase the rutting potential of the mixture at the early serviceability.

2.1.5.3: Dynamic Modulus Testing

In this case study, the dynamic modulus (|E*|) tests were conducted according to AASHTO TP62-03. The temperatures used were -10°C, 4°C, 21.3°C and 39.2°C. The frequencies used in this test ranged from 0.1Hz to 25Hz.

10 different types of mixtures were tested in this study: control HMA, and WMA made with ADVERA® WMA at the rate of 0.15%, 0.25% and 0.35% based on mixture weight compacted at 100°C, 115°C and 130°C. The recoverable axial micro-strain in this test was controlled within 75 and 125 micro strains so that the material is in a visco-elastic range [54,55].

In order to compare control HMA with all WMA samples, master curve technique was used to shift all |E*| values at various frequencies and temperatures into one single curve. As mentioned previously, the concept of a sigmoidal master curve is to “shift” the relative |E*| from different temperatures to the time of loading using the sigmoidal fitting model, so that the various curves can be aligned to form a single master curve. In this study, a sigmoidal master curve was constructed for the measured |E*| for control and WMA mixtures, and are shown in Figure 2.14. During the formation of the sigmoidal master curve, 4°C was used as the reference temperature.

Based on the test results, it is found that the production temperature and amount of ADVERA® WMA used to produce WMA did not affect the |E*| of WMA; however, it is observed that all WMA mixtures made with ADVERA® WMA are lower than control HMA especially at higher temperature (at lower reduced frequency). A statistical method, paired t-test, with 95% confidence level was performed to evaluate the effect of ADVERA® WMA, shown in Table 2.5. Based on the statistical analysis, the |E*| for all WMA made ADVERA® WMA are significantly lower than the control HMA. A higher |E*| means the mixture has better performance in terms of rutting resistant [55]. Based on the |E*| test results, it can be concluded that the WMA made with ADVERA® WMA has higher rutting potential compared to HMA (i.e. control mixture).

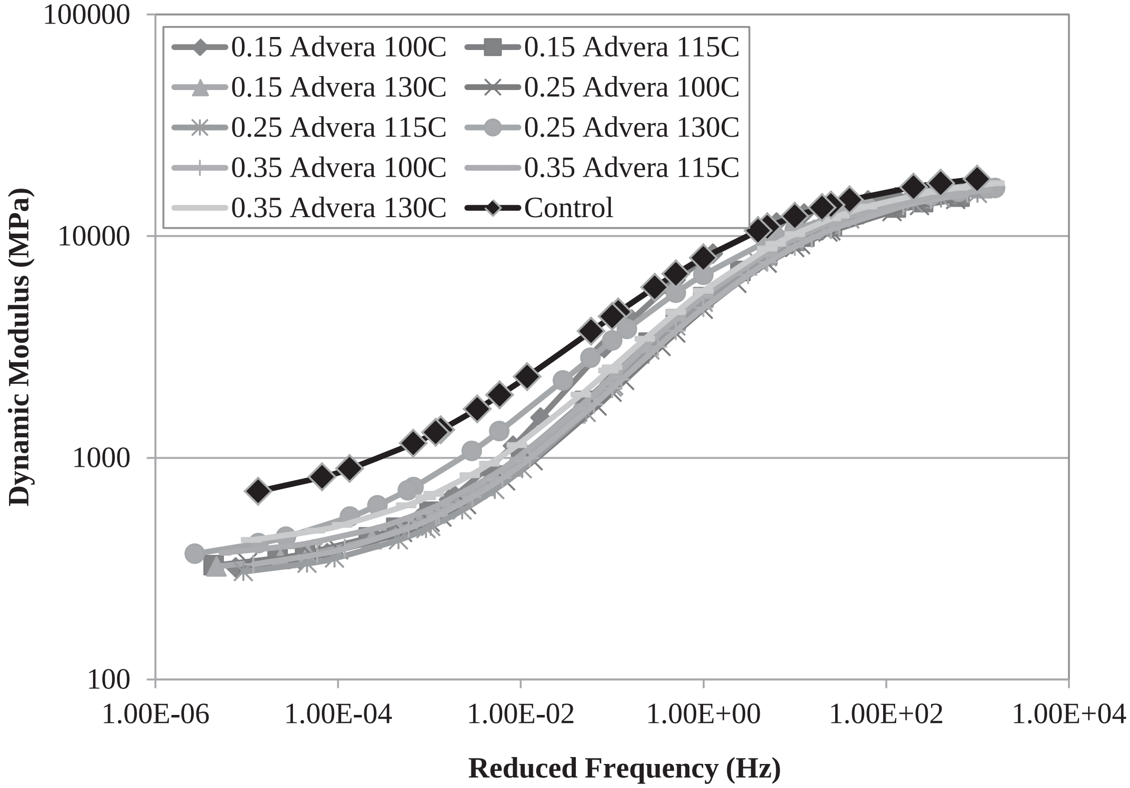


Figure 2.14 Sigmoidal Master Curve of Dynamic Modulus Test Results for Control HMA and WMA Mixtures

Table 2.5 Paired t-test with 95% Confidence Level for |E*| of Control HMA versus WMA

WMA	Result of Pair T-Test [Control HMA vs WMA]
0.15 Advera 100C	(2170, 16798)
0.15 Advera 115C	(6709, 21826)
0.15 Advera 130C	(6301, 19409)
0.25 Advera 100C	(7617, 22642)
0.25 Advera 115C	(6917, 20903)
0.25 Advera 130C	(3273, 13533)
0.35 Advera 100C	(7435, 21142)
0.35 Advera 115C	(5884, 17846)
0.35 Advera 130C	(5039, 13768)

2.1.5.4: Moisture Susceptibility Test Using Tensile Strength Ratio (TSR)

The purpose of tensile strength ratio testing is to evaluate asphalt mixture's fatigue potential and moisture susceptibility. In the past, researchers found out the tensile strength of asphalt mixture can be well related to fatigue cracking in asphalt pavement [62]. A higher tensile strength means that asphalt pavement can tolerate higher strains before it fails (i.e. cracking). Additionally, the moisture susceptibility of the asphalt mixture can be evaluated by comparing the tensile strength of asphalt mixture at wet and dry condition. In this study, the tensile strength ratio of control and WMA mixtures were tested based on AASHTO T283 [63]. Samples were prepared at the size of 100mm in diameter and 63.5mm in height. The temperature and loading rate used in this study were 25ºC and 0.085mm/s. Figure 2.15 shows the tensile strength testing setup, and Figure 2.16 shows a typical result from the indirect tensile strength test.

Figure 2.17 shows the TSR testing results for Control and WMA mixtures made with ADVERA® WMA. The result shows that most of the TSR for WMA passed the minimum TSR value required by the AASHTO T283 specification (TSR = 0.80). However, it was found that the tensile strength of WMA is significantly lower than HMA. A lower tensile strength means that the fracture energy of WMA is lower than

HMA. Wen and Kim [64] found that fracture energy was highly correlated with field fatigue performance. They also found that mixture with higher fracture energy has lesser fatigue cracking. Hence, this may indicate that the WMA made with ADVERA® WMA has higher fatigue cracking potential compared to HMA.

From Figure 2.17, it is also observed that for WMA produced at lower temperature (i.e. 100°C), the trend shows that the tensile strength of WMA decrease when more ADVERA® WMA was added. However, it is not significant for WMA produced at other temperature (i.e. 130°C and 115°C). In general, it was found that the TSR value of WMA is similar or higher than control HMA which indicated WMA has similar or better moisture susceptibility; however, the lower tensile strength of WMA indicated that WMA has higher fatigue potential.

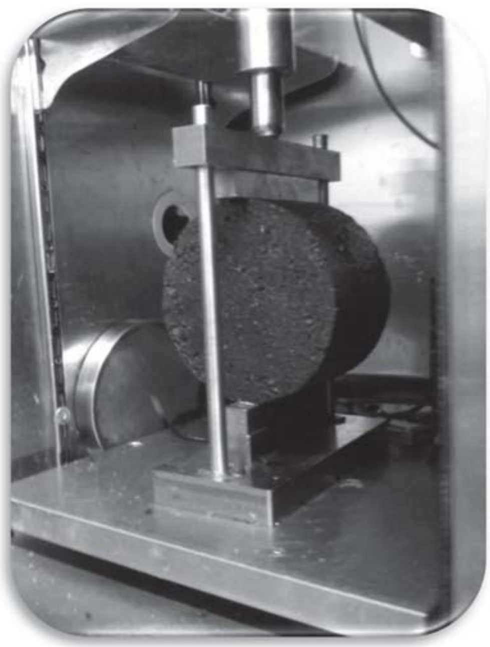


Figure 2.15 Indirect Tensile Strength Testing Setup

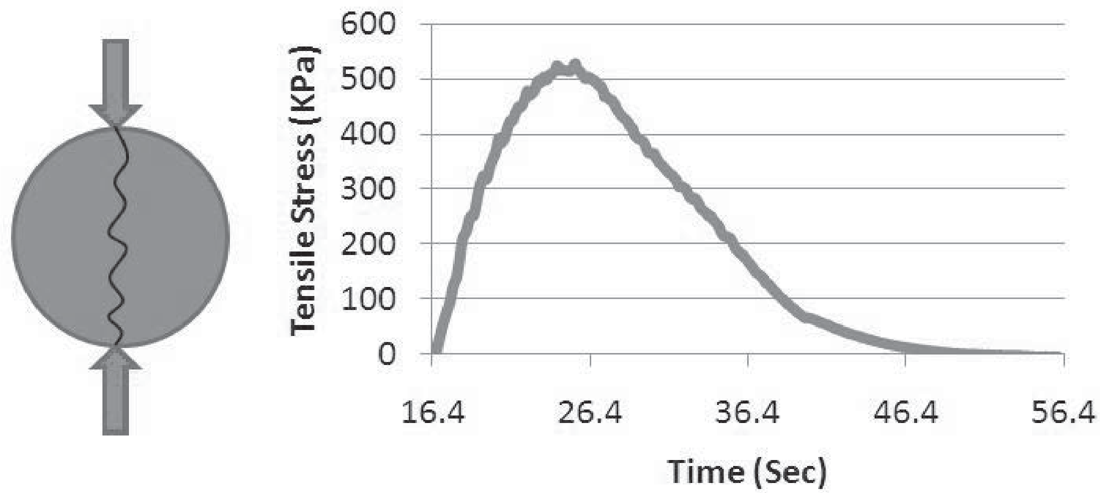


Figure 2.16 Typical Result for Indirect Tensile Strength

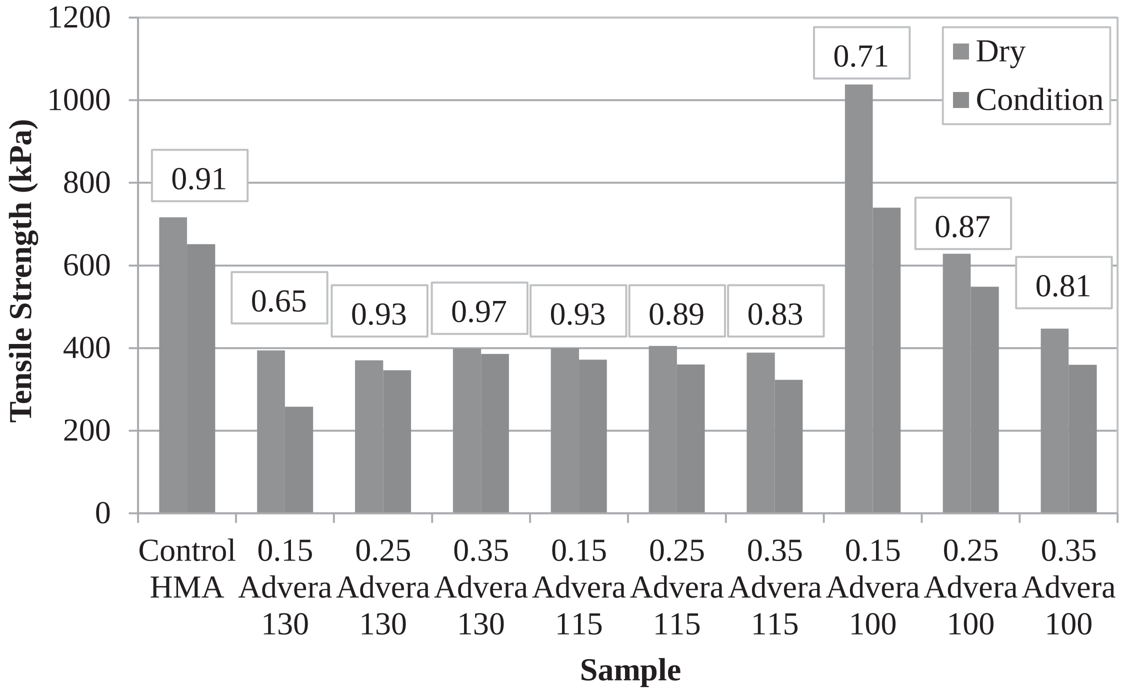


Figure 2.17 Tensile Strength Testing Results for Control HMA and WMA made with ADVERA® WMA

2.1.5.5: Four Point Beam Fatigue Testing

The results from the four-point beam fatigue tests are presented in this section. Fatigue is the damage occurring in a material due to the application of cyclic loading. The purpose of this test is to determine the fatigue life of the asphalt mixture subjected to the repeated bending until failure where the fatigue failure was defined as 50% reduction of initial stiffness [65]. In this test, a frequency of 10 Hz and 400 micro-strains (constant strain) were used for all the samples tested. As mentioned previously, control HMA, and WMA made with 0.15%, 0.25% and 0.35% ADVERA® WMA (based on mixture weight) produced at 100°C, 115°C and 130°C were used in this study. The results of the four-point beam fatigue testing are presented in Figure 2.18.

From Figure 2.18, it can be found that for most of the WMA, made with ADVERA® WMA fatigue life is higher than the control HMA. It is also noticed that the fatigue life of WMA is slightly higher when lower temperature was used; however, this finding is not significant. Additionally, the fatigue life of WMA was not affected by the amount ADVERA® added based on Figure 2.18.

There are several factors that would affect the fatigue life associated with production temperatures, and WMA additives when comparing HMA and WMA, including 1) absorption – lower mixing temperature (WMA) may result in less binder absorption into the aggregate, which will reduce the adhesion and thus affect the asphalt mixture fatigue life [6] and; 2) aging of the asphalt binder – lower mixing temperature of WMA will reduce binder's aging and thus improve workability of asphalt mixture.

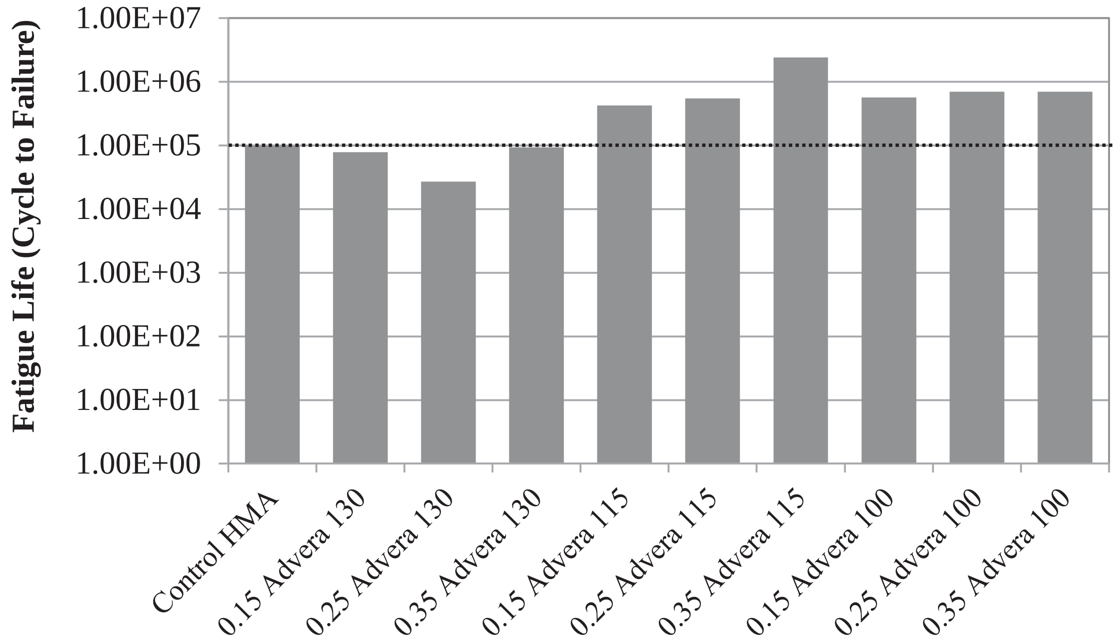


Figure 2.18 Results of Four Point Beam Fatigue Testing for Control HMA and WMA made with ADVERA® WMA

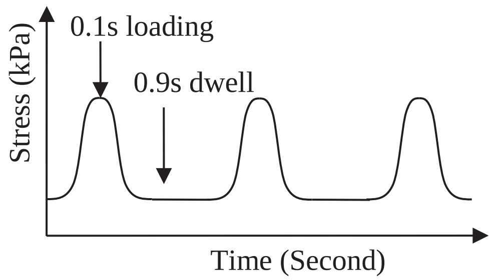
2.1.5.6: Flow Number Testing

The flow number (F_N) test, often referred to as the dynamic creep or repeated load testing, has been used as a quality control and quality assurance (QC/QA) test for rutting resistance as well as the permanent deformation characteristics for the past several years[66,67]. During the mid-70s, Brown and Snaith [68] conducted an experiment to analyze the cause and effect of an asphalt mixture from repeated loads. They indicated that the failure of the asphalt mixture was defined as the cycle number when a significant deformation was observed. Zhou and Scullion [69] indicates that F_N is better when distinguishing the performance and quality of asphalt mixtures in terms of rutting distress when compared with the $|E^*|$ [69,70]. Faheem et. al. [71] indicated that F_N is an important mixture property and has a strong correlation to the Traffic Force Index (TFI), which represents the densification loading by the traffic during its service life [71]. More recently, studies conducted by Witczak [72] and Dongre et al. [73] also showed a good correlation between F_N and field rutting performance.

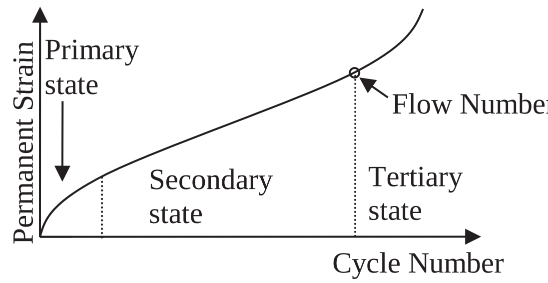
The flow number test is based on results from repeated loading and unloading of a Hot Mix Asphalt (HMA) specimen where the permanent deformation of the specimen is recorded as a function of load cycles. Normally, a 0.1 second loading followed by a 0.9 second dwell (rest time) is applied to the specimen as shown in Figure 1(a) [74,75]. Additionally, an effective temperature of 45°C, often referred to as rutting temperature, is used in this test [76,77].

There are three stages of flow that occurred during the test: primary, secondary and tertiary flow [76]. Under primary flow, there is a decrease in the strain rate with time. With continuous repeated load applications, the next phase is secondary flow, which is characterized by a relatively constant strain rate. The material enters tertiary flow when the strain rate begins to increase dramatically as the test progresses [78]. Tertiary flow indicates that the specimen begins to deform significantly, and the individual aggregates that make up the skeleton of the mix moves past each other [79-81]. The point or cycle number at which pure plastic shear deformation occurs is referred to as the "Flow Number". Figure 1(b) illustrates a typical relationship between the total accumulative plastic strain and number of load cycles. Flow number is based upon the initiation of tertiary flow or the minimum point of the strain rate curve [76] as shown in Figure 1(c). In addition, the flow number has been recommended as a rutting indicator for asphalt mixtures [66,72,78].

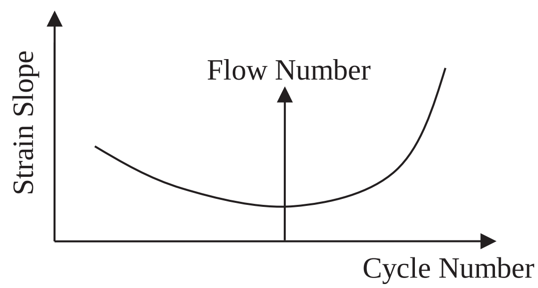
Figure 2.24 shows the testing results for control HMA and WMA made with 0.15%, 0.25% and 0.35% ADVERA® WMA produced at 100°C, 115°C and 130°C, respectively. Overall, Figure 2.24 shows that the F_N for WMA is lower than the control HMA. These results are in line with the findings from |E*| which WMA has a higher rutting potential. As mentioned previously, the reason was due to lesser aging of WMA during the production.



(a) Loading and unloading



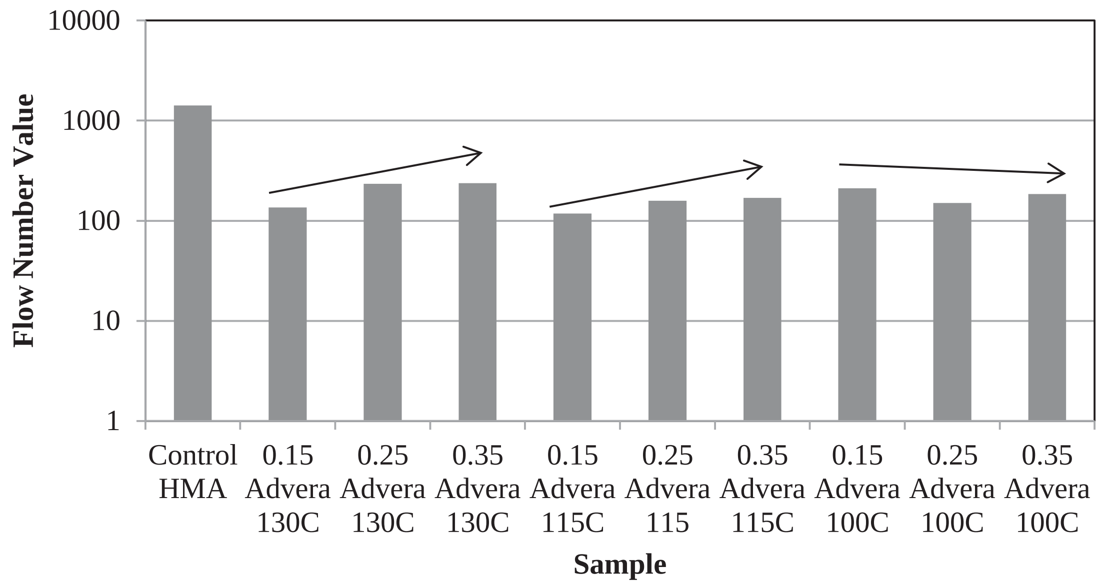
(b) Dynamic Creep Test Result



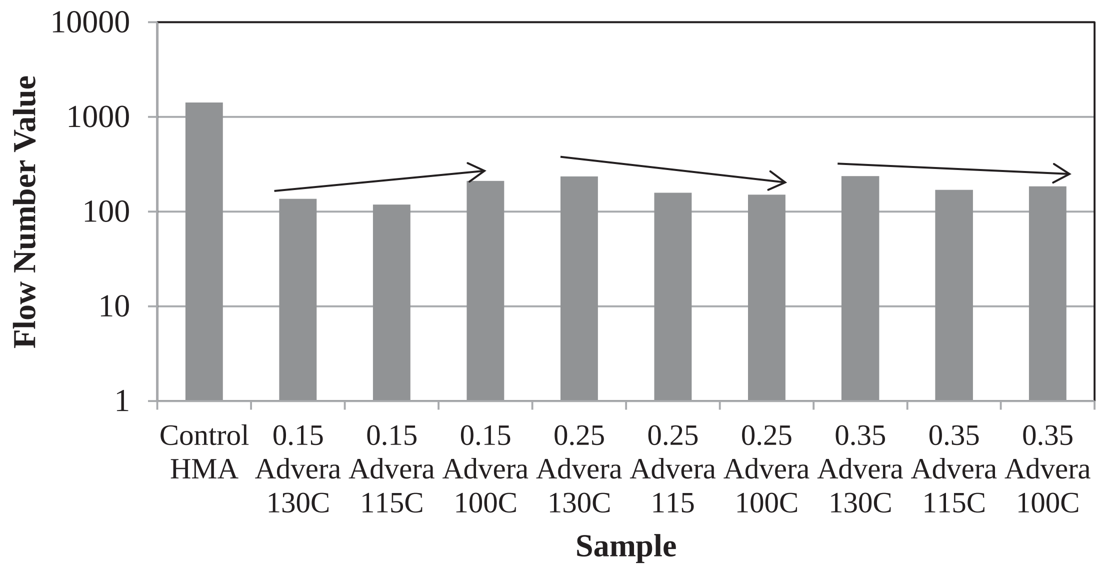
(c) Strain Rate versus Cycle Number
from Dynamic Creep Test

Figure 2.19 Flow Number Testing and the Flow Number Value

From Figure 2.20, it is also observed that when more ADVERA® WMA is added and/or the production temperature increased, the F_N increases. The main reason is that the additional ADVERA® aids the compaction of WMA to achieve denser mixes and thus increases the F_N, and higher production temperature increases the aging of mixture and results in stiffer mixture (due to stiffer binder).



(a) Based on ADVERA® WMA Added



(b) Based on Production Temperature

Figure 2.20 Flow Number Test Results for Control HMA and WMA Made with ADVERA® WMA

2.1.5.7: Asphalt Pavement Analyzer (APA) Rutting Test

The rutting tests were conducted through the Asphalt Pavement Analyzer (APA) device based on AASHTO TP 63-03 at 58°C (136.4°F). The purpose of this test was to determine the rutting resistance for WMA and compare the results with the control HMA. The results of the APA test are presented in Figure 2.21. Based on the results conducted, it was found that most of the WMA has higher rutting depth compared to the control HMA mixture. Figure 2.21 also shows that WMA made with 0.25% produced at 100°C has the highest rutting depth; and the lowest of the WMA samples have either similar or slightly higher rutting depth compare to control HMA. The findings in this study are in line with the |E*| and F_N testing where rutting potential for WMA is higher in general which is mainly due to aging.

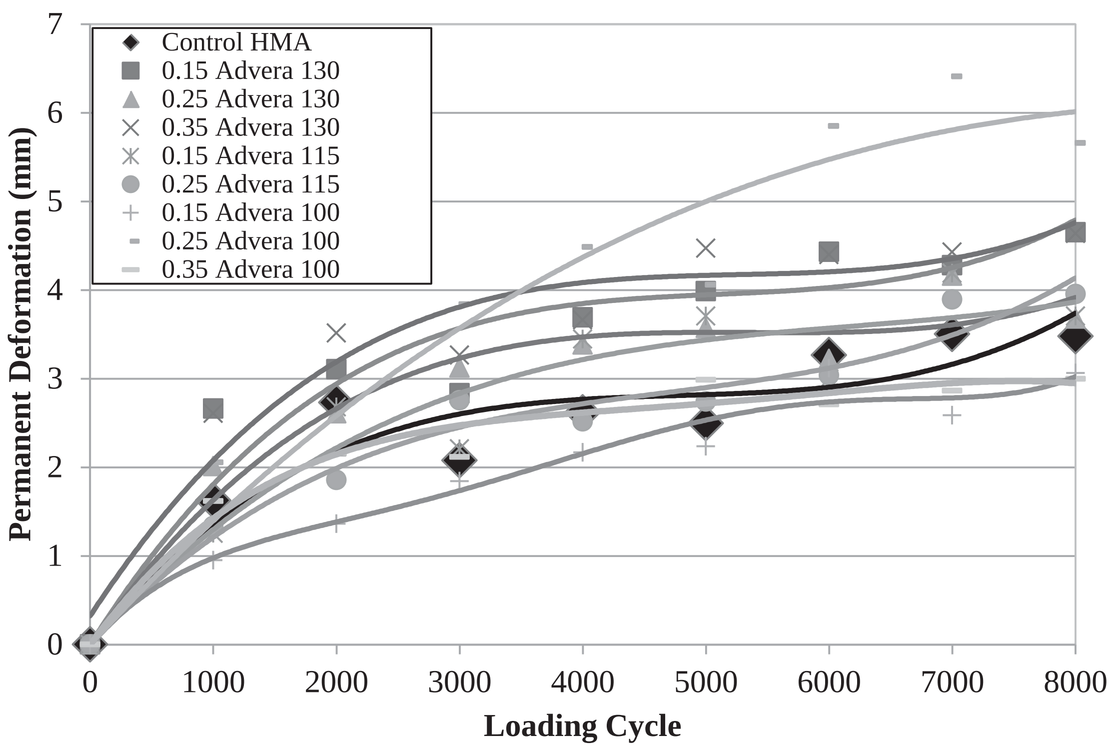


Figure 2.21 APA Rutting Test Results for Control HMA and WMA made with ADVERA® WMA

2.1.5.8: Summary

This case study presented laboratory results of WMA made with ADVERA® WMA, and the summary of findings in this case study are presented below:

1. Based on the volumetric testing, the compaction and/ or mixing temperature of WMA does not affect the air void level and compaction energy index
2. Through the DSR testing, it was found that WMA has significantly lower aging factor compare to control HMA, and a lower aging factor would result in higher rutting at the early stage of pavement serviceability.
3. Based on the |E*| testing, it was found that the production temperature and amount of ADVERA® used to produce WMA did not affect the |E*| of WMA; however, it is observed that all WMA mixtures made with ADVERA® WMA are lower than control HMA especially at higher temperature (at lower reduced frequency).
4. Through the TSR testing, it was found that TSR value of WMA is similar or higher than control HMA which indicated WMA has similar or better moisture susceptibility; however, the lower tensile strength of WMA indicated that WMA has higher fatigue potential.
5. Based on the four point beam fatigue testing, it was found that WMA made with ADVERA® WMA fatigue life are higher than the control HMA. It is also noticed that there the fatigue life of WMA is slightly higher when lower temperature was used; however, this finding is not significant. Additionally, the fatigue life of WMA does not affect by the amount ADVERA® added.
6. Based on the F_N and APA rutting tests, it was found that WMA has a higher rutting potential compared to control HMA. The result from F_N test also indicated that when more ADVERA® WMA was added and/or the production temperature increased, the F_N will increase.

2.1.6: Case Study 3: WMA using Foaming Method through Laboratory Setup

When producing the Wma using free water system, usually a separate laboratory foaming is device is needed. The foamed WMA using free water system is produced by introducing pressurized water and air into the heated asphalt at around 160°C to 180°C in specially designed nozzles. Figure 2.22 shows an example of foaming nozzle and Figure 2.27 shows the foaming device for laboratory scale produced by Wirtgen Inc. [82]. From Figure 2.27, it is observed that a typical foaming device consists of a heated asphalt binder, water tank, and pressure pump (foaming nozzle).

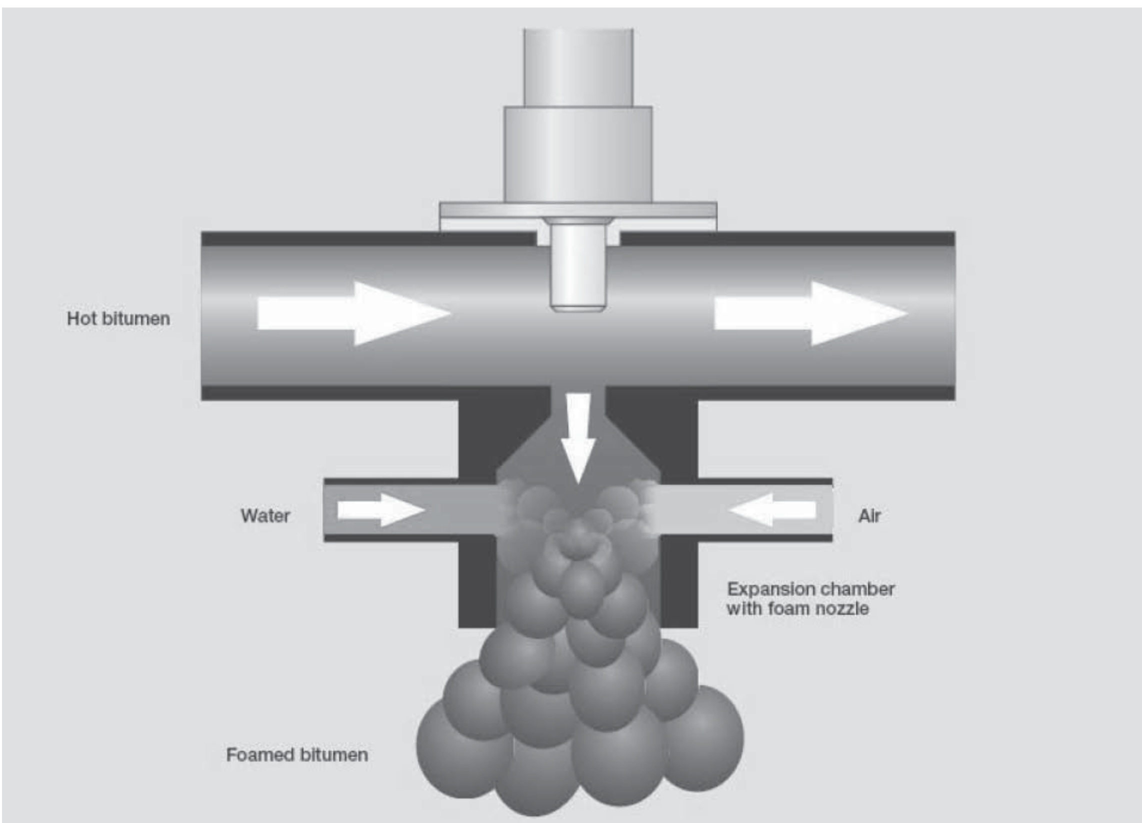


Figure 2.22 Wirtgen WLB 10 Foaming Nozzle

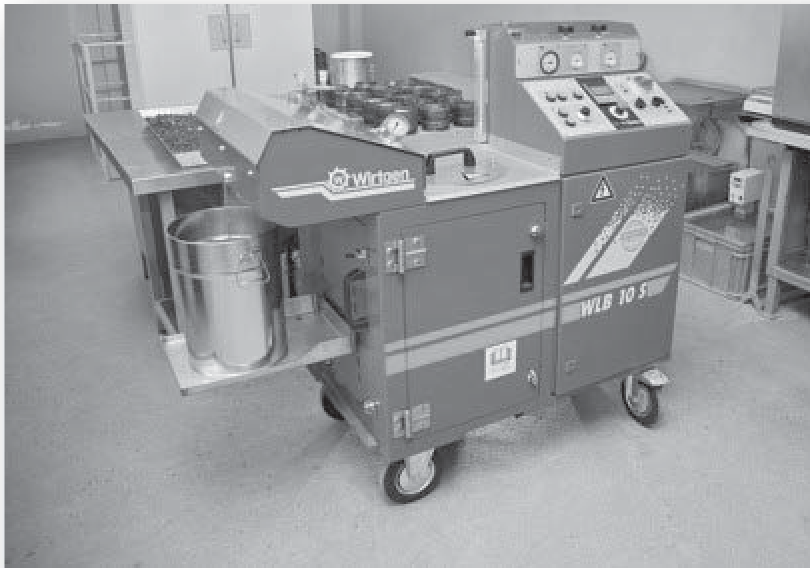


Figure 2.23 WLB 10 S Laboratory Foaming Device

The foam WMA using free water system was characterized by two properties: expansion ratio (E_r) and half-life (λ). The E_r is defined as the ratio of maximum volume of foamed asphalt and the original volume of asphalt; and λ is defined as the time for foamed asphalt to shrink from maximum expanded volume to half of its maximum expanded volume [83].

The water content, binder temperature and type of binder are the main factors affecting the parameters of E_r and λ of foamed WMA using free water system. Studies from the past indicated that E_r can be increased by increasing the water content and temperature during the foaming process; but, this would decrease the λ at the same time [83,84]. In terms of asphalt binder type, researchers [85] indicated that softer binders tend to produce more stable foam compared to harder binders , and it was recommended to be used for cold-in-place, warm and half-warm asphalt mixtures.

In order to produce the best performing foamed asphalt mixture, researchers indicated that the E_r and λ should be maximized to find out the optimum water content[84,86,87]. This can be easily achieved by conducting a series of foaming tests using different water content. Figure 2.28 shows an example of foaming properties of asphalt binder in terms of E_r and λ [84].

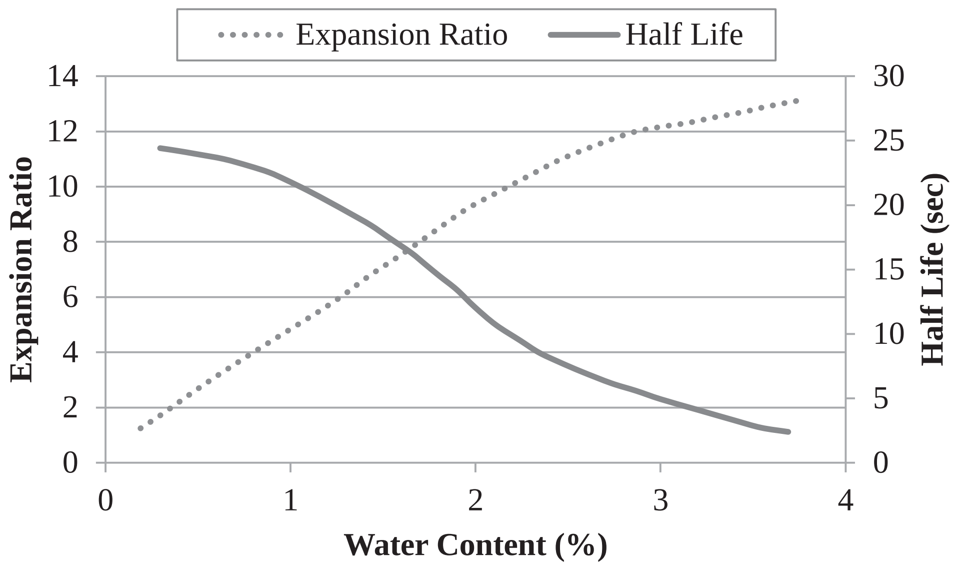


Figure 2.24 Example of Foaming Properties of Asphalt Binder

2.1.6.1: Asphalt Binder Characteristic

Since there are no additional additives added to modify asphalt binder, the characteristic of asphalt binder used for free water system will be affected by aging factor due to different mixing/ compacting temperatures. In this case, the aging factor for binder used in free water system is similar to the previous case study shown in

. As described previously, binder aged at a lower temperature has a lower aging factor and a lower aging factor would result in higher rutting potential for pavement at early serviceability.

2.1.6.2: HMA and WMA Mixture Preparation

In this study, a simple laboratory setup was designed to mimic the free water system in the asphalt plant. HMA mixtures (control) and WMA mixtures that were produced using the foaming method were evaluated and compared. All the mixture gradations were designed based on specifications for a local asphalt mixture used in Michigan, USA. The nominal maximum aggregate size is 9.5mm and the designed traffic level is less than 3 million equivalent single axles loads (ESALs) based on the current Superpave^{TM} asphalt mixture design procedure. A performance grade of PG 58-34 asphalt binder was used in this study. Tap water at the rate of 1%, 1.5% and 2% (based on binder weight) was injected into the asphalt binder using a syringe. It should be noted that a certain pressure should be applied to the syringe to allow water injected into the asphalt a short period of time (less than a second). Additionally, it was noteworthy that the asphalt binder was heated up to mixing and compacting temperature, which were 100°C, 115°C and 130°C, before the water was introduced. When the water came into contact with the asphalt, the molecules of the water became very volatile due to the high temperature of asphalt which was close to or above its boiling point. The water then vaporized and turned into steam. Immediately after water was injected to the bottom part of the asphalt binder, a spatula was used to rapidly mix the asphalt and the water in order to allow the steam to disperse completely in the asphalt binder. Figure 2.25 shows the procedure for producing the foamed asphalt binder.

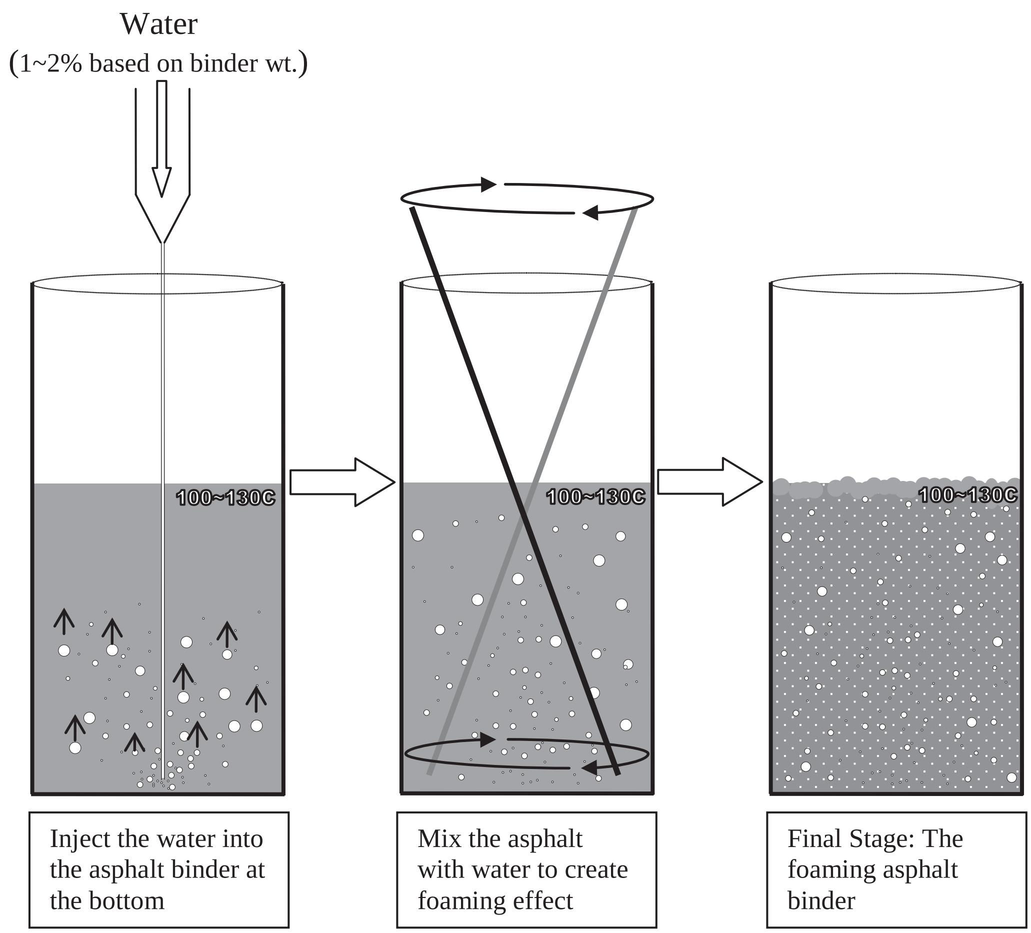


Figure 2.25 Procedure to Produce Foamed Asphalt Binder

When foam formed throughout the asphalt binder, the asphalt binder was then immediately mixed with the aggregate at the same temperature (100°C, 115°C, and 130°C, respectively). The foamed asphalt mixtures, also referred to as foamed WMA, were compacted at the temperature similar to its mixing temperature (100°C, 115°C, and 130°C, respectively). A gyration number of 86 was applied during the compaction process using the Superpave^{TM} gyratory compactor. Figure 2.26 shows the procedure of mixing and compaction of foamed WMA in this study; and Figure 2.27 shows the final product of WMA using this foaming method. The control mixtures were mixed at 165°C and compacted at 153°C. A similar gyration number of 86 was used for the control HMA mixture, and the Superpave^{TM} specification was followed in the mix preparation. The volumetric properties of samples were evaluated as well after the compaction. It was found that the average air void level for control samples are 6.1%; and for WMA samples ranged from 5.5% to 7.9%.

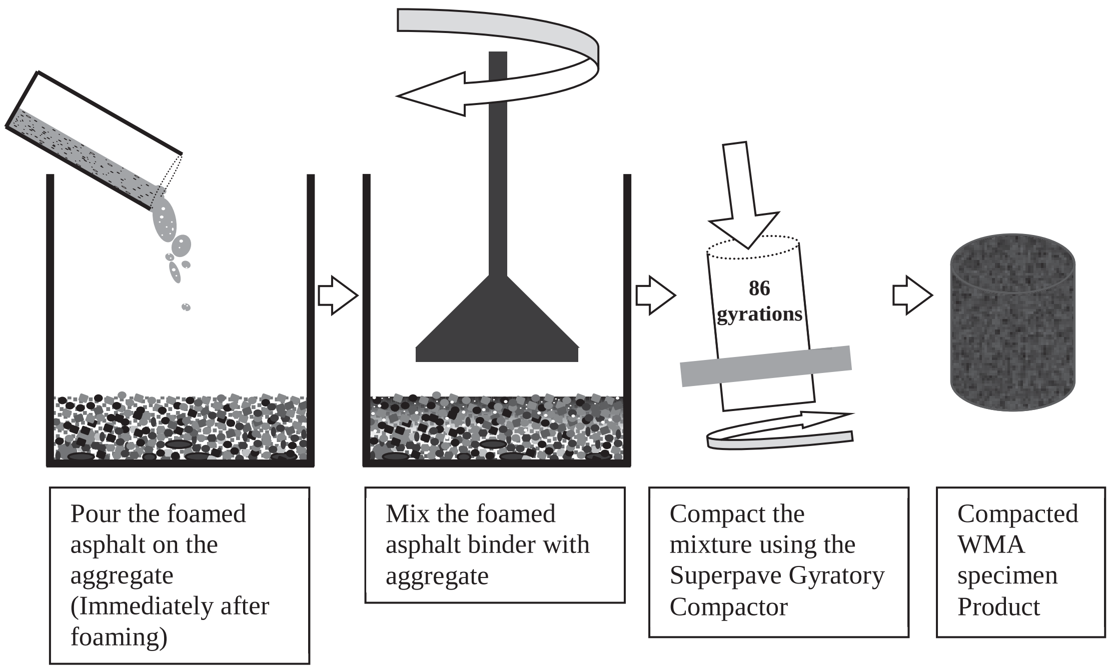


Figure 2.26 Mixing and Compacting the Foamed Asphalt with Aggregate

Figure 2.27 Warm Asphalt Mixture Produced using the Water Foaming Method

2.1.6.3: Asphalt Mixture Performance Testing

In this study, five performance tests to access rutting, fatigue and moisture susceptibility of asphalt mixture were conducted – dynamic modulus, indirect tensile strength ratio (TSR), four-point beam fatigue, flow number and APA rutting tests. Samples used in this case study included control HMA samples produced at 163°C, and foamed WMA mixtures containing 1%, 1.5% and 2% water produced at temperatures of 100°C, 115°C and 130°C using the Superpave^{TM} gyratory compactor. A gyration number of 86 was used for samples during the compaction. For the four-point beam fatigue testing, the linear kneading compactor was used. Three replicated samples were used for each testing. It is noteworthy that the descriptions used in the graphs for each asphalt mixture are shown in Table 2.6.

Table 2.6 Description of Asphalt Mixture used in the Graphs

Descriptor	Description
CTRL	Control HMA Mixture
1% Water 100C	WMA using 1% water compacted at 100°C
1% Water 115C	WMA using 1% water compacted at 115°C
1% Water 130C	WMA using 1% water compacted at 130°C
1.5% Water 100C	WMA using 1.5% water compacted at 100°C
1.5% Water 115C	WMA using 1.5% water compacted at 115°C
1.5% Water 130C	WMA using 1.5% water compacted at 130°C
2.0% Water 100C	WMA using 2.0% water compacted at 100°C
2.0% Water 115C	WMA using 2.0% water compacted at 115°C
2.0% Water 130C	WMA using 2.0% water compacted at 130°C

2.1.6.4: Dynamic Modulus Testing

In this case study, the dynamic modulus (|E*|) tests were conducted based on the AASHTO TP62-03. The temperatures used were -10°C, 4°C, 21.3°C and 39.2°C , and frequencies ranged from 0.1Hz to 25Hz. Control HMA and WMA produced using 1.0%, 1.5% and 2.0% water (based on binder weight) at temperature of 100°C, 115°C and 130°C were used in this study.

The result of the |E*| testing was obtained and analyzed using the master curve technique. The concept of master curve is to “shift” the relative |E*| from different temperatures and frequencies to the time of loading using the sigmoidal fitting model, so the various curved obtained from different temperatures can be aligned to form a single master curve. In order to compare the control HMA and WMA, master curve technique was used in this study. In this study, a sigmoidal master curve was constructed for the measured |E*| for control and WMA mixtures, and are shown in Figure 2.28. During the formation of the sigmoidal master curve, 4°C was used as the reference temperature.

Based on the test results, it is found that the production temperature and amount of water used to foam the WMA did not affect the |E*| of WMA; however, it is observed that all foamed WMA mixtures are lower than control HMA. Based on the |E*| test results, it can be concluded that the foamed WMA has higher rutting potential compare to HMA (i.e. control mixture).

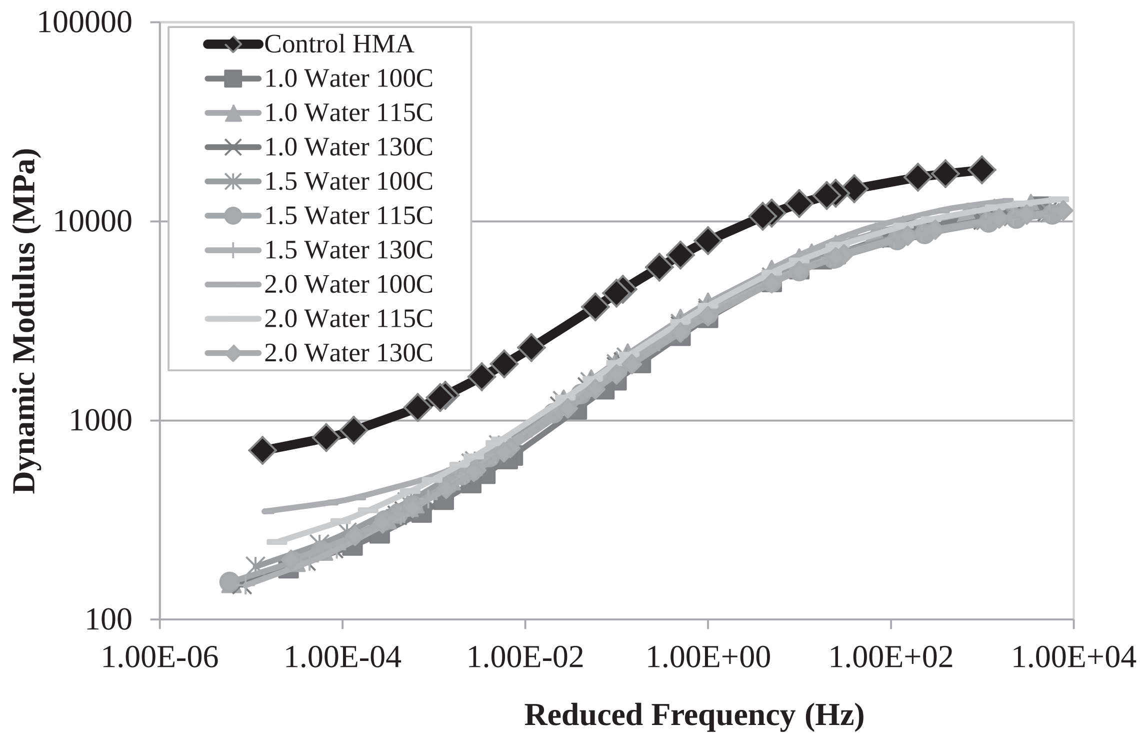


Figure 2.28 Dynamic Modulus Test Results for Control HMA and WMA produced using Water Foaming

2.1.6.5: Moisture Susceptibility Test Using Tensile Strength Ratio (TSR)

The moisture susceptibility of WMA was evaluated using tensile strength ratio (TSR) testing. The TSR is the ratio of tensile strength of dry and conditioned mixture (mixtures went through one freeze-thaw cycle). Previous studies indicated that the tensile strength is also one of the key parameters to access the fatigue potential of HMA[62] where higher tensile strength is preferred at all cases because it can tolerate higher strains before failing. In this study, all samples were tested based on AASHTO T283 [63] using a loading rate of 0.83 mm/s and a testing temperature of 25°C. As mentioned previously, control mixtures and foamed WMA mixtures using the 1%, 1.5% and 2% water produced at 100°C, 115°C and 130°C were evaluated.

Figure 2.29 shows the results for the tensile strength testing. Based on the results, it was observed that the foamed WMA have lower tensile strength in general compared to the control mixtures. One interesting finding is that during testing, the tensile strength for all the foamed WMA at production temperatures at around 115°C was the highest among all the foamed WMA mixtures tested. Additionally, the production temperature at around 115°C could be the effective temperature for WMA because it shows the highest tensile strength compared to WMA produced at 100°C and 130°C. The main reason behind this was likely due to the effect of binder aging and aggregate coating. Aged binder from higher production temperature (stiffer binder) could result in lower tensile strength value. On the other hand, using lower mixing temperature could result in another problem that the aggregate may not be fully coated.

In this study, the TSR testing results are shown in Figure 2.29 as well. Typically, the final result for TSR testing would have a value of less than 1.00 because it is expected that the conditioned samples would suffer moisture damage and exhibit lower tensile strength; this phenomenon was observed in the control sample. However, it was found that some of the foamed WMA mixtures exhibited TSR values greater than 1.00. Similar results were also observed by other studies [22,88-91], and this unusual TSR values were due to the finer and "tender" mixes such as 9.5mm mix used in this study [92]. Additionally, this indicated that the sample after conditioning has higher tensile strength. The best mixture in this case was the foamed WMA mixture using 1% water compacted at 130°C. Additionally, it was observed that when the WMA production temperature increased, the TSR increased this held true in most cases.

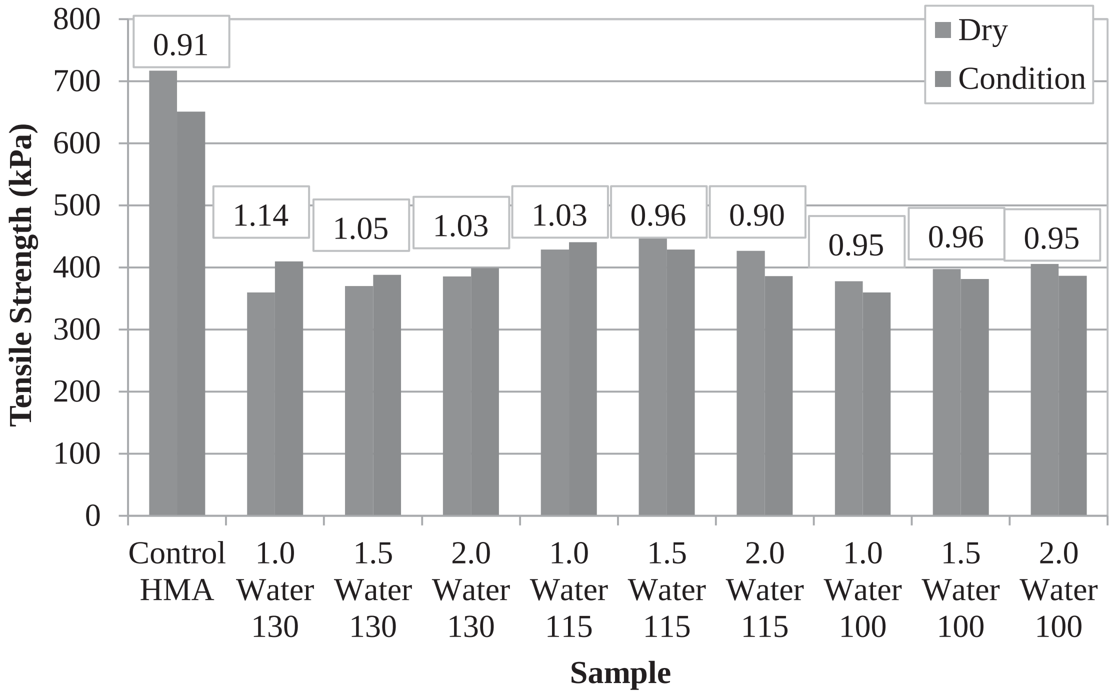


Figure 2.29 Comparison of Indirect Tensile Strength and TSR for the Control Mixture, and WMA using 1%, 1.5% and 2% Water at 100°C, 115°C and 130°C

2.1.6.6: Four-Point Beam Fatigue Testing

The results from the four-point beam fatigue tests are presented in this section. The purpose of this test is to determine the fatigue life of the asphalt mixture subjected to the repeated bending until failure where the fatigue failure was defined as 50% reduction of initial stiffness [65]. In this test, a frequency of 10 Hz and 400 micro-strain (constant strain) were used for all the samples tested. All mixtures were tested except WMA foamed with 2.0% water produced at 130°C and 115°C due to the limited material available. The results of the four-point beam fatigue testing are presented in Figure 2.30.

From Figure 2.30, it can be found that all the foamed WMA fatigue life was higher than the control HMA. It is also noticed that when the water content used to foam increased, the fatigue life increased as well. There are several factors that would affect the fatigue life associated with production temperatures, and WMA additives when comparing HMA and WMA, including: 1) absorption – lower mixing temperature (WMA) may result in less binder absorption into the aggregate, which will reduce the adhesion and thus affect the asphalt mixture fatigue life [6] and; 2) aging of the asphalt binder – lower mixing temperature of WMA will reduce binder's aging and thus improve workability of asphalt mixture.

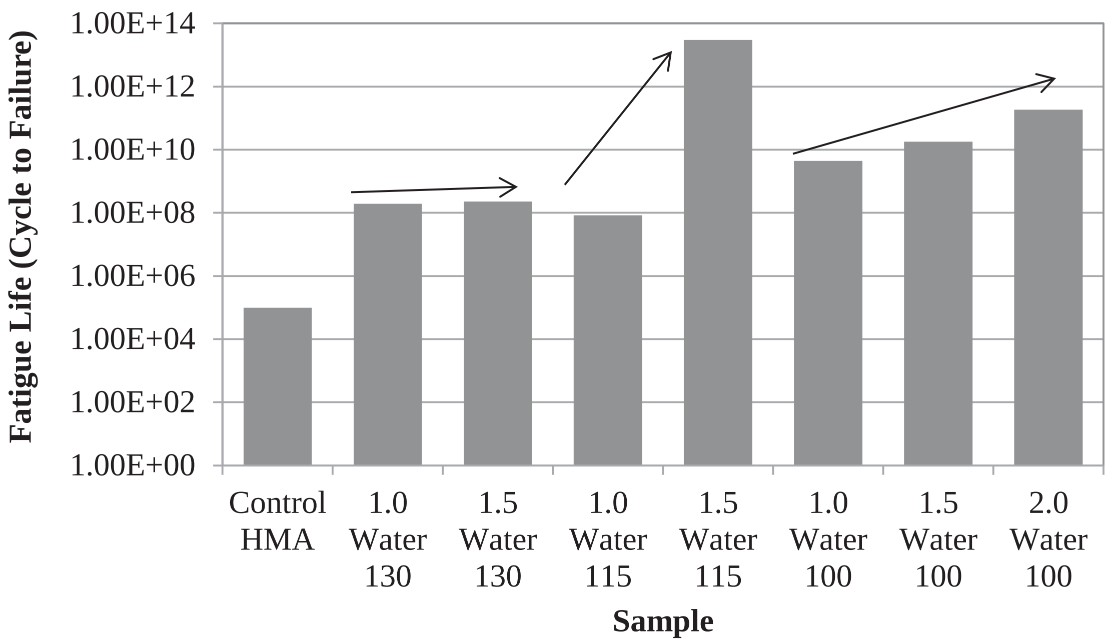


Figure 2.30 Comparing the Fatigue Life of Control HMA and Foamed WMA

2.1.6.7: Flow Number Testing

In this section, HMA control and WMA foamed with 1.0%, 1.5% and 2.0% water content produced at 100°C, 115°C and 130°C were used. The flow number test was conducted for each sample based on NCHRP 9-29 [93]. The testing results for control HMA and foamed WMA are shown in Figure 2.31. Generally, Figure 2.31shows that the F_N for all WMA samples are lower than the control HMA. These results are in line with findings from |E*| which WMA has a higher rutting potential. As mentioned previously, the reason was due to lesser aging of WMA during the production. From Figure 2.31, it is also observed that the amount of water content used to foam WMA and the mixing/ compacting temperature did not affect the F_N of WMA. This finding is consistent with the results from |E*| testing where the foamed WMA has higher rutting potential.

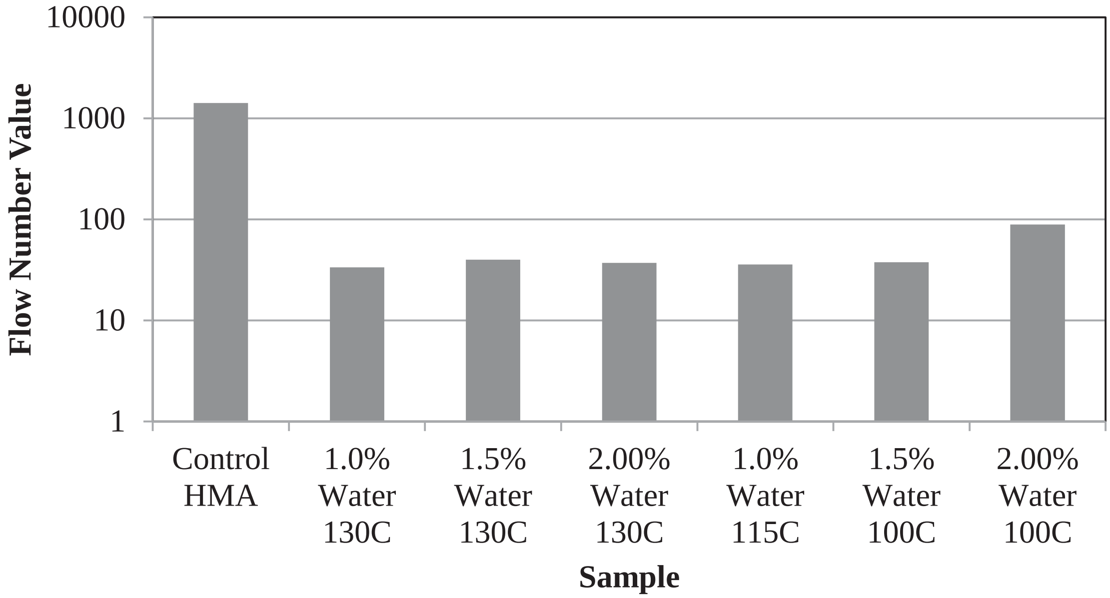


Figure 2.31 Flow Number Test Results for HMA control and Foamed WMA with Water

2.1.6.8: Asphalt Pavement Analyzer (APA) Rutting Test

The rutting tests were conducted through the Asphalt Pavement Analyzer (APA) device based on AASHTO TP 63-03 at 58°C (136.4°F). The purpose of this test was to determine the rut resistance for WMA and compare the results with the control HMA. The results of the APA test are presented in Figure 2.32. Based on the results conducted, it was found most of the WMA has higher rutting depth compare to the control mixture except WMA foamed at 130°C. Figure 2.32 also shows that WMA produced at temperature of 100°C has the highest rutting depth in general. This can be explained by the aging of the asphalt binder where high production temperature tends to have higher aging which resulted in stiffer mixture.

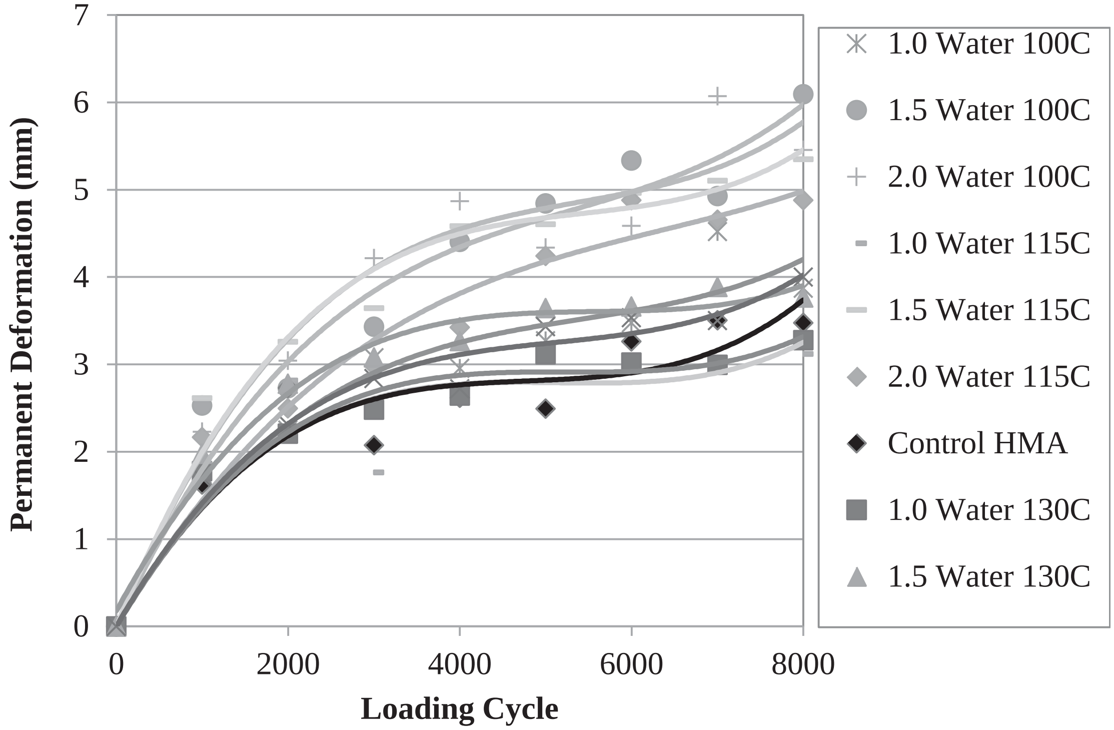


Figure 2.32 APA Rutting Results for HMA Control and Foamed WMA with Water

2.1.6.9: Summary

The average air void level for control samples (HMA) are 6.1%, and for WMA samples are ranged from 5.5% to 7.9%. The performance was compared based on the |E*|, FN, TSR, four point beam fatigue and APA rutting tests. The summary of findings in this case study is presented below:

1. The WMA has significantly lower aging factor compare to control HMA, and a lower aging factor would result in higher rutting potential.
2. Based on the |E*| testing, it was found that the production temperature and amount of water use to foam the WMA did not affect the |E*| of WMA; however,

it is observed that |E*| of all foamed WMA mixtures are lower than control HMA, which lead to higher rutting potential.

3. Through the TSR testing, it was found that some of the foamed WMA mixtures exhibited TSR values greater than 1.00. This indicated that the sample after conditioning has higher tensile strength. The best mixture in this case was the foamed WMA mixture using 1% water compacted at 130°C. Additionally, it was observed that when the WMA production temperature increased, the TSR increased this held true in most cases.
4. Based on the four point beam fatigue testing, it was found all the foamed WMA fatigue life was higher than the control HMA.
5. Based on the F_N and APA rutting tests, it was found the F_N for all WMA samples is lower than the control HMA. Additionally, it is observed that the amount of water content used to foam WMA and the mixing/ compacting temperature did not affect the F_N of WMA.
6. Based on the APA rutting test, it was found that most of the WMA has higher rutting depth compare to the control mixture except WMA foamed at 130°C. In addition, the WMA produced at temperature of 100°C has the highest rutting depth in general.

2.2: WMA using Organic Additives

Waxes and fatty acid amide are commonly classified as the organic additives used in WMA. In general, the organic additive reduced binder viscosity when heated above their melting point. The organic additives have carbon chains greater than C45 (carbon atom that has the length of 45 carbon backbone chain). The longer the carbon chain, the higher the melting point. Examples of WMA technologies use organic additives include Sasobit® [94] and Licomont BS-100 [95].

2.2.1: Case Study: WMA Using Sasobit®

Sasobit® is a fine crystalline, long-chain aliphatic polymethylene hydrocarbon produced from coal gasification using the Fischer-Tropsch (FT) process. The chemical structure for Sasobit® is shown in Figure 2.33. The product is also known as FT hard wax. In the Fischer-Tropsch synthesis, coal or natural gas (methane) is partially oxidized to carbon monoxide which is subsequently reacted with hydrogen (H_2) under catalytic conditions producing a mixture of hydrocarbons having molecular chain lengths of carbon (C_5) to C_{100} plus carbon atoms. The process begins with the generation of synthesis gas then reacted with either an iron or cobalt catalyst to form products such as synthetic naphtha, kerosene, gasoil and waxes. The liquid products are separated, and the FT waxes are recovered or hydrocracked into transportation fuels or chemical feed stocks. The Sasobit® recovered is in the carbon chain length range of C_{45} to C_{100} plus[96]. By comparison, macrocrystalline bituminous paraffin waxes have carbon chain lengths ranging from C_{25} to C_{50}. The longer carbon chains in the FT wax lead to a higher melting point. The smaller crystalline structure of the FT wax reduces brittleness at low temperatures as compared to bitumen paraffin waxes.

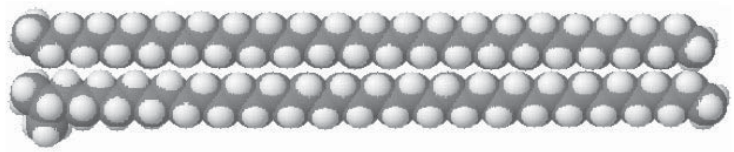


Figure 2.33 Chemical Structure Long Chain Aliphatic Polyethylene Hydrocarbon (from Sasol Wax Americas[4]) [97]

2.2.1.1: Asphalt Rheological Properties

In this study, a Dynamic Shear Rheometer (DSR) was used to evaluate the rheological properties of WMA. DSR is a device that allows users to characterize the viscous and elastic behavior of asphalt binders at high and intermediate service temperatures. The asphalt binder with the grade of PG52-34 (control binder) was used in this study and a WMA additive, Sasobit® was added to the binder PG52-34 at the amount of 2%, 3% and 4% based on the total binder weight. In this study, only neat (unaged) binder was tested, and a total of six frequencies (ranging from 0.01hz to 25hz) and three temperatures (46°C, 55°C and 58°C) were used.

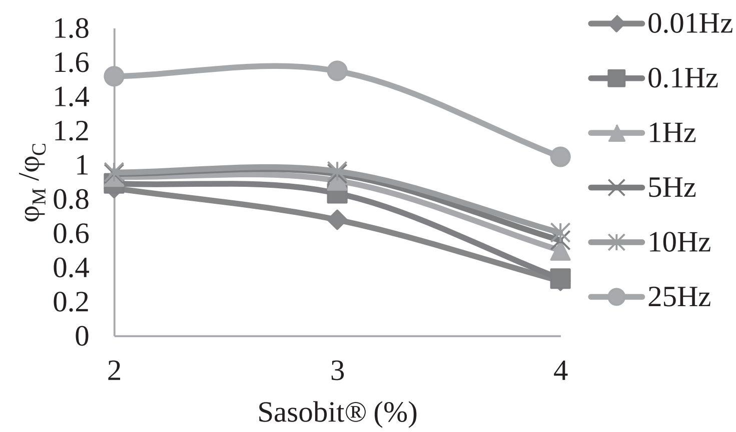
The results from the DSR for WMA and control binders were compared and shown in Figure 2.34 and Figure 2.35. Note ϕ_M and $\phi_C$are phase angles of WMA and control binders, respectively; G_M and G_C are dynamic shear moduli forWMA and control binders, respectively. It was found that most of the ratios of phase angles between WMA and control binders were smaller than one, which indicates that the WMA binder has a smaller phase angle. It is observed that when the amount of Sasobit® increased from 2% to 4%, the average ratios of phase angles decreased from 0.961 to 0.323. Additionally, it was found that the ratio of phase angles at a testing frequency of 25hz was significantly higher compared to others in most cases.

In Figure 2.35, the initial trend shows that the ratio of dynamic shear modulus slightly decreased when the rate of Sasobit® added increased (i.e. from 2% to 3% Sasobit®). However, the ratio of dynamic shear modulus increased dramatically when

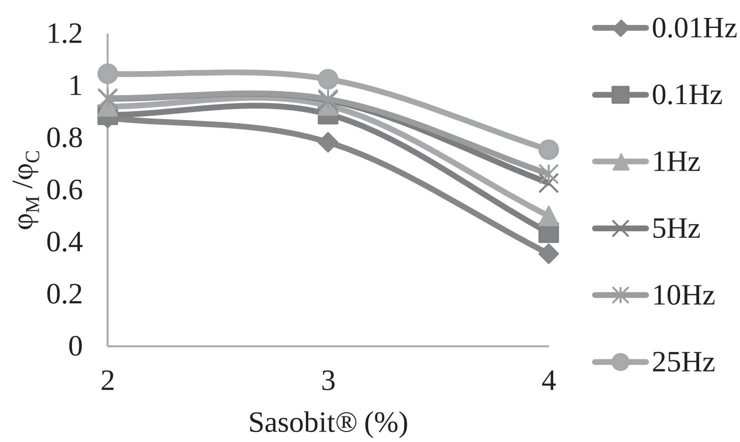
[4] Image obtained from Sasol Wax Americas with permission – Please refer to Appendix 1

4% of Sasobit® is used (rate ranged from 5.06 to 235 over all the frequencies tested). This indicates that the additional Sasobit® might bump up the binder grade and would potentially improve asphalt rutting resistant. However, the increment of dynamic shear modulus may indicate that the asphalt has less resistance to fatigue cracking.

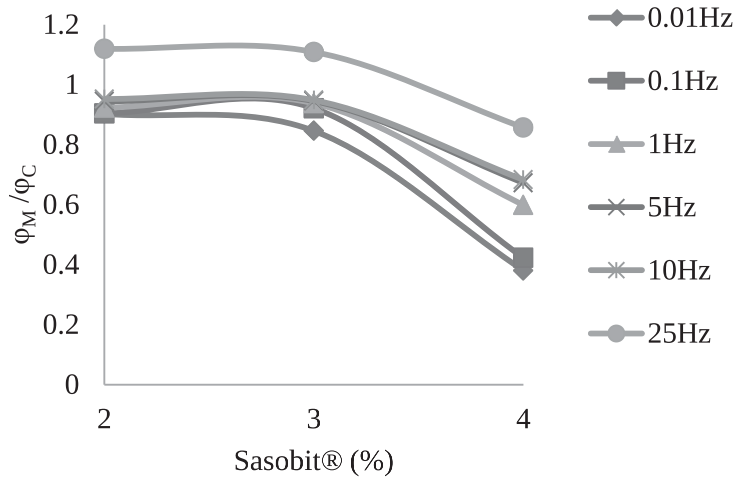
In general, the results indicated that when frequencies increase, dynamic shear modules increase while phase angles decrease. It was observed that temperature affects the value of both the phase angle and dynamic shear modulus ratios.



(a) 46°C

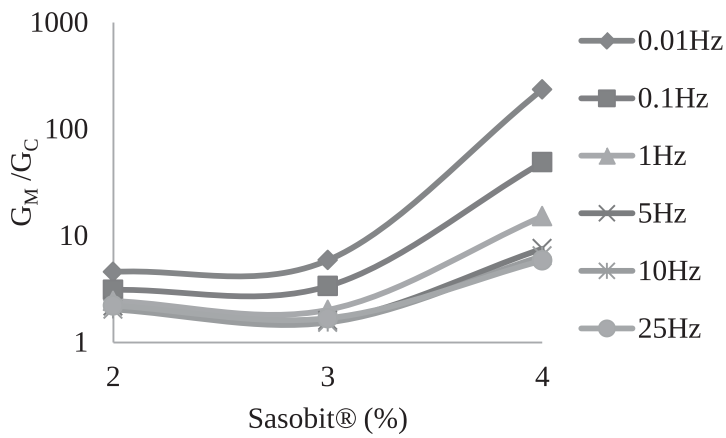


(b) 55°C

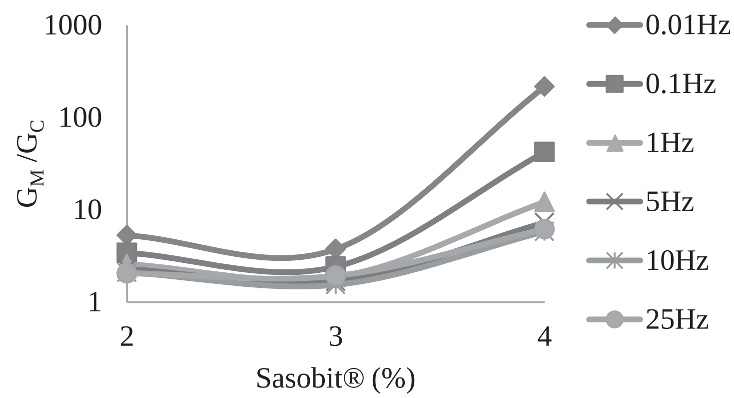


(c) 58°C

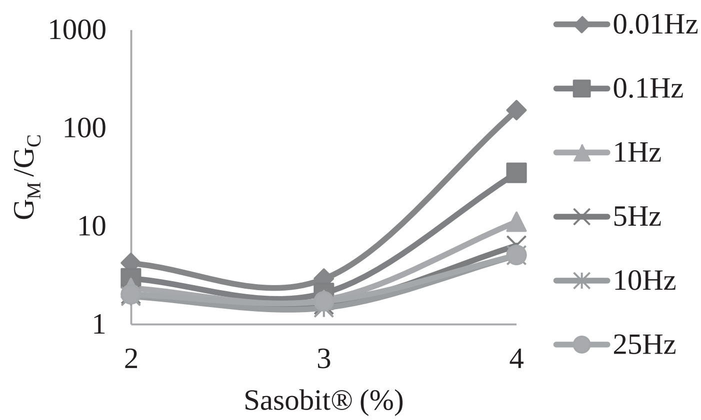
Figure 2.34 Ratios of Phase Angles for WMA and Control Binders overDifferent Percentages of Sasobit® Additive at (a)46°C, (b)55°C and (c) 58°C



(a) 46C



(b) 55C



(c) 58C

Figure 2.35 Ratios of Dynamic Shear Modulus between modified and control binders overDifferent Percentages of Sasobit® Additiveat (a)46°C, (b)55°C and (c) 58°C

2.2.1.2: Asphalt Aging Factor

In this section, the binder performance grade PG58-34 binder was used in this test and it was tested at unaged and short-term aging condition. As mentioned previously, the aging factor was the ratio of G*/sin (δ) before and after short-term aging. The short-term aging process is known as the asphalt binder condition after pavement construction and is simulated by heating in the oven for 12 hours. For WMA samples, four different temperatures were used for short-term aging in this case study: 100°C, 115°C and 130°C for WMA. For the control HMA, 163°C was used during aging process. Table 2.7 shows G*/sin (δ) and aging factor of HMA and WMA aged at different temperatures. Based on Table 2.7, it shows the aging factors for Sasobit® aged at 130°C are higher than the control HMA. From Table 2.7, it also shows that when the temperature increases, the aging factor increases. A higher aging factor indicated that it could increase the rutting resistance of the mixture at the early serviceability; however, the fatigue potential after long-term serviceability would increase as well.

Table 2.7 Aging Factor for HMA and WMA made with Sasobit®

Sample	G*/ sin (δ)		Aging Factor
	Unaged	12 hours age	
Control 165°C	1345.94	2609.44	1.93875
0.5 Sasobit 100	1786.17	1917.65	1.07361
0.5 Sasobit 115	1457.28	1883.06	1.29218
0.5 Sasobit 130	1391.05	1891.47	1.35974
1.5 Sasobit 100	1917.63	3520.88	1.83606
1.5 Sasobit 115	1640.78	3198.99	1.94967
1.5 Sasobit 130	1384.02	3771.48	2.72502
3.0 Sasobit 100	3348.46	4382.71	1.30887
3.0 Sasobit 115	1604.16	3882.75	2.42042
3.0 Sasobit 130	1377.51	2872.11	2.08500

2.2.1.3: Field Study

In September 2007, a field demonstration consisting of WMA and HMA was held at M-95, north of US-2 at Iron Mountain, Michigan. The construction of the field demonstration was performed using mixture design of 5E3 (9.5mm maximum aggregate size and traffic level ≤3 Million ESALs). Control HMA and WMA made with Sasobit® was discussed in this study. During the production of WMA, Sasobit® was added a rate of 1.5% by mass of binder. A total of 850 tons of WMA were placed using the same volumetric design as HMA (control). The mixing temperature used for WMA was 260˚F (126.7˚C) and HMA was 320˚F (160˚C).

During the WMA production, emission was significantly reduced compared to HMA production. Figure 2.36 shows the comparison of truck load out emissions between HMA and WMA during the production. It was reported that a reduction of 14% in NOx, 5% decrease in CO_2 and a slightly decrease in VOC when compared to HMA[98].

(a) Hot Mix Asphalt **(b) Warm Mix Asphalt**

Figure 2.36 HMA versus WMA

The WMA was mixed and compacted at the temperature of 126.7°C. Table 2.8 shows the measured volumetric properties (average value) for WMA and HMA after compaction. The maximum specific gravity for WMA was found to be slightly lower than HMA. The initial investigation indicated that the G_{mb} of Sasobit® is lower than asphalt and hence, the maximum specific gravity of mixture might drop slightly when Sasobit® was added.

The bulk specific gravity (G_{mb}) for WMA and HMA were back-calculated at each gyration number using Superpave™ mix design guide. It was found that even though WMA compacted at a lower temperature, the G_{mb} of both HMA and WMA does not show any significant difference. The largest difference between HMA and WMA was found to be 0.34%, which was insignificant. Thus, this showed that WMA made with 1.5% Sasobit® could be compacted at least 25°C lower than the HMA, and at the same time, it would not affect the volumetric property. Additionally, advantages such as energy/ fuel saving and emission reduction could be achieved based on the results conducted.

Table 2.8 Volumetric Properties of WMA and HMA

Description	HMA	WMA
Maximum Specific Gravity, G_{mm}	2.573	2.569
Bulk Specific Gravity (G_{mb}) at the end of Compaction	2.441	2.455
Air Void Level	5.13%	4.45%
Asphalt Binder Content	5.52%	5.52%

2.2.1.4: Comparison of Cooling Rate between HMA and WMA

The cooling rate of asphalt mixture is always important in cold weather paving because it determines the allowable time for compaction before cessation temperature is reached. In addition, a slower cooling rate will allow a longer hauling distance during the cold weather paving. In this study, the cooling rate for HMA and WMA was compared. The climate condition of Iron Mountain (Michigan) was used, and they were obtained from Michigan State Climatology Office shown in Table 2.9. The cool-down rate of HMA and WMA were then evaluated using MultiCool Program developed at the University of

Minnesota [99]. It was assumed that the HMA was heated up to 18ºC higher than its compaction temperature (i.e. 171ºC) for cold weather paving. For WMA, it was assumed that the compacting temperature is similar to HMA, which is 171ºC in order to compare the hauling and compacting time with HMA.

Table 2.9 Weather Condition at Iron Mountain on September 2007

Description	Value
Ambient Air Temperature (ºC)	7.66
Surface Temp. (ºC)	11.61
Average Wind Speed (km/h)	8.05
Latitude (Deg. North)	88.08

Figure 2.37 shows the calculated asphalt mixture cooling time using the MultiCool program. It is observed that the time needed for cooling down the WMA is significantly longer than HMA, which is about 27 minutes more than the time needed for HMA. Contractor/ engineer could produce the WMA at a lower temperature (lower than 171 ºC in this case) if the time needed for the entire process (hauling and compacting) is lesser. Thus, the use of WMA technology can significantly improve the cold weather paving by extending the hauling distance and paving time.

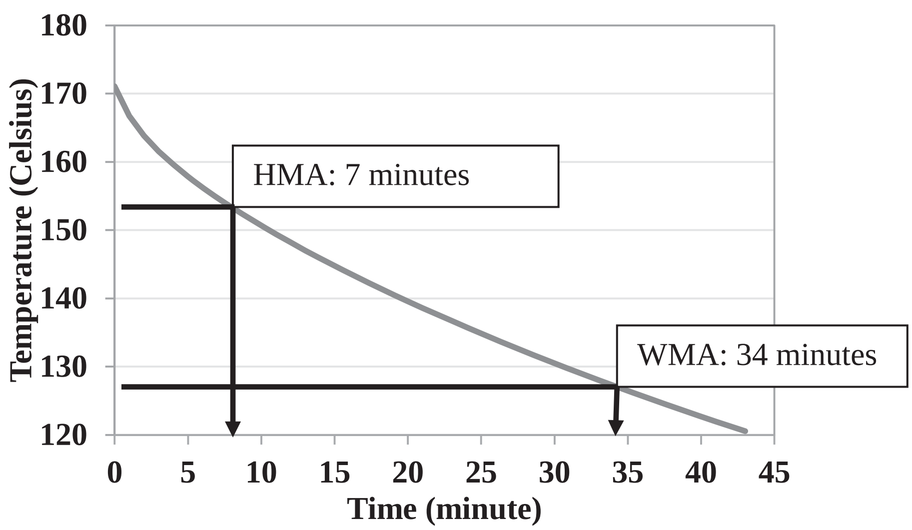


Figure 2.37 Mixture Cooling time calculated using MultiCool Program

2.2.1.5: Performance of HMA and WMA made with Sasobit® Collected from Field Trial

The rutting tests were conducted through the Asphalt Pavement Analyzer (APA) device based on AASHTO TP 63-03 at 58°C (136.4°F). Samples collected from the field (HMA and WMA made with 1.5% Sasobit®) were used in this test. The purpose of this test was to determine the rut resistance for WMA and compare the results with the control mixture (HMA). The results of the APA test are presented in Figure 2.42. Based on the results conducted, it was found that WMA has a similar rutting depth compare to the control mixture. It is noteworthy that WMA was compacted at 126.7˚C (260˚F), which is about 25˚C (45˚F) lower than traditional HMA (compacted at 152˚C). The results also indicated that WMA with a reduction of 25˚C (45˚F) in compaction temperature has a similar rutting performance to HMA.

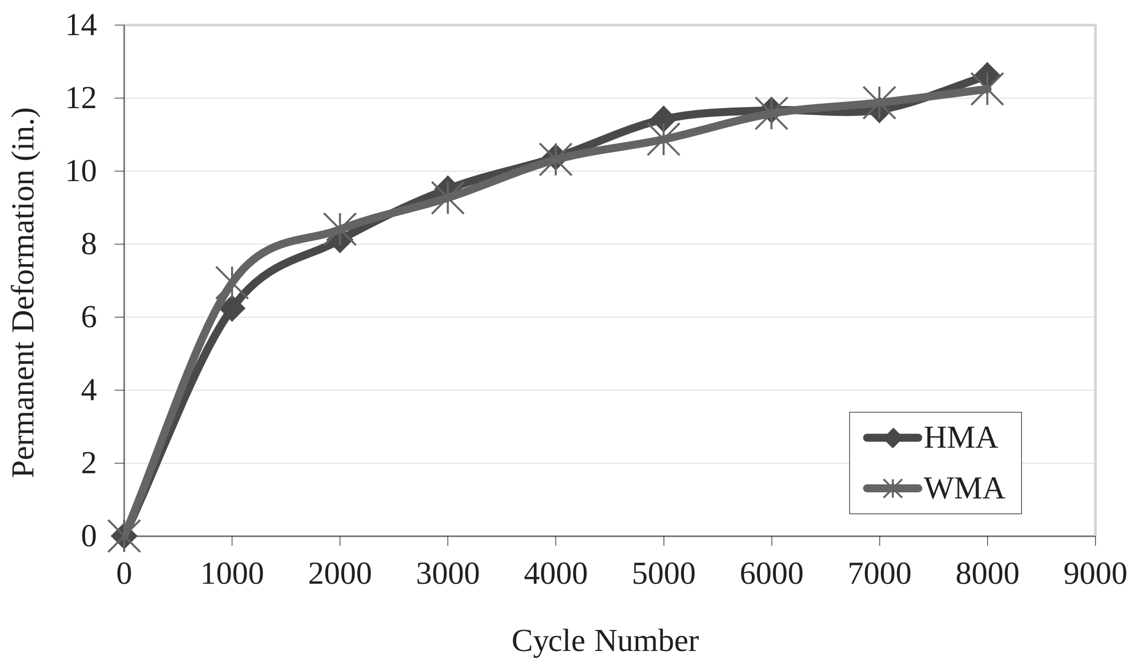


Figure 2.38 Comparison of APA Rutting for HMA and WMA collected from Field Trial

2.2.1.6: Sample Preparation for Laboratory Evaluation

In this case study, 5E3 Superpave™ mix design and PG58-34 binder were used for both control and WMA mixtures.. The Superpave™ specification [46-48] was followed in the mix preparation. For control HMA, the mixture was batched, mixed and compacted in the lab at 163°C; where WMA made with 0.5%, 1.5%, 3.0% (based on binder weight) were produced under the same environment at temperature of 100°C, 115°C and 130°C. All the mixtures (HMA and WMA) were compacted using the 86 gyration numbers.

The volumetric properties and compaction energy index [61] were measured and shown in Table 2.10. It is observed that the WMA made with Sasobit® has an average air void levels ranged from 4.17% to 5.79%, and VMA ranged from 25.01 to 28.53. It is also observed that no significant trend was found when comparing the amount of dosage (Sasobit®) added, compaction temperature used with measured air void level and compaction energy. The initial hypothesis was when the compaction temperature increase, the air void level decreased and/ or the compaction energy index decrease. However, the testing results show that the compaction temperature does not affect the air void level and compaction energy index in this case.

Table 2.10 Volumetric Properties of HMA and WMA made with Sasobit®

Mixture Type	Average G_{mm}	Average G_{mb}	Average Air Void	VMA[1]	Compaction Energy Index
Control HMA	2.5730	2.4411	5.13%	25.37	61.62
0.5 Sasobit 130C	2.5525	2.4307	4.77%	25.96	43.53
1.5 Sasobit 130C	2.5602	2.4271	5.20%	25.74	55.40
3.0 Sasobit 130C	2.5629	2.4341	5.03%	25.72	51.23
0.5 Sasobit 115C	2.5593	2.4280	5.13%	25.90	79.59
1.5 Sasobit 115C	2.5593	2.4234	5.31%	25.42	83.69
3.0 Sasobit 115C	2.5527	2.4415	4.36%	25.01	44.28
0.5 Sasobit 100C	2.5551	2.4485	4.17%	25.68	99.19
1.5 Sasobit 100C	2.5537	2.4359	4.61%	25.98	53.42
3.0 Sasobit 100C	2.5578	2.4098	5.79%	28.53	106.14

[1] Void in Mineral Aggregate

These samples were then evaluated using dynamic modulus, tensile strength ratio, four point beam fatigue, flow number and asphalt pavement analyzer (APA) rutting tests to access their fatigue and rutting potential. It is noteworthy that all testing was completed within two months.

2.2.1.7: Dynamic Modulus Testing

The dynamic modulus test was performed according to AASHTO TP62-03 in this section. The temperatures used to measure |E*| are -10°C, 4°C, 21.3°C and 39.2°C. The frequencies used in this test were 0.1Hz, 0.5Hz, 1Hz, 5Hz, 10Hz, and 25Hz. A total of three replicates samples were tested for each of the HMA and WMA samples at each single test. The recoverable axial micro-strain in this test was adjusted to a value between 75 and 125 so that the material is in the viscoelastic range.

In order to have a better comparison between HMA and WMA mixtures throughout all the temperatures and frequencies, a sigmoidal mastercurve was constructed with reference temperature of 4˚C. The comparison of the |E*| master curve across a range of reduced frequencies for the HMA and WMA mixtures is shown in Figure 2.39. It was observed that there were no significant differences between |E*| for the HMA and WMA. It is also observed that the lowest |E*| is WMA made with 0.5% Sasobit® produced at 100°C; and the highest |E*| is WMA made with 3.0% Sasobit® produced at 130°C. Based on the test results, it is also observed that |E*| increased when additional Sasobit® and/ or higher production temperature were used. Witczak (2008) indicated that |E*| is one of the most important considerations in evaluating the rutting potential for an asphalt mixture. Mixtures with higher |E*| generally have a higher rutting resistance[93]. Thus, it can be concluded that WMA made with Sasobit® has similar rutting potential compared to the control HMA in this case.

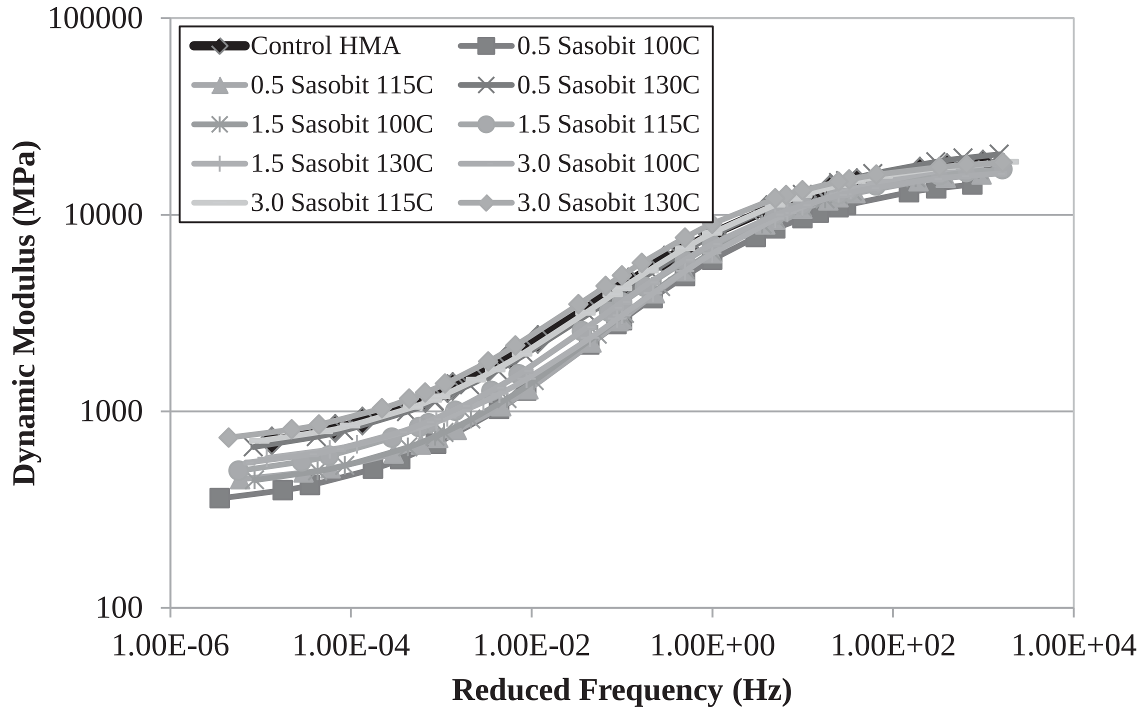


Figure 2.39 Dynamic Modulus Results for Control Mixture and WMA Mixture

2.2.1.8: Moisture Susceptibility Test Using Tensile Strength Ratio (TSR)

The purpose of tensile strength ratio testing is to evaluate asphalt mixture's fatigue potential and moisture susceptibility. In the past, researchers found the tensile strength of asphalt mixture can be well related to fatigue cracking in asphalt pavement [62]. A higher tensile strength means that asphalt pavement can tolerate higher strains before it fails (i.e. crack). Additionally, the moisture susceptibility of the asphalt mixture can be evaluated by comparing the tensile strength of asphalt mixture at wet and dry condition. In this study, the tensile strength ratio of control and WMA mixtures were tested based on AASHTO T283 [63]. Samples were prepared at the size of 150mm in diameter and 95mm in height. The temperature and loading rate used in this study were 25ºC and 0.085mm/s. Figure 2.40 shows the TSR testing results for control HMA and WMA mixtures made with Sasobit®. The result shows that the TSR value for WMA made with Sasobit® is slightly higher than HMA. However, it was found that the tensile strength of

WMA is significantly lower than HMA. Past research indicated that the wettability of asphalt binder over aggregate and adhesion in dry condition will increased as the Sasobit® content increased [100]. Although the wettability and adhesion of asphalt binder increased when addition Sasobit® was used, adhesion of asphalt binder between aggregate was reduced in wet condition due to an increase in the acidity of asphalt binder [101]. Thus it is observed that the TSR values decrease as the dosage of Sasobit® was decrease.

It was also found that the tensile strength of WMA is significantly lower than HMA. A lower tensile strength means that the fracture energy of WMA is lower than HMA. Wen and Kim [64] found that fracture energy was highly correlated with field fatigue performance. They also found that mixture with higher fracture energy has lesser fatigue cracking. Hence, this may indicate that the WMA made with Sasobit® has higher fatigue cracking potential compared to HMA

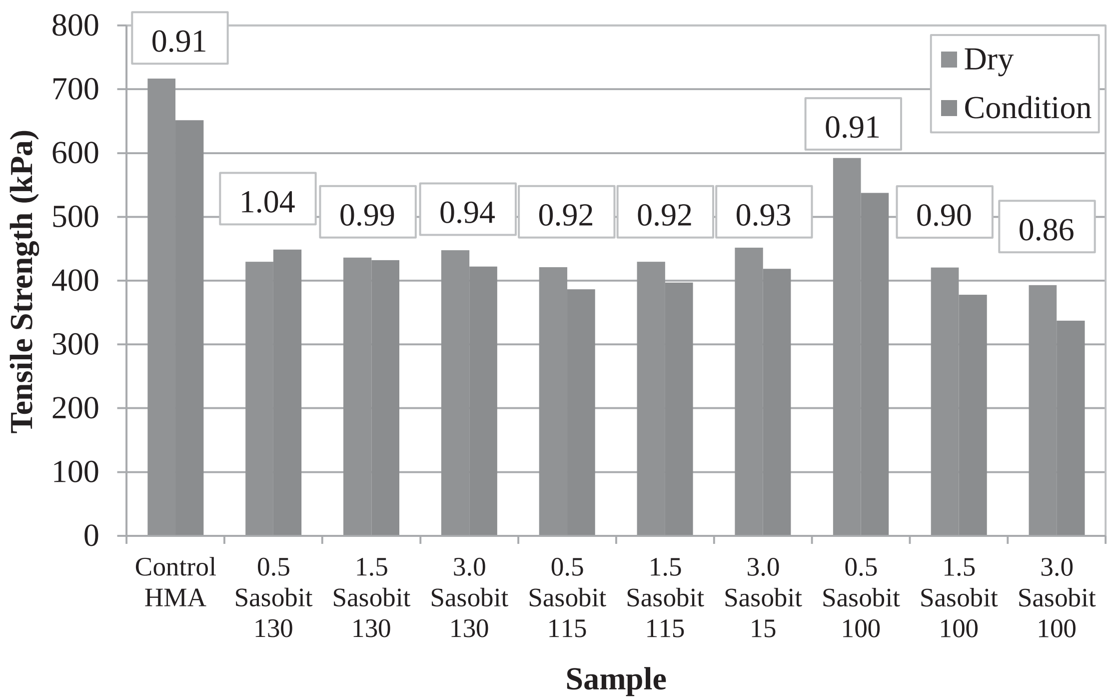


Figure 2.40 Tensile Strength Ratio Result for Control and WMA Mixtures

2.2.1.9: Four Point Beam Fatigue Testing

The results from the four-point beam fatigue tests are presented in this section. Fatigue life of control HMA and WMA made with Sasobit® were evaluated in this section. It is noteworthy that the fatigue life of the asphalt mixture subjected to the repeated bending until failure where the fatigue failure was defined as 50% reduction of initial stiffness [65]. In this test, a frequency of 10 Hz and 400 micro-strains (constant strain) were used for all the samples tested. The results of the four-point beam fatigue testing are presented in Figure 2.41.

From Figure 2.41, it can be found that there are no significant different for all the fatigue life of WMA made with Sasobit® compared to control HMA. Even though earlier testing result show that the aging factor of WMA would affect its fatigue potential due to higher aging factor, however, the four point beam fatigue results shows that this factor doesn’t affect the fatigue life. As mentioned previously, there are several factors that would affect the fatigue life associated with production temperatures and WMA additives when comparing HMA and WMA, including absorption, aging and coating of aggregate.

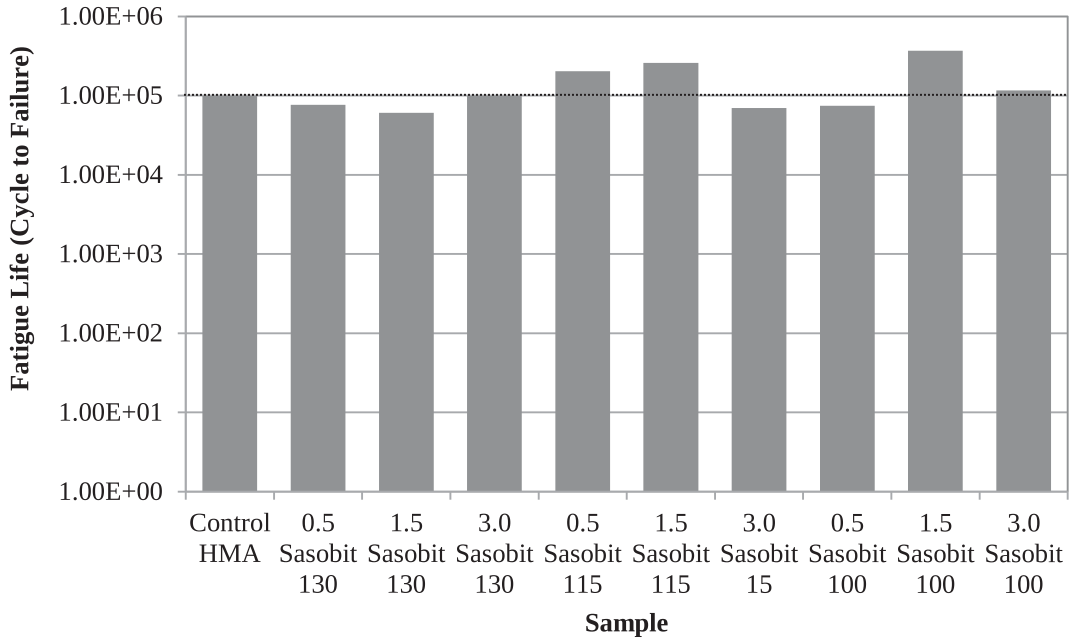
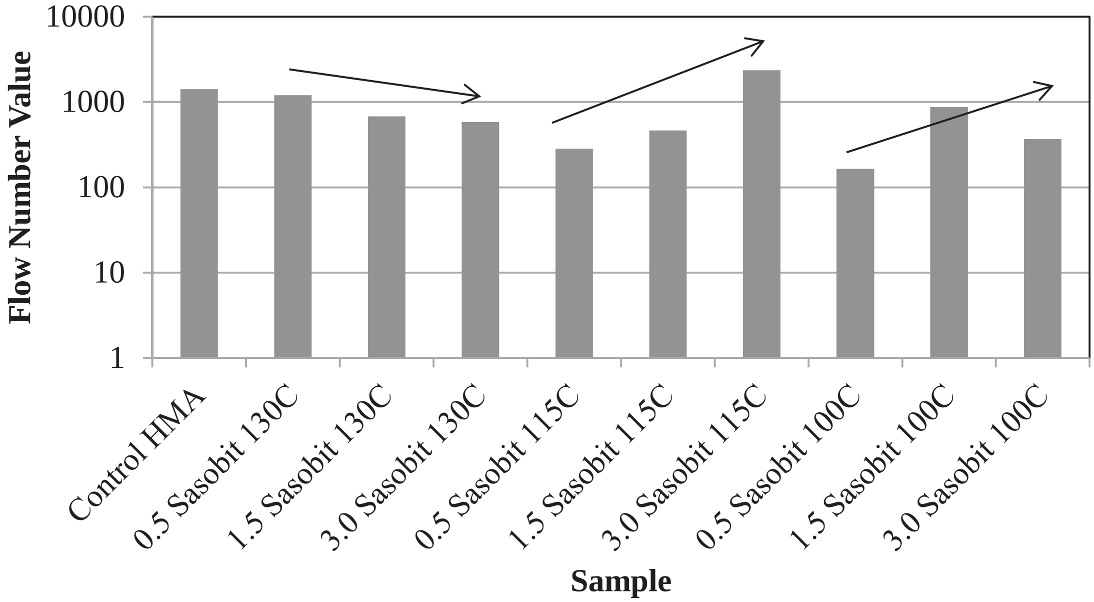


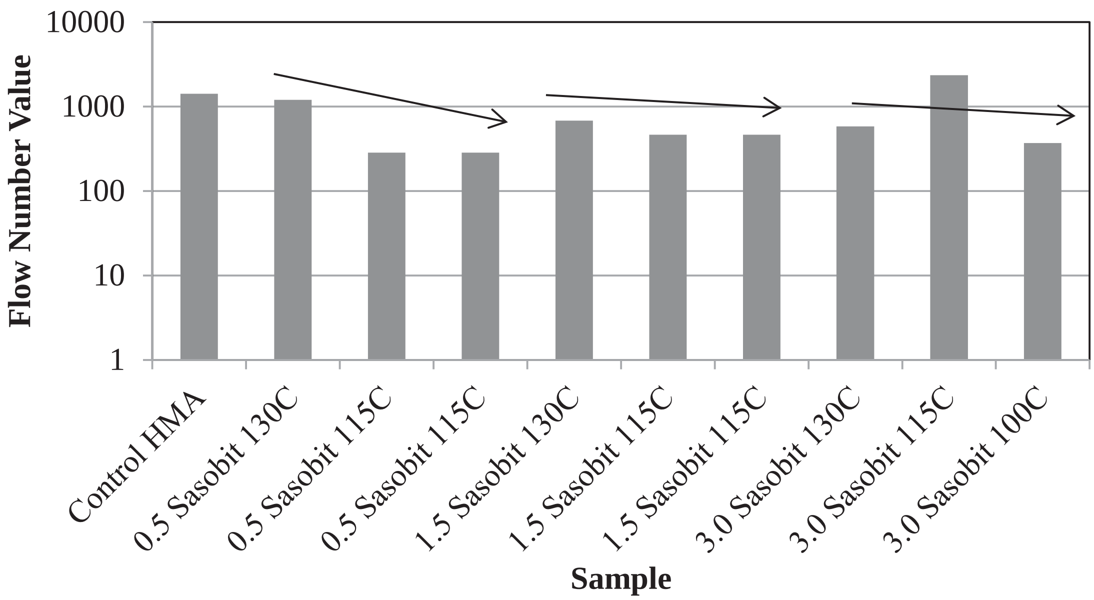
Figure 2.41 Four Point Beam Fatigue Testing Results for Control HMA and WMA made with Sasobit®

2.2.1.10: Flow Number Testing

In this section, HMA control and WMA made with 0.5%, 1.5% and 3.0% Sasobit® (based on binder weight) produced at 100°C, 115°C and 130°C were used. The flow number test was conducted for each sample based on NCHRP 9-29 [93]. The testing results for control HMA and foamed WMA are shown in Figure 2.46. Generally, Figure 2.46shows that the F_N for all WMA samples is similar to the control HMA. These results are in line with the findings from |E*| in which additional Sasobit® didn't affect the F_N of an asphalt mixture. From Figure 2.46, it is also observed that the F_N increase when more Sasobit® was added and/ or the production temperature was increased.



(a)



(b)

Figure 2.42 Flow Number Results for HMA Control and WMA made with Sasobit®

2.2.1.11: Asphalt Pavement Analyzer (APA) Rutting Test

The rutting tests were conducted through the Asphalt Pavement Analyzer (APA) device based on AASHTO TP 63-03 at 58°C (136.4°F). The purpose of this test was to determine the rut resistance for WMA made with Sasobit® at lower production temperature and compare with the control HMA. The results of the APA test are presented in Figure 2.43. Based on the results conducted, it was found that most of the WMA produced at 100°C (except 3.0% Sasobit®) have higher rutting depth compared to control HMA; and the rest of the WMA samples have comparable rutting depth after 8000 loading cycles compared with HMA control. It was found that WMA made with Sasobit® produced at 100°C has the highest rutting depth which this result is consistent with |E*| and F_N result. This can be explained by the aging of the asphalt binder where high production temperature tends to have higher aging which resulted in stiffer mixture.

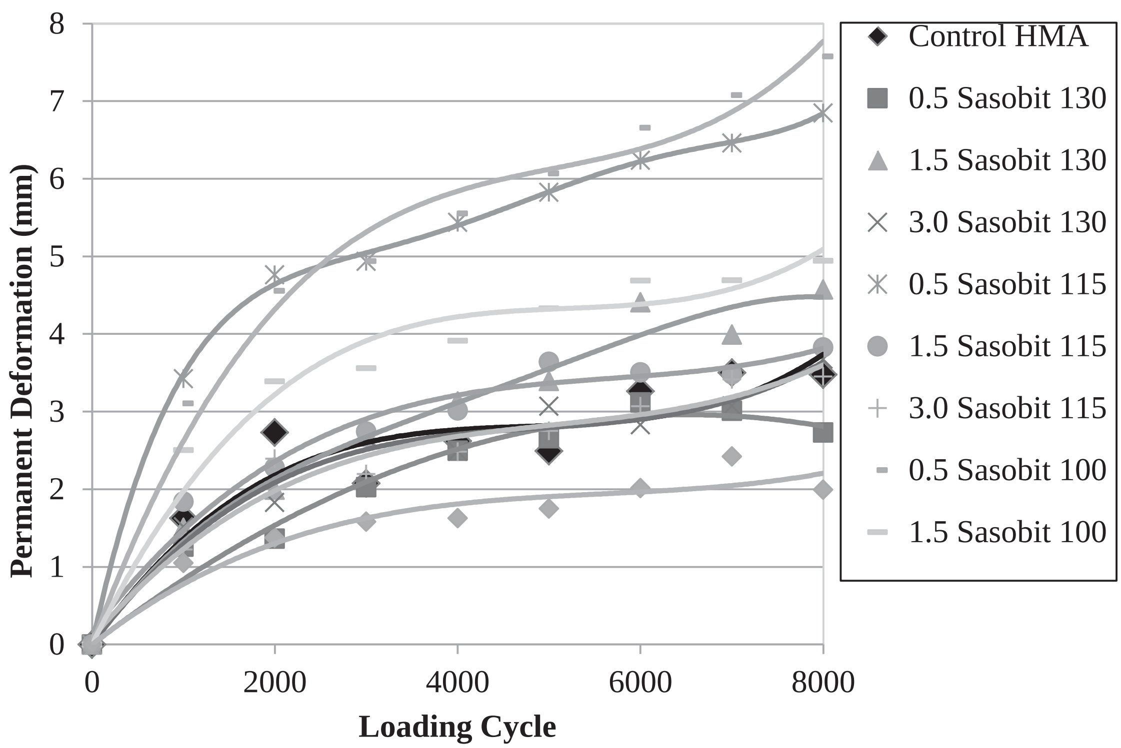


Figure 2.43 APA Rutting Results for Control HMA and WMA made with Sasobit®

2.2.1.12: Summary of Findings

This paper presented the results of a field study of WMA made with 1.5% Sasobit®. The observation shows that emissions from WMA were significantly reduced compared to HMA production. For the WMA volumetric properties, it was found that the G_{mb} of both HMA and WMA did not show any significant difference even though WMA used a lower mixing and compacting temperatures (25°C lower). Cooling time for HMA and WMA was also evaluated in this study using MultiCool program with the assumptions of the mixing temperature for WMA and HMA are same. Both mixtures were produced 18ºC higher than the conventional temperature (171ºC in this case, for cold region paving). It was found that WMA extend the paving time by 27 minutes which will allow a longer hauling distance during the construction. The performance was compared based on the |E*|, F_N, TSR, four point beam fatigue and APA rutting tests. The summary of findings in this case study is presented below:

1. The amount of Sasobit® used and compaction and/ or mixing temperature of WMA made with Sasobt® does not affect the air void level and compaction energy index
2. The WMA made with Sasobit® has lower aging factor in general compare to control HMA. The result shows that the aging factors for Sasobit® aged at 130°C are higher than control HMA; and when the temperature increase, the aging factor increase as well for all the WMA made with Sasobit®.
3. Based on the |E*| testing, it was found that there are no significant difference between control HMA and WMA made with Sasobit®. Thus it is concluded that WMA made with Sasobit® has similar rutting potential compared to the control HMA in this case.
4. Through the TSR testing, it was found that the TSR for WMA is compatible with the HMA (control mixture), which could indicate there are no significant difference between WMA made with Sasobit® and HMA in terms of moisture

damage. However, it was found that the tensile strength of WMA is significantly lower than HMA.

5. Based on the four point beam fatigue testing, it was found that there are no significant different for all the fatigue life of WMA made with Sasobit® compared to control HMA. Even though earlier testing result show that the aging factor of WMA would affect its fatigue potential due to higher aging factor, however, the four point beam fatigue results shows that this factor doesn't affect the fatigue life.
6. Based on the F_N testing, it was found that the F_N for all WMA samples is similar to control HMA. These results are in line with the findings from |E*| for which additional Sasobit® didn't affect the F_N of the asphalt mixture. Additionally, the F_N increased when more Sasobit® was added and/ or the production temperature was increased.

Results from APA rutting test shows that most of the WMA produced at 100°C (except 3.0% Sasobit®) have higher rutting depth compared to control HMA; and the rest of the WMA samples have comparable rutting depth after 8000 loading cycles compared with HMA control. It was found that WMA made with Sasobit® produced at 100°C has the highest rutting depth which this result is consistent with |E*| and F_N result.

2.3: WMA Using Chemical Package

The chemical package often includes anti-striping agents and does not change asphalt viscosity[26,102]. The chemical additive that used surfactant acted as “lubricant” and work at the microscopic interface of aggregate and the asphalt [14]. The “lubricant” reduced the internal friction when asphalt mixture is subjected to high shear rates (i.e. mixing process) and high shear stress (i.e. compacting). This “lubricant” is effective at a certain temperature ranged from 85°C to 140°C typically. The Examples of WMA technologies using chemical package include Cecabase® RT[103], Evotherm[104] and Rediset^{TM} WMX [105].

2.3.1: Case Study: WMA Using Cecabase® RT

Cecabase® RT is a patented chemical package developed by CECA, a division of Arkema Group [15,103]. It was made up by 50% of renewable raw materials that produce increased workability to the asphalt mixture a lower temperature [103]. The Cecabase® RT is available in liquid form and can be injected directly into the asphalt. Figure 2.44 shows the Cecabase® RT used in this study.

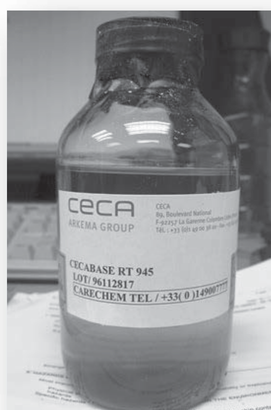


Figure 2.44 Cecabase® RT

2.3.1.1: Sample Preparation

Rheological and aging property of control HMA and WMA made with 0.2%, 0.35% and 0.5% Cecabase® RT were tested with Dynamic Shear Rheometer (DSR). For asphalt mixture testing, the mixture design used in this study was based on specifications for a local asphalt mixture used in Michigan, USA. Asphalt mixture Superpave™ design [46-48] of 5E3 (nominal maximum aggregate size of 12.5mm and designed traffic level less than 3 million ESALs) were used. A PG58-34 binder tested with DSR was used for both control and WMA mixtures. The control and WMA mixtures were batched and mixed using a bucket mixture in the lab. For control mixture, the samples were mixed and compacted at 163°C and 153°C, respectively. For WMA mixture, Cecabase® RT was added at the rate of 0.2%, 0.35% and 0.50% based on binder weight, and they were mixed and compacted at 100°C, 115°C and 130°C. All the mixtures (HMA and WMA) were compacted using the 86 gyration numbers.

The volumetric properties and compaction energy index [61] were also measured in this study. Table 2.10 shows that the WMA made with Cecabase® RT has an average air void levels ranged from 3.47% to 7.39%, and VMA ranged from 25.37 to 27.58. It is also observed that no significant trend was found when comparing the amount of dosage (Cecabase® RT) added, compaction temperature used with measured air void level and compaction energy. Initial hypothesis stated that when the compaction temperature increased, the air void level decreased and/ or the compaction energy index decrease. However, the testing results show that the compaction temperature does not affect the air void level and compaction energy index in this study.

In terms of performance test, the control mixture and WMA mixture were evaluated using dynamic modulus, tensile strength ratio, four point beam fatigue, flow number and asphalt pavement analyzer (APA) rutting tests. All the performance testing were completed within two months.

Table 2.11 Volumetric Properties of HMA and WMA made with Cecabase® RT

Mixture Type	Average G_{mm}	Average G_{mb}	Average Air Void	VMA[1]	Compaction Energy Index
Control HMA	2.5730	2.4411	5.13%	25.37	61.62
0.2 Cecabase 130C	2.559	2.3717	7.32%	27.11	74.15
0.35 Cecabase 130C	2.5561	2.3897	6.51%	26.99	65.74
0.5 Cecabase 130C	2.5785	2.3871	7.42%	27.76	63.82
0.2 Cecabase 115C	2.5517	2.3919	6.26%	27.23	28.95
0.35 Cecabase 115C	2.5492	2.4067	5.59%	27.58	22.05
0.5 Cecabase 115C	2.5826	2.3964	7.21%	27.48	41.24
0.2 Cecabase 100C	2.5657	2.4551	4.31%	27.22	37.40
0.35 Cecabase 100C	2.5657	2.4767	3.47%	27.27	23.19
0.5 Cecabase 100C	2.5666	2.4437	4.79%	25.37	30.48

[1] Void in Mineral Aggregate

2.3.1.2: Asphalt Rheological Properties and Aging Factor

The rheological properties and aging factor were evaluated by Dynamic Shear Rheometer (DSR). PG58-34 Superpave™ graded binder was used as the base binder for control HMA and WMA. Cecabase® RT was added to the WMA binder at the rate of 0.2%, 0.35% and 0.50% based on binder weight. The short-term aging process is known as the asphalt binder condition after pavement construction and is simulated by heating in the oven for 12 hours. Additionally, four different temperatures were used for short-term aging in this case study and they were 163°C for control, and 100°C, 115°C and 130°C for WMA.

Temperature of 58°C and frequency of 10 rad/s were used for the DSR testing. Table 2.12 presents the testing results of DSR testing and the aging factor of control HMA and WMA. It is observed that the control HMA aged at temperature 163°C has higher aging factor compared to WMA. It is also observed that the aging factor for WMA doesn't affect the aging temperature and also the amount of Cecabase® RT. Additionally, Table 2.12 shows that all the binders meet the Superpave™ specification requirement (i.e., minimum 1.00KPa).

Table 2.12 Dynamic Shear Modulus Test Results and Aging Factor for Control HMA and WMA made with Cecabase® RT

Sample	G*/ sin (δ)		Aging Factor
	Unaged	12 hours Aged	
Control 165°C	1345.94	2609.44	1.93875
0.2 Ceca 100	1357.1	1469.7	1.083
0.2 Ceca 115	1364.6	1615.1	1.1836
0.2 Ceca 130	1476	1701.5	1.1528
0.35 Ceca 100	1283	1887.5	1.4712
0.35 Ceca 115	1323	1561.4	1.1802
0.35 Ceca 130	1282.1	1525.3	1.1897
0.50 Ceca 100	1287.1	1780.4	1.3833
0.50 Ceca 115	1272.4	1485.7	1.1676
0.50 Ceca 130	1353.8	1951.1	1.4412

2.3.1.3: Dynamic Modulus Testing

The dynamic modulus testing was performed using UTM 100 from IPC according to AASHTO TP62-03. The temperatures used were -10°C, 4°C, 21.3°C and 39.2°C. The frequencies used in this test ranged from 0.1Hz to 25Hz.

10 different types of mixtures were tested in this study: control HMA, and WMA made with Cecabase® RT at the rate of 0.20%, 0.30% and 0.50% based on asphalt binder weight compacted at 100°C, 115°C and 130°C. The recoverable axial micro-strain in this test was controlled within 75 and 125 micro strains so that the material is in a visco-elastic range [54,55].

Dynamic modulus of the control HMA and WMA made with Cecabase® RT was evaluated and compared using the master curve technique. The master curve technique was used to shifted all |E*| values at various frequencies and temperatures into one single curve. As mentioned previously, the concept of a sigmoidal master curve is to "shift" the relative |E*| from different temperatures to the time of loading using the sigmoidal fitting model, so that the various curves can be aligned to form a single master curve. In this study, a sigmoidal master curve was constructed using a reference temperature of 4°C for the measured |E*| for control and WMA mixtures, and are shown in Figure 2.45.

Figure 2.45 shows that the production temperature and amount of Cecabase® RT used to produce WMA did not affect the |E*| of WMA; however, it is observed that all WMA mixtures made with Cecabase® RT are lower than control HMA. A higher |E*| means the mixture has better performance in terms of rutting resistance[55]. The |E*| test results indicate that the WMA made with Cecabase® RT has higher rutting potential compared to HMA (i.e. control mixture).

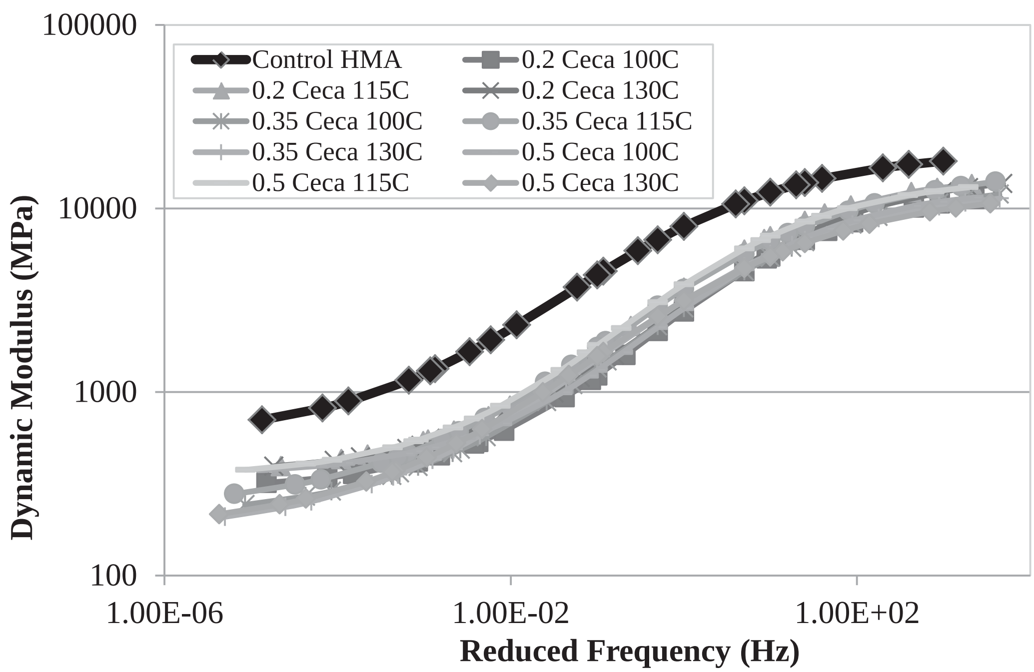


Figure 2.45 Master Curve of Dynamic Modulus of Control HMA and WMA made with Cecabase® RT

2.3.1.4: Moisture Susceptibility Test Using Tensile Strength Ratio (TSR)

The moisture susceptibility of the control HMA and WMA made with Cecabase® RT was tested with tensile strength ratio based on AASHTO T283 [63]. In addition, the tensile strength of the samples was evaluated as well. The tensile strength of asphalt mixture can be well related to fatigue cracking in asphalt pavement [62], and a higher tensile strength indicated that asphalt pavement can better resist cracking (tolerate higher strains before it fails). In this study, the control HMA and WMA samples were prepared at the size of 100mm in diameter and 63.5mm in height. The temperature and loading rate used in this study were 25ºC and 0.085mm/s.

Figure 2.50 shows the TSR testing results for Control and WMA mixtures made with Cecabase® RT. The result shows that most of the TSR for WMA passed the minimum TSR value required by the AASHTO T283 specification (TSR = 0.80). It is noticed that some of TSR values of WMA mixtures are greater than 1.00 mainly because the Cecabase® RT itself presents some anti-strip properties [103,106] and "tender" mixture design used in this study [92]. It was found that the tensile strength of WMA is lower than control HMA in general. It is also observed that the amount of Cecabase® RT added and the temperature used to produce WMA does not significantly affect the TSR and tensile strength. This indicated that the WMA produced with Cecabase® RT at lower temperature has higher fatigue potential; however, the TSR value shows that WMA has similar moisture susceptibility compared to control HMA.

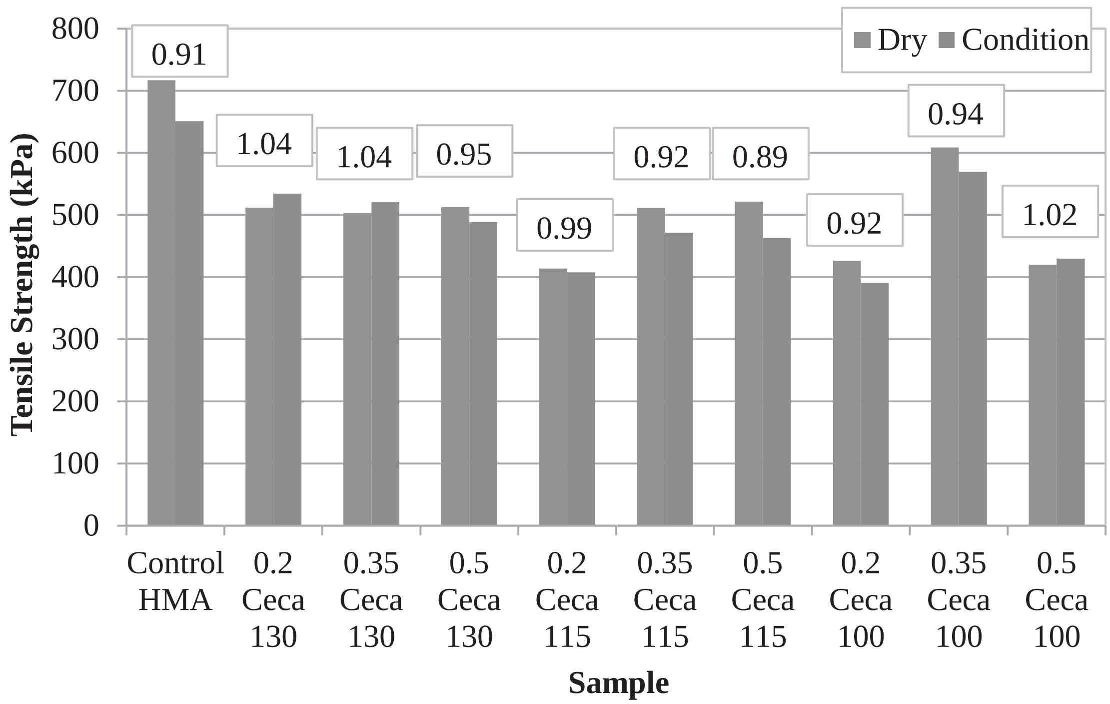


Figure 2.46 TSR Results of Control HMA and WMA made with Cecabase® RT

2.3.1.5: Four Point Beam Fatigue Testing

The results from the four-point beam fatigue tests are presented in this section. The purpose of this test is to determine the fatigue life of the asphalt mixture subjected to the repeated bending until failure where the fatigue failure was defined as 50% reduction of initial stiffness [65]. A frequency of 10 Hz and 400 micro-strains (constant strain) were used for all the samples tested in this study. Control HMA, and WMA made with 0.20%, 0.35% and 0.50% Cecabase® RT (based on asphalt binder weight) produced at 100°C, 115°C and 130°C were used in this study. The results of the four-point beam fatigue testing are presented in Figure 2.47. The test results show that most of the fatigue life for WMA made with Cecabase® RT is significantly higher than the control HMA. It is also noticed that the fatigue life of WMA does not affect by the amount of Cecabase® RT added and temperature used to produced WMA in this case.

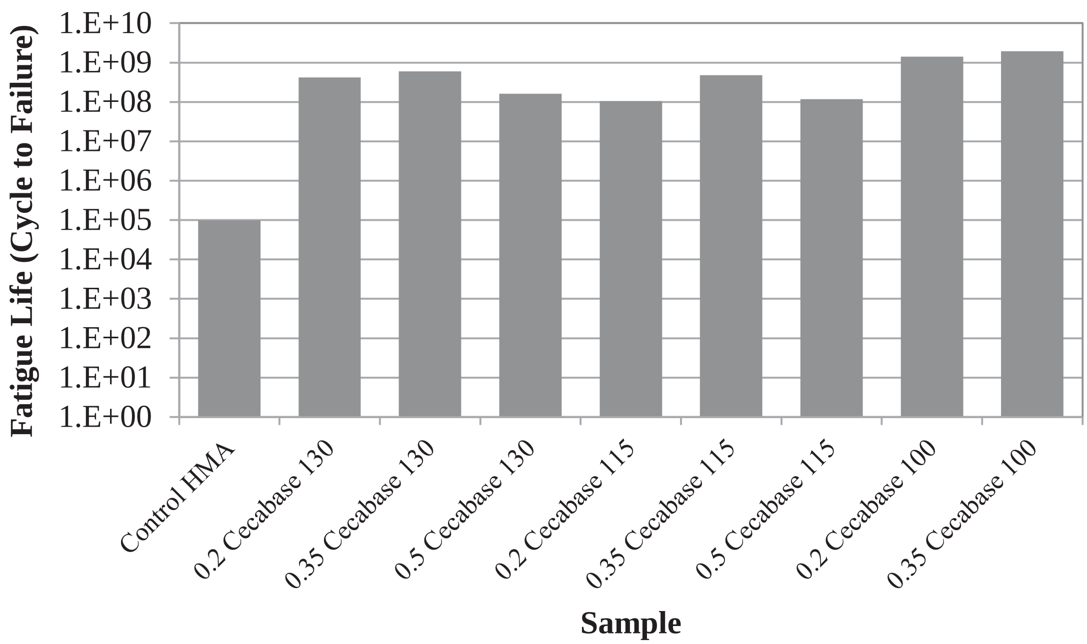


Figure 2.47 Four Point Beam Fatigue Test Results for Control HMA and WMA made with Cecabase® RT

2.3.1.6: Flow Number Testing

The flow number test is often referred to as the dynamic creep or repeated loading test where the permanent deformation of the specimen is recorded as a function of load cycles. In this study, an effective temperature (rutting temperature) of 45°C was used[76,77]. Figure 2.48 shows the test results for control HMA and WMA made with 0.20%, 0.35% and 0.50% Cecabase® RT produced at 100°C, 115°C and 130°C.

From Figure 2.48, the test results show that the F_N for WMA made with Ceabase® RT are lower than the control HMA. These results are in line with the findings from |E*| which shows that WMA has a higher rutting potential. As mentioned previously, the reason was due to lesser aging of WMA during the production. The testing results also indicated that the F_N slightly decreases when more Cecabase® RT is added.

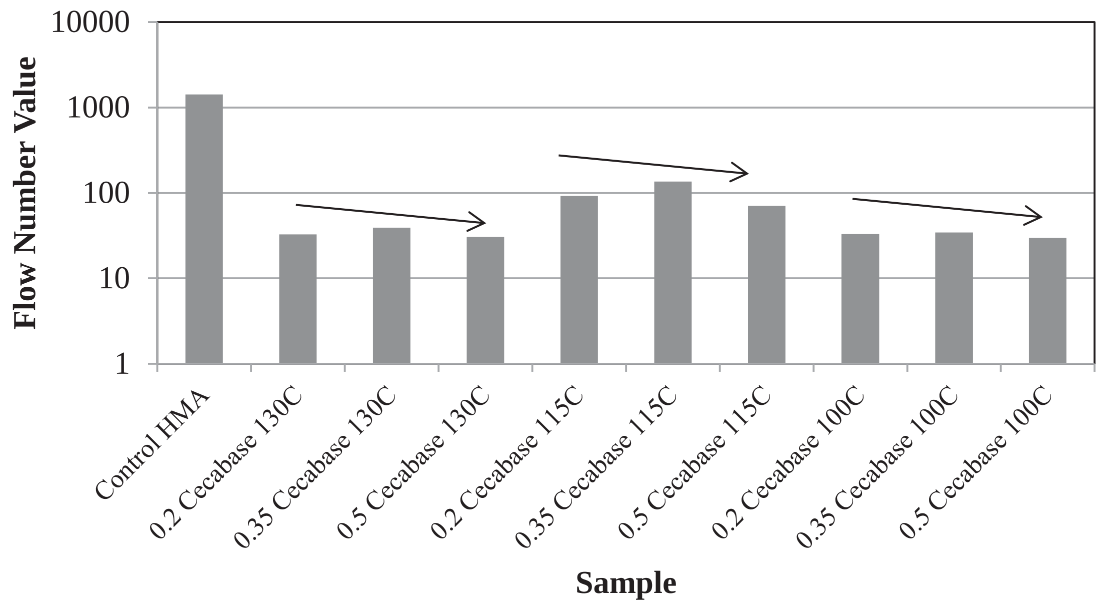


Figure 2.48 Flow Number of Control HMA and WMA made with Cecabase® RT

2.3.1.7: Asphalt Pavement Analyzer (APA) Rutting Test

The rutting tests were conducted through the Asphalt Pavement Analyzer (APA) device based on AASHTO TP 63-03 at 58°C (136.4°F). The purpose of this test was to evaluate the rut potential of WMA and compare the results with the control HMA. The results of the APA test are presented in Figure 2.48. Based on the results conducted, it was found most of the WMA has higher rutting depth compared to the control mixture. Figure 2.48 also shows that WMA made with 0.5% Cecabase® RT produced at 100°C has the highest rutting depth; and this finding is consistent with the result from F_N. In Figure 2.48, it is also found that WMA made with 0.2% Cecabase® produced at 130°C has the lowest rutting depth. The finding in this study is similar to F_N testing where rutting potential for WMA is higher in general which is mainly due to aging. Additionally, the rutting potential increases when more Cecabase® is added and lower mix/ compact temperatures were used.

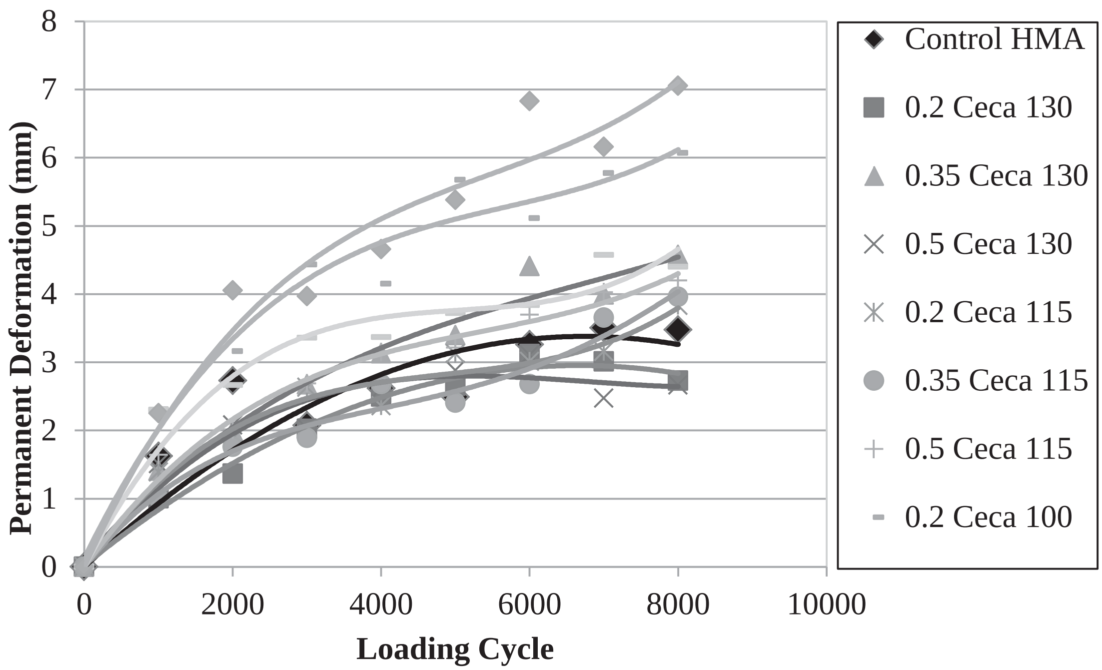


Figure 2.49 APA Rutting Results for Control HMA and WMA made with Cecabase® RT

2.3.1.8: Summary

This case study presented laboratory results of WMA made with Cecabase® RT, and the summary of findings in this case study are presented below:

1. Through the DSR testing, it was found that WMA has significantly lower aging factor compare to control HMA, and a lower aging factor would result in higher rutting at the early stage of pavement serviceability.
2. Based on the |E*| testing, it was found that the production temperature and amount of Cecabase® RT used to produce WMA did not affect the |E*| of WMA; however, it is observed that all WMA mixtures made with Cecabase® RT are lower than control HMA.
3. Through the TSR testing, it was found that the tensile strength of WMA is lower than control HMA in general. It is also observed that the amount of Cecabase®

RT added and the temperature used to produce WMA does not significant affect the TSR and tensile strength.

4. Based on the four point beam fatigue testing, it was found that most of the fatigue life for WMA made with Cecabase® RT is significantly higher than the control HMA. It is also noticed that the fatigue life of WMA does not affect the amount of Cecabase® RT added and temperature used to produce WMA in this case.
5. Based on the F_N and APA rutting tests, it was found that WMA has a higher rutting potential compared to control HMA; and the rutting potential of the WMA increases when more Cecabase® RT is added and lower mixing/ compacting temperatures were used.

Chapter 3: WMA Aging Effects

Aging in is an important factor to the serviceability of pavement. It is noteworthy that different WMA additives affect the property of aging of asphalt binders and mixtures and thus affect the long-term pavement performance.

In asphalt pavement industry, there are two types of aging which classified as short-term aging and long-term aging. Short-term aging refers to the oxidation and volatilization that occurs during construction of pavement – mixing process, storage, transportation and paving process. For long-term aging, it simulates the aging occurred over the serviceability of pavement after the construction.

Case studies presented previously show the reduction in mixing and compacting temperatures caused a reduction in the Flow Number, Dynamic Modulus and APA rutting tests. Similar results were found by researcher [107] indicating that WMA did not perform as well as HMA in rutting related testing due to less aging. A study on field trial was conducted by Hurley et al. [108] showed that the reduced aging in WMA resulted in increased moisture susceptibility. Hurley et al. [108] also indicated that Sasobit® WMA exhibited reduced aging when compare to the control binder.

Several studies have been conducted to study the performance of WMA [5,11,27,109,110]; however, the aging properties of WMA have not been studied in great detail. This chapter presents studies conducted in evaluating the aging factor of control binder PG58-34, binder (PG58-34) with WMA additives (Sasobit® and Cecabase® RT) and formed WMA. Additionally, reheating study was conducted in this chapter as well to determine if the sample reheating would affect the mechanical properties of WMA mixtures. WMA made with Advera® was used in this study. Performance testing includes dynamic modulus and flow number testing was used in this study to evaluate the reheating effects of WMA.

3.1: Binder Aging

The lower mixing/ compacting temperatures in WMA will produce a less aging of WMA during the construction. The reduced aging of binder may result in increasing the rutting potential of the asphalt mixture. In this study, aging factor of WMA was evaluated. The aging of the asphalt binder was performed by conditioning the binder at mixing temperature for 12 hours. For instance, control binder was aged at 163°C and WMA was aged at 100°C, 115°C and 130°C. WMA using forming method (free water system), WMA made with Sasobit® and WMA made with Cecabase® RT were used in this study. Dynamic shear rheometer (DSR) device was used to measure the complex shear modulus (|G*|) and phase angle (δ) of asphalt binder. The aging factor was determined using the equation below:

$$Aging\ Factor = \frac{\left({|G^*|}/{\delta} \right)_{Aged}}{\left({|G^*|}/{\delta} \right)_{Original}}$$

Where, |G*| is the complex shear modulus, and δ is the phase angle. Figure 3.1 shows the comparison of aging factor for HMA and WMA.

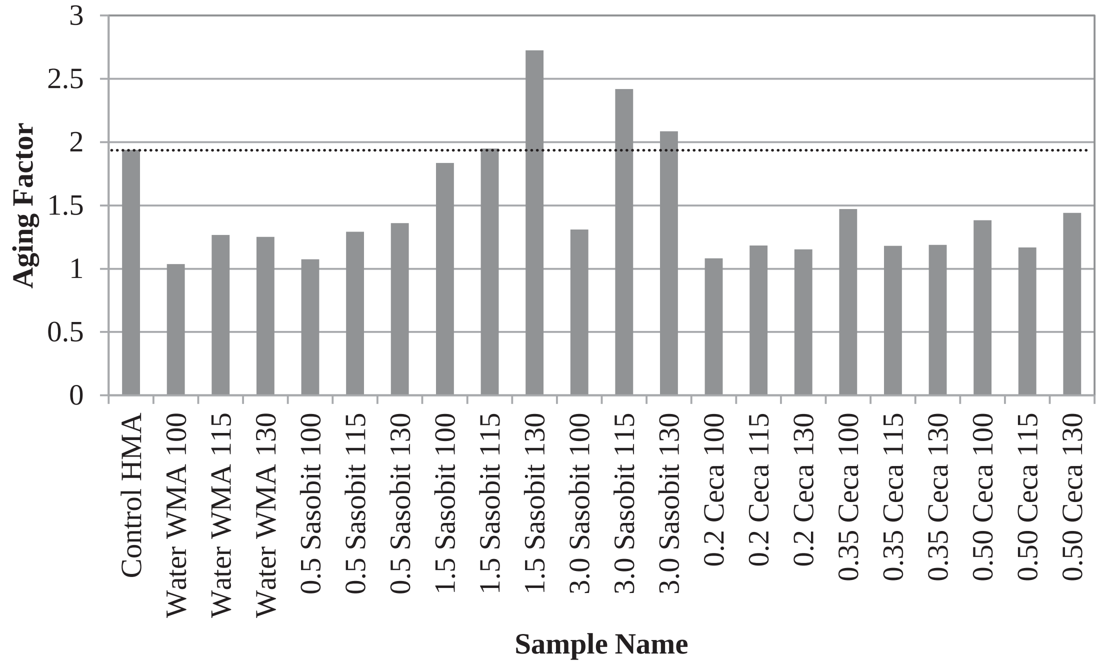


Figure 3.1 Aging Factors for HMA and WMA

From Figure 3.1, it is observed that most of the WMA binder has lower aging factor compared with control HMA binder except WMA made with 1.5% Sasobit® aged at 130°C and WMA made with 3.0% Sasobit® aged at 115°C and 130°C. These results are in line with the previous case study where WMA using foaming method and WMA made with Cecabase® RT have higher rutting potential – lower F_N and |E*| value, and higher rutting depth based on APA rutting test. In addition, the findings from previous case study also indicated that WMA made with Sasobit® has comparable rutting potential compared to control HMA, and the findings are consistent with the results shown in Figure 3.1.

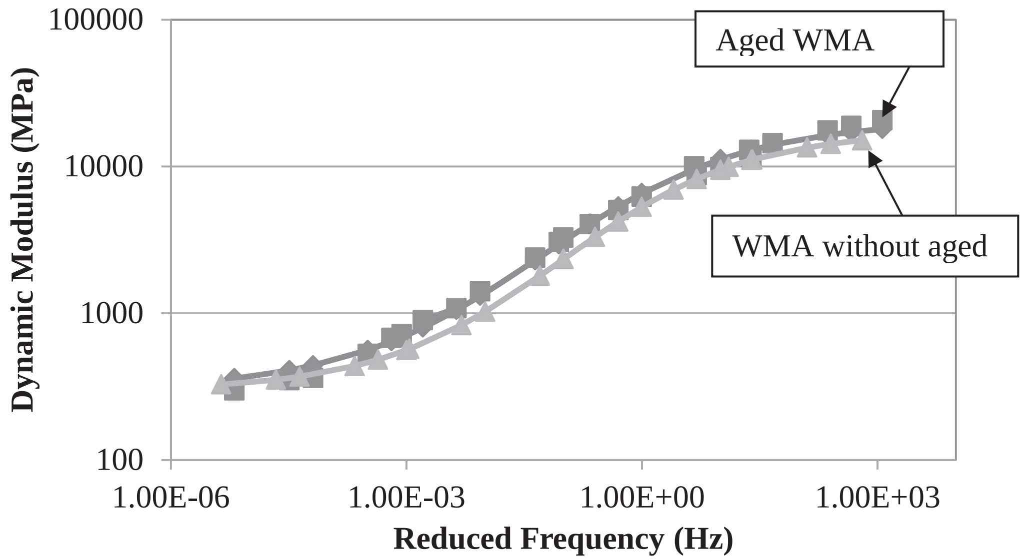
3.2: Effects after Reheating WMA

Generally, the traditional HMA was reheated for a variety of application and/ or performance tests. For WMA, since it includes irreversible component such as foaming, sample reheating may not be feasible for volumetric acceptance. In the other hand, reheated WMA samples can be used for evaluating its mechanical properties if the effect of reheating is not significant. In this study, unanged WMA (WMA tested immediately after produced) and 3-month aged WMA (the loose mix of WMA reheated after aged for three months under room temperature) were evaluated to determine if the sample reheating significantly affects the mechanical properties of WMA. It is noted that all WMA was mixed and compacted at temperature of 115°C.

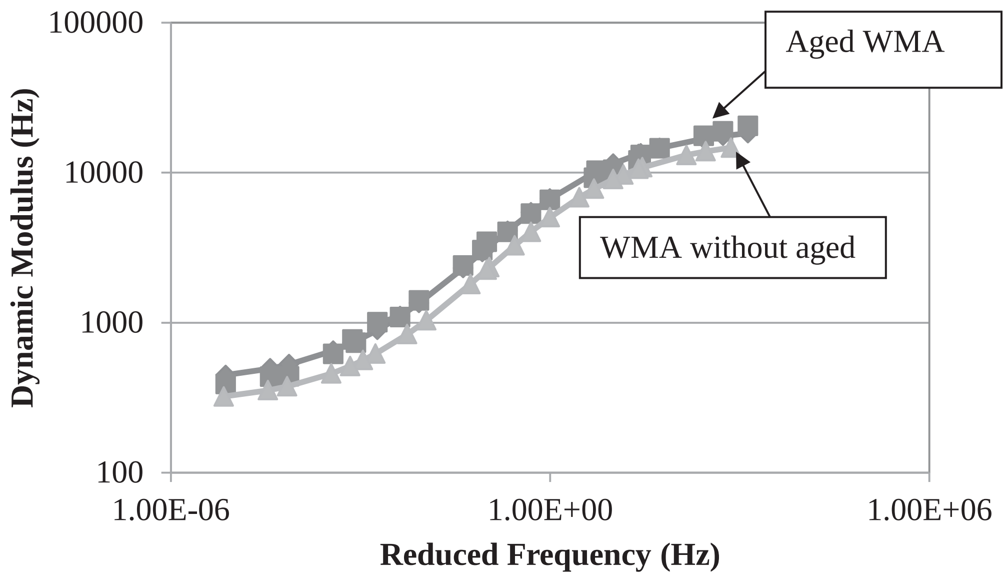
3.2.1: Dynamic Modulus

In this study, unaged and aged WMA (WMA reheated after 3 months aged under room temperature) was compared using |E*|. The dynamic modulus (|E*|) tests were conducted according to AASHTO TP62-03 at -10°C, 4°C, 21.3°C and 39.2°C, and frequencies ranged from 0.1Hz to 25Hz. The master curve technique using the reference temperature of 4°C was used to analyze the |E*| of aged and unaged WMA. The comparisons of |E*| for both aged and unaged WMA are shown in Figure 3.2.

Figure 3.2 shows that the |E*| for 3-month aged WMA is slightly higher compared to unaged WMA, which is expected due to stiffer asphalt binder. In order to determine whether the reheating would significantly affects the performance, a statistical method and paired t-test with 95% confidence level was performed. It was found that the range of the mean difference between the aged and unaged WMA is (690, 1722) for 0.15% Advera and (901, 2005) for 0.35% Advera® based on the 95% confidence interval. Based on the pair-t test result, it is concluded that the reheating would affect the performance of WMA using foaming method. This in line with recent studies conducted by Kvasnak et al. [111] and Al-Qadi et al. [112] where they also found out that reheated WMA resulted in greater |E*|.



(a)



(b)

Figure 3.2 Comparison of the |E*| for aged and unaged (a) WMA made with 0.15% Advera®; and (b) WMA made with 0.35% Advera®

3.2.2: Flow Number

In this section, unaged WMA and aged WMA – WMA that reheated after aged for three months under room temperature was compared using flow number. The flow number test was conducted for each sample based on NCHRP 9-29 [93] at temperature of 45°C. Figure 3.3 shows the F_N testing results for aged and unaged WMA made with 0.15% and 0.35% Advera®. In Figure 3.3, it shows that the F_N aged WMA is significantly higher than unaged WMA for both 0.15% and 0.35% Advera®, which is expected due to the stiffer binder. The results are consistent with |E*| testing result which again concluded that the reheating would affect the performance of WMA using foaming method.

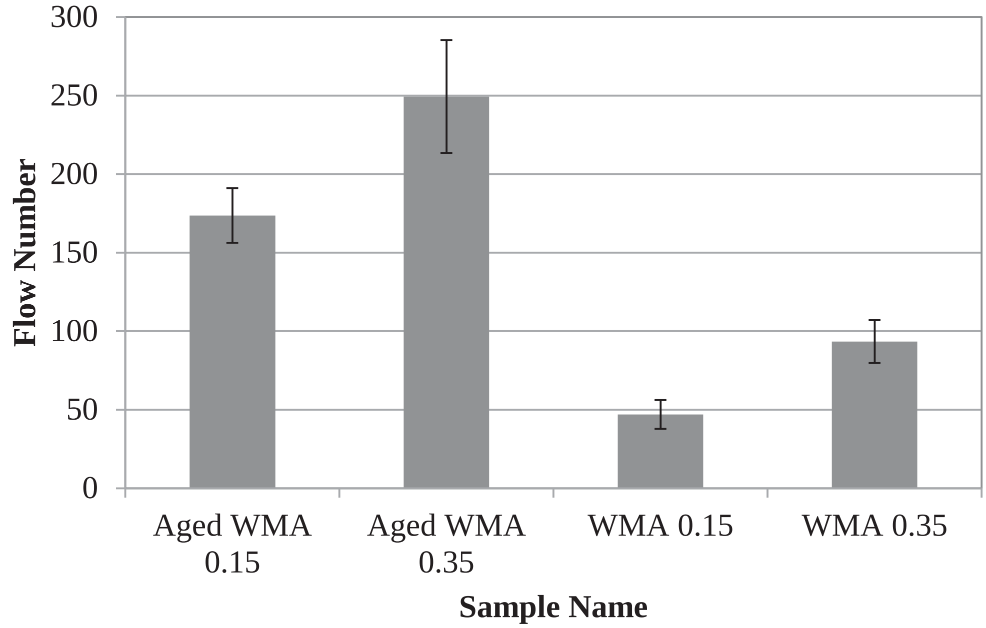


Figure 3.3 Comparison of Flow Number for Unaged WMA and WMA Aged after 3 Months

3.3: Summary Findings

The results from binder testing indicated that most of the WMA binder tested has lower aging factor compared with the control binder. The aging factor was determined based on the ratio between G*/sin(δ) of un-aged and short term aging [13]. Generally, a lower aging factor indicated better pavement life because pavement aged slower over its serviceability [13].

Performance testing – Dynamic Modulus and Flow Number for reheating WMA indicated that the reheating could significantly affect the performance of WMA in terms of stiffness. Results from Dynamic Modulus testing showed that a significant increase in |E*| value for reheated sample based on statistical analysis paired t-test. Results from flow number testing again concluded that the reheated sample improve the rutting resistant of WMA.

Chapter 4: WMA Design Framework

To date, contractors and state agencies have introduced the WMA technologies into existing mix designs, including Ohio [29], Iowa [113], Minneapolis [114], Virginia [115], etc. In addition, numerous laboratory studies were also conducted throughout the United States to access the rutting, fatigue and moisture susceptibility of WMA [7,100,116,117]. For instance, National Center for Asphalt Technology (NCAT) has conducted an extensive study on WMA using several kinds of technologies [12,17,26]. Although various studies have been conducted on WMA, there are still many uncertainties when using WMA in an existing mixture design. In this , a complete laboratory evaluation of WMA that covers most of the WMA technologies used to date (i.e. foaming, organic additive and chemical package) were presented to access the rutting, fatigue and moisture susceptibility of WMA. The findings from laboratory evaluation will be discussed in this section to develop the WMA mix design framework.

The summary of the performance testing results for all WMA case studies are presented in Table 4.1. From Table 4.1, it is observed that most of the WMA technologies used in this study have higher rutting potential based on the results from $|E^*|$, F_N and APA rutting. In terms of fatigue cracking potential, all WMA shows either similar or have higher fatigue life based on four point beam fatigue results. For moisture susceptibility test, all WMA shows either similar or higher TSR value; however, one concern found during the testing is that the tensile strength of WMA is significantly lower than control HMA in most cases. As for asphalt binder properties, only WMA using organic additive would increase the stiffness of the binder; however, the aging factors of all WMA are significantly lower than control HMA due to different aging temperature, and this would significantly affect the WMA rutting performance.

In the following sections, a recommended WMA mix design framework based on all the case studies was presented in order to allow contractors and state agencies to successfully design WMA. The current WMA design framework will be discussed in the following five sections: WMA technology selection, asphalt binder, WMA mixing and compacting, aggregate gradation, WMA technology handling and critical WMA performance testing. The WMA design work flow is shown in Figure 4.1.

Table 4.1 Summary of WMA Performance Testing

		Asphalt Binder		Rutting			Fatigue	Moisture Susceptibility
		Complex Shear Modulus	**Aging Factor[1]**	**Dynamic Modulus**	**Flow Number**	**APA Rutting**	**Four Point Beam Fatigue**	**Tensile Strength Ratio**
Foaming	**Aspha-min®**	No Change	Lower	Similar or Higher |E*| Comparable or better rutting resistant	-	Lower Rutting Rutting decrease when mix/ compact temp. increase	-	-
	Advera® WMA	No Change	Lower	Lower |E*| Increase rutting potential	Lower F_N	Higher Rutting	Higher Fatigue Life	TSR value no change or higher; But, lower tensile strength was found
	Water Foaming	No Change	Lower	Lower |E*| Increase rutting potential	Lower F_N	Higher Rutting	Higher Fatigue Life	TSR increase when mix/ compact temp. increase
Organic Additive	**Sasobit®**	Increase	Samples at 130°C has higher aging factor. Aging factor increase when temp. increase	No Significant Different	No Significant Different	Samples with less Sasobit® have higher rutting.	No Significant Different	No Significant Different Lower tensile Strength was found
Chemical Package	**Cecabase ® RT**	No Change	Lower	Lower |E*| Increase rutting potential	Lower F_N F_N decrease when more Cecabase® RT was added	Samples produced at 100°C have higher rutting. No significant for the rest of the samples.	Higher Fatigue Life	TSR value no change or higher; But, lower tensile strength was found

[1] aged at lower temperature compared control HMA: Control aged at 163°C; WMA aged at 100°C, 115°C and 130°C; Aging factor $=[G^*/\sin(\delta)_{aged}]/[G^*/\sin(\delta)_{unaged}]$

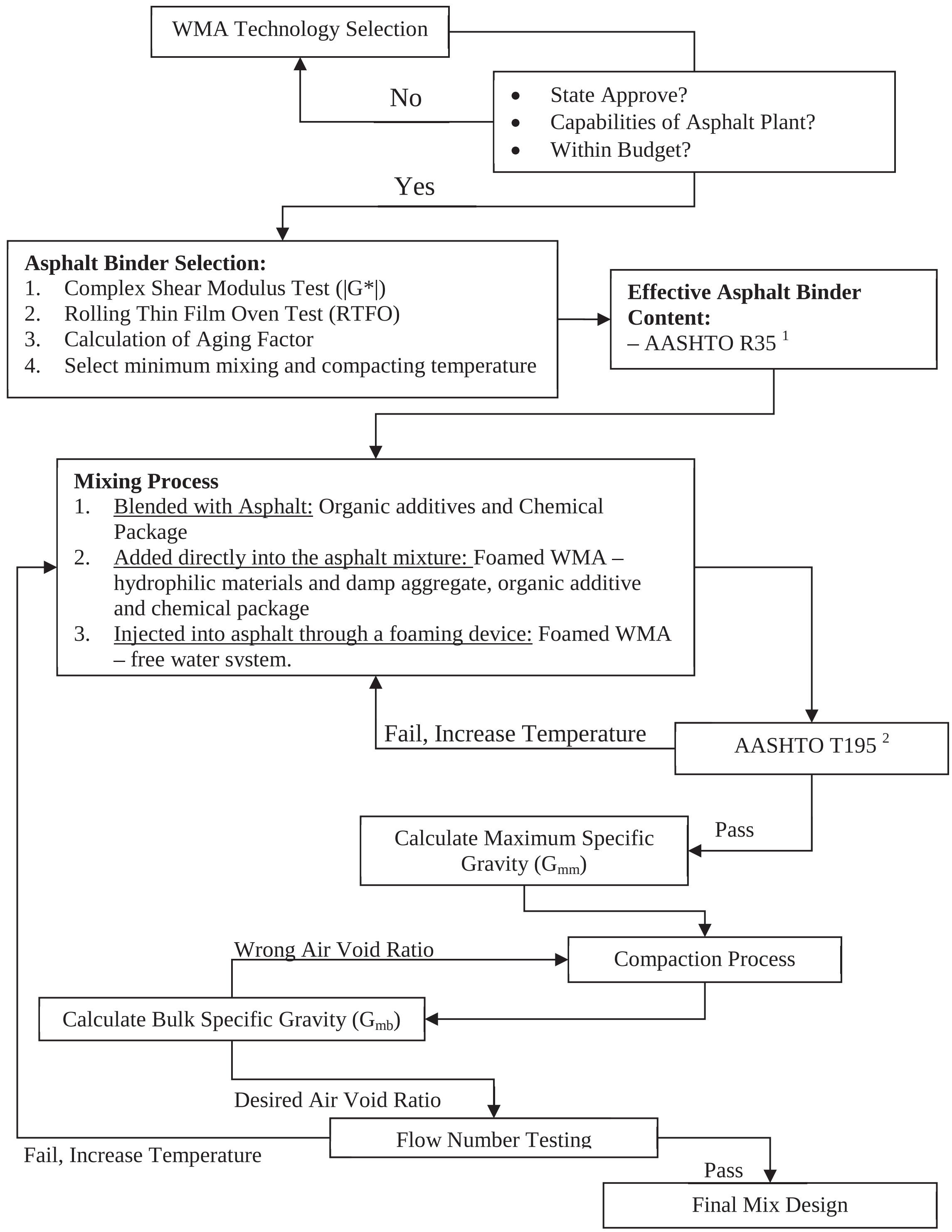


Figure 4.1 WMA Mix Design Work Flow

4.1: WMA Technology Selection

The first step when designing the WMA is to select the appropriate WMA technology for the pavement construction. Based on the literatures and findings in this study, the selection should be based on several factors:

1. State Approval on type of WMA technologies
2. Asphalt mixture production temperature that was planned
3. The capabilities for asphalt plant
4. The budget for the pavement construction

4.2: Asphalt Binder

Once the WMA technology was selected, the next step is to select an appropriate asphalt binder grade. The selection of asphalt binder performance grade (PG) should be based on the climate and traffic level at the construction site, and the PG should be adjusted based on the plant discharge temperature. From the laboratory studies, the DSR testing results indicated that the aging factor plays an important role in mixture performance. Hence, this factor should be considered in this asphalt binder design. The aging factor of the asphalt binder should be measured using following equation:

$$Aging\ Factor = \frac{\left({|G^*|}/{\delta} \right)_{RTFO}}{\left({|G^*|}/{\delta} \right)_{Original}}$$

Where, |G*| is the complex shear modulus, and δ is the phase angle. The high temperature of asphalt PG should be bumped by one grade if the anticipated plant discharge temperatures are less than the temperatures given in

Table 4.2 [118]. However, asphalt binder that uses organic additives (i.e. Sasobit®) may not need a binder grade adjustment since this kind of WMA technology can alter the binder grade.

Table 4.2 Recommended Minimum Production Temperature [118]

PG High Temperature Grade	Aging Factor											
	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6
	Min. WMA Mixing Temperature Not Requiring PG Grade Increase, °C											
52	<100	<100	<100	<100	<100	<100	105	105	110	110	110	110
58				105	110	110	115	115	120	120	120	120
64			105	110	115	115	120	120	120	125	125	125
67		105	110	115	120	120	125	125	125	125	130	130
70		105	110	120	120	120	125	125	125	130	130	130
76		110	115	120	125	125	130	130	130	130	130	135

Next is to select appropriate binder content for the WMA which is one of the critical procedures in this study. It is recommended that selection of the binder content should follow the traditional HMA procedure – AASHTO R35 [1].

4.3: Aggregate Gradation

Based on the literature reviews and findings from this study, the aggregate gradation does not significantly affect the performance of WMA and thus it is suggested that aggregate gradation using Superpave™ mix design should be followed.

4.4: WMA Mixing and Compacting

Mixing and compacting are one of the most critical procedures in developing WMA mix design framework. In this study, it was found that F_N, |E*| and APA rutting improved when higher temperatures of WMA were used. Thus in this section, the mixing and compacting temperatures should be designed to meet the minimum requirement discussed in later section – Critical WMA Performance Testing. If the WMA produced does not meet the minimum requirement, it is recommended to increase the mixing and compacting temperatures.

During the WMA mixing process, aggregate coating is an important factor to minimize the moisture damage of WMA. Thus, it is suggested that the coating of the aggregate should be tested with AASHTO T195 [2] to make sure all the aggregate should be fully coated.

For WMA compaction, the gyration number required for Superpave™ gyratory compactor can be determined by backcalculation the first trial compaction. The procedure for determining the gyration number required for WMA is recommended as follows:

1. WMA sample weighted 3000 grams was first compacted to gyration numbers of 120 at optimum binder content and anticipated compaction temperature
2. The correction factor will then be determined using the equation below:

$$C = \frac{Gmb_{measured}}{Gmb_{theoretical}}$$

$Gmb_{measured}$: Lab measured bulk specific gravity of sample after sample was compacted with 120 gyrations

$Gmb_{theorethical}$: Volume of sample at 120 gyrations multiply with sample weight

3. The estimated air void level for each gyration number was then determined using the equation below:

$$AV_i = 100 - \frac{C \times Gmb_{theoretical-i}}{Gmm}$$

AV_i: Estimated Air void level at each gyration number (within 120 gyrations)

C: correction factor

$Gmb_{theorethical-i}$: Bulk specific gravity of sample at each gyration number (within 120 gyrations)

Gmm: Maximum specific gravity of the sample

4. The last step is to locate the gyration number using the equation below:

$$N_D = \text{minimum}(|\text{AV}_i - \text{AV}_{desired}|)$$

N_D:	Desired gyration number
AV_i:	Estimated Air void level at each gyration number (within 120 gyrations)
$AV_{desired}$:	Design/ desired air void level

4.5: WMA Technology Handling

Since there are various types of WMA technologies appearing in different forms, the WMA technology handling become critical in the WMA design Framework. As discussed in this study, there are three main categories of WMA including WMA using foaming method, organic additive and chemical package; and these WMA technologies were applied to the mixture through three basic methods:

i. Blended with asphalt: Organic Additive and Chemical Package
ii. Added directly into the asphalt mixture: Foamed WMA – hydrophilic materials and damp aggregate, organic additive and chemical package
iii. Injected into asphalt through a foaming device – Foamed WMA – free water system.

Each of the WMA technology uses these methods with slightly different approach, discussed in previous sections. For other WMAs that were not mentioned in this study, contractor and/ or state agencies should seek for advice by referring to the manufacture/ producer of the WMA technology used for the project.

4.6: Critical WMA Performance Testing

Based on the results from the laboratory evaluation, it was found that rutting performance of WMA should be examined. The increased rutting potential of WMA due to lesser aging during the production becomes the main concern. In this study, |E*|, F_N and APA rutting were used to access the rutting potential of WMA and thus one of those tests are recommended to be used as WMA QA/QC. Among |E*|, F_N and APA rutting tests, F_N test is recommended since it is easier to interpret and the previous study indicated that the F_N was well correlated to field performance [93]. Additionally, F_N was used in the past study to develop the specification of Superpave™ Simple Performance Test, currently referred to as Asphalt Mixture Performance Test (AMPT), in the state of Michigan [119]. In the past study, F_N for the mixture collected from a total of 20 test sections around the state of Michigan were evaluated and minimum values of F_N for each traffic level were developed as well. Hence in this study, the minimum F_N shown in Table 4.3 is recommended to be used as the WMA QC/QA. It is noteworthy that the F_N was tested under unconfined condition; the effective temperature (rutting temperature) used for the F_N testing is 45°C; and the stress level and contact stress are 600kPa and 30kPa, respectively.

Table 4.3 Minimum Flow Number Requirement Tested at 45°C

Traffic Level	Minimum Flow Number
< 1 million ESALs	430
<3 million ESALs	480
<10 million ESALs	560
<30 million ESALs	2860

Chapter 5: WMA with High Percentage of Recycled Asphalt Pavement

5.1: Recycled Asphalt Pavement (RAP)

Dwindling sources of traditional aggregate, increasing haulage distance, and increasing asphalt unit price were the primary reasons that leading to the development of the Reclaim Asphalt Pavement (RAP). Previous research indicated that the life cycle cost for a pavement is lower if the pavement is maintained at an acceptable level of service [120,121].

RAP has been developed for many years. During the 1930's, the Hot In-Place Recycling (HIR) technology was first discovered in the asphalt recycling area [120]. During the 1970's, two events – the petroleum crisis of the early 1970's, and the development of large scale cold planning equipment and tungsten carbide milling tools – led to an interest in asphalt recycling technology. Since then, paving contractors have been making extensive use of RAP and various kinds of research were conducted intensively to evaluate its performance.

Typically, asphalt will become stiffer, often referred to as aging, with time. Researchers [122] reported that different kind of solvents, extraction and recovery method resulted in a significant variability on the properties of asphalt binder. Researchers also studied the aging effect of the binder and investigated the effect of each composition on asphalt recycling agents. Lewandowski et al. (1992) were trying to simulate the aging effect of the binder through microwaving and studied its performance by using the Gel Permeation Chromatography (GPC), Fourier-Transform Infrared Spectroscopy (FTIR), and Dynamic Mechanical Analysis (DMA) [123]. The results indicated there was a large change in molecular size when a recycling agent was incorporated into the asphalt. In addition, the shear modulus, G* was found to increase during microwaving which correlated with the measured decrease in penetration (increase in viscosity). Similar results were also found from the FTIR test. Peterson et al. (1994) investigated the effect of metals, asphaltenes, and paraffins content on the properties of recycled aged asphalts [124]. The composition of asphalt (asphaltenes, aromatics, oils, and waxes) was separated by supercritical fractionation. Peterson et al. indicated that asphaltenes increase the hardening rate but not the oxidation rate and the effect of saturation depended on the asphaltene content. Wax doesn't show any significant effect toward the hardening of asphalt and asphalt shows robust performance when highly aromatic recycling agents were added. Researchers [125] also studied the fractions of asphalt by GPC, high-performance liquid chromatography, and viscosity to determined its aging effect. The main objective of this study was utilizing part of the asphalt fraction as recycling agents. The results indicated that all the RAPs tested have superior aging index compared to the original asphalt. Researchers [125,126] also indicated that the RAP will harden more slowly than the original asphalt and the hardening degree was highly correlated with the total saturated content in the RAP.

Several laboratory tests were also conducted on RAP to investigate the mixture characteristics and its performances. Because RAP is stiffer than a new asphalt mixture, researchers [127,128] studied the compactability of the mixture containing RAP. It was found out that the mixture can be compacted as easily as a general mixture at a new compacting temperature estimated from penetration-index. However, Daniel and Lachance (2005) indicated that the void in mineral aggregate (VMA) and void filled with asphalt (VFA) increased when different percentages of RAP were added [129]. McDaniel et al. (2007) studied the properties of Plant-produced RAP mixture using Dynamic Modulus (E*) test, G* test, low temperature creep compliance test and indirect tensile strength test [130]. They found out that there are no statistical differences in mean strength and E* for mixtures with 15% and 25% RAP level. However, the E* for the mixture with 40% RAP was found to be significantly different (higher E*) at the high test temperature based on statistical analysis (pair-t test). Chehab and Daniel (2006) evaluated the sensitivity of the predicted performance of the RAP mixture and found that the MEPDG predicted IRI was not sensitive to the RAP content [131].

The specifications of the asphalt binder in the United States are usually based on Superpave binder criteria. However, for RAP binder, Kandhal and Foo reported that Dynamic Shear Rheometer (DSR), one of the Superpave Binder Tests, was not recommended for RAP binder because it is too liberal [132]. A series of recommended guidelines and specifications for RAP to be used in the field were developed under the National Cooperative Highway Research Program (NCHRP) Report 9-12 [133-135]. This report mainly discussed how the RAP acted through the "black rock study", examined the effect in asphalt binder through "binder effect study," and evaluated the effect of additional RAP in the asphalt mixture.

Several RAP projects were constructed in the United States and Canada to investigate its field performance and RAP up to 50% was used in the pavement [136-140]. These field projects show the performance of the recycled pavements containing RAP have similar or better performance, in some cases, compared to the virgin asphalt pavement.

5.2: WMA with High RAP Content

WMA technologies are acted as compaction aids particularly at reduced temperature [12,26,59] and it has a symbiotic relationship with RAP. Durability of RAP mixture had been a concern when higher percentage of RAP was used that will result in increasing cracking potential. For WMA, as mentioned in previous section, the concern was the less aging (less oxidation) due to low production temperature. Hence, mixture using both RAP and WMA technology may offset these concerns, and a higher percentage of RAP can be incorporate in WMA mixture without changing the asphalt binder grade.

5.2.1: High RAP Mixture Design

When designing the HMA with high RAP content, blending charts were normally used to determine the asphalt binder grade as well as in optimizing the amount of RAP used [141]. However, most of the State DOTs were reluctant to permit the practice of RAP due to highly expensive and time-consuming binder extraction and recovery testing [142]. Additionally, the State DOTs were concern on the quality of HMA with high RAP content due to limited past experiences [143].

In recent years, technique of fractionation was introduced to design HMA with high RAP content. Fractionation is an advance technique of processing and separating RAP into several sizes which usually coarse fraction and fine fraction. It was reported that fractionation technique allows higher RAP content to be used in HMA due to more uniformity [143,144].

In this study, all RAP materials were fractionated in eight different sizes – 4.75mm, 2.36mm, 1.18mm, 0.6mm, 0.3mm, 0.015mm and 0.0075mm and size passing 0.0075mm. The RAP was obtained from Lake Annie, MI. Table 5.1 and Table 5.2 show the gradation design for HMA contains 50% and HMA contains 75% RAP, respectively. From Table 5.1 and Table 5.2, it is observed that all RAP used in this study are fine aggregate which the size is similar or smaller than 4.75mm. It is also observed that most RAP size used in this study was retained at 4.75mm and 2.36mm.

Table 5.1 Gradation Design for HMA contains 50% RAP

Size	Percent Passing	HMA (% Retained)	RAP (% Retained)
1/2" (12.5mm)	100	0.00	0.00
3/8" (9.5mm)	99.1	0.90	0.00
#4 (4.75mm)	75	0.00	24.10
#8 (2.36mm)	55.9	0.00	19.10
#16 (1.18mm)	41.3	10.52	4.08
#30 (0.6mm)	27.5	12.44	1.36
#50 (0.3mm)	14.5	12.32	0.68
#100 (0.015mm)	7.5	6.73	0.27
#200 (0.0075mm)	5.5	1.73	0.27
Pan		5.36	0.14
Sum		50.00	50.00

Table 5.2 Gradation Design for HMA contains 75 % RAP

Size	Percent Passing	HMA (% Retained)	RAP (% Retained)
1/2" (12.5mm)	100	0.00	0.00
3/8" (9.5mm)	99.1	0.90	0.00
#4 (4.75mm)	75	0.00	24.10
#8 (2.36mm)	55.9	0.00	19.10
#16 (1.18mm)	41.3	5.06	9.54
#30 (0.6mm)	27.5	4.26	9.54
#50 (0.3mm)	14.5	3.46	9.54
#100 (0.015mm)	7.5	5.73	1.27
#200 (0.0075mm)	5.5	0.73	1.27
Pan		4.86	0.64
Sum		25.00	75.00

During the production of RAP mixture, for control RAP mixture, the aggregate (together with RAP) was superheated to 180°C and the binder was heated to 163°C prior mixing process, 153°C was used during the compaction process. For WMA, the aggregate and RAP were superheated to 180°C and the binder was heated to 130°C prior to the mixing process, and 130°C was used during the compaction process. The optimum binder content for RAP mixture were determined using Superpave™ mix design method [145] in this case. Figure 5.1 and Figure 5.2 shows the optimum binder content for HMA mixture contains 50% RAP and 75%, respectively. From Figure 5.1 and Figure 5.2, it shows that HMA with 50% RAP has an optimum binder content of 4.43% and 4.13% for HMA with 75% RAP.

Study in the past indicated that not all the binder from RAP were contributing to working binder content and/ or participating in the blending process with new binder, instead, some asphalt from the RAP may acted as “black rock”. Researcher [143] indicated that by identify the existing “black rock” in the RAP, up to 20% RAP can be used in

HMA without affecting the binder grade. However, for 40% or more RAP content in HMA, a bump in high temperature binder grade could be happened as well as low temperature binder grade. Researcher [143] indicated that the calculation of void in mineral aggregate (VMA) was relatively important as the amount of black rock changes is related to RAP mixture volumetric characteristics resulting from differing VMA. Hence in this study, the VMA was controlled to the value of 22 for all RAP mixture design during the RAP mixture production.

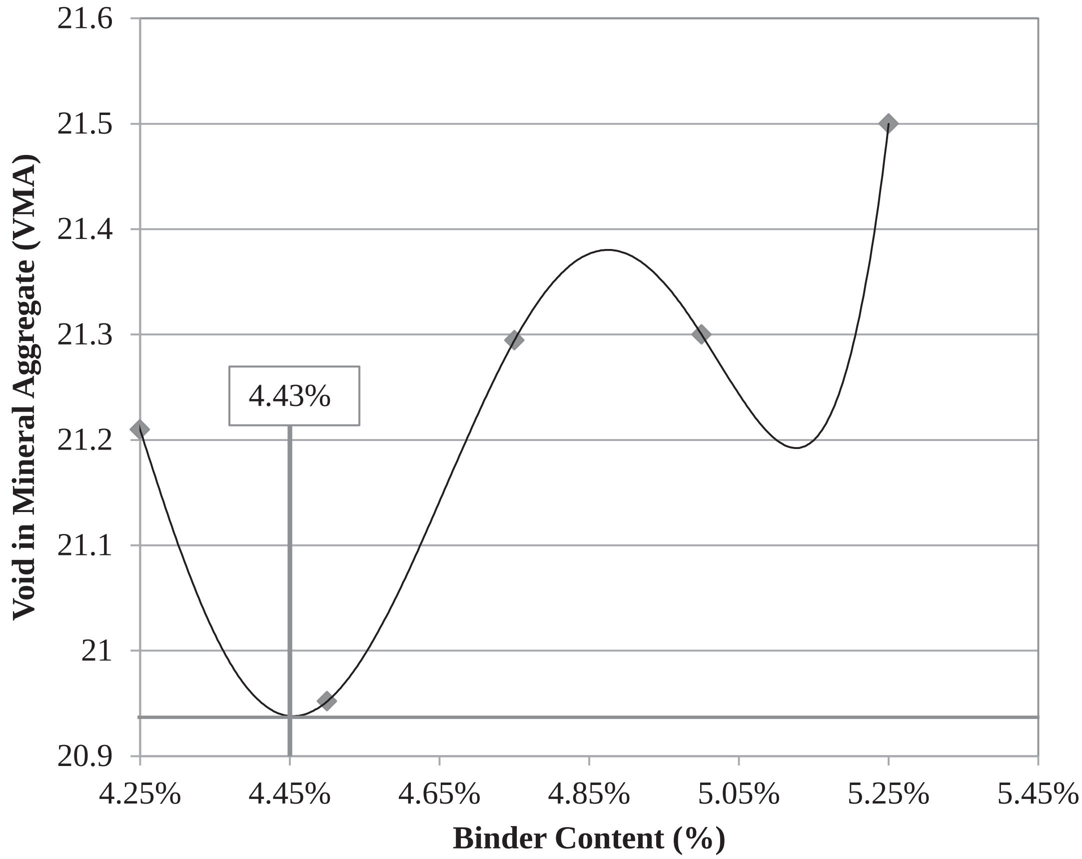


Figure 5.1 Void in Mineral Aggregate (VMA) versus Binder Content for HMA contains 50% RAP

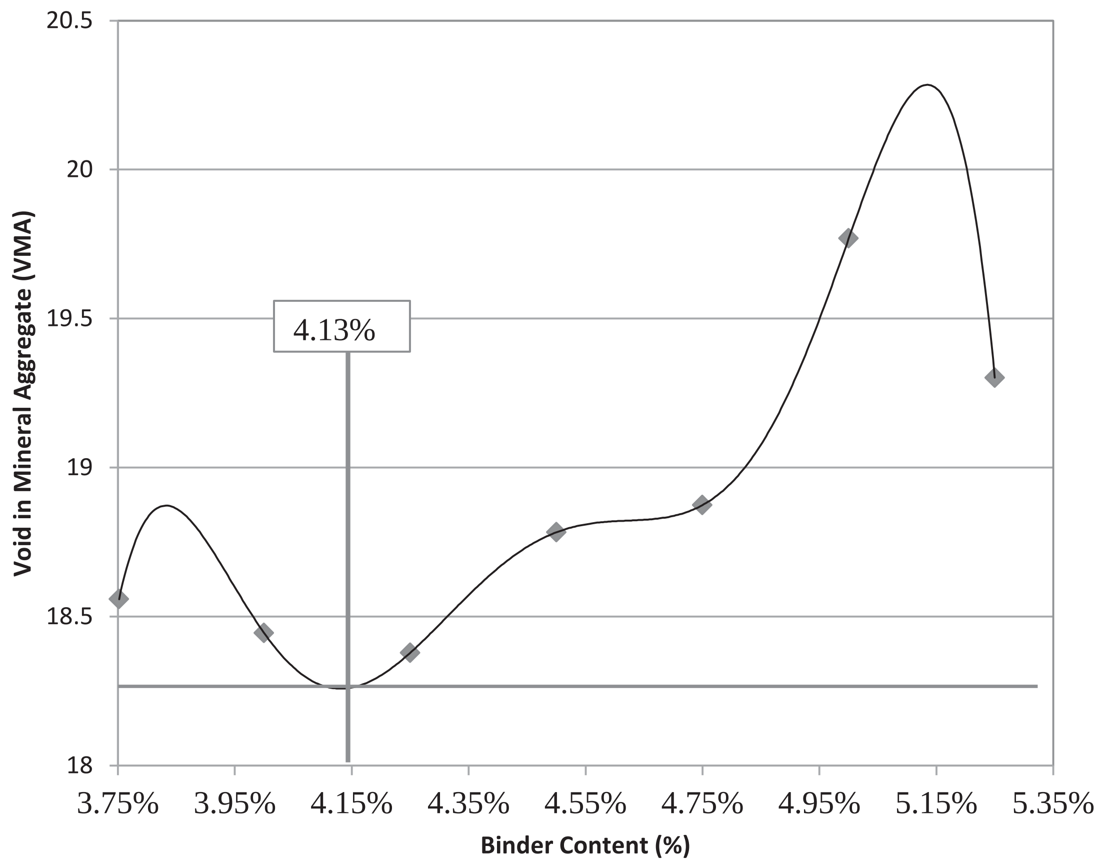


Figure 5.2 Void in Mineral Aggregate (VMA) versus Binder Content for HMA contains 75% RAP

5.3: Performance of High RAP Mixture

The performance of RAP mixture were accessed by dynamic modulus, flow number and tension strength ratio (TSR). Six types of RAP mixtures were used in this study, they are HMA with 50% RAP, WMA with 50% RAP using Advera®, WMA with 50% RAP using Sasobit®, HMA with 75% RAP, WMA with 75% RAP using Advera® and WMA with 75% RAP using Sasobit®. 0.25% Advera® based on mixture weight and 3.0% Sasobit® based on asphalt binder weight (new asphalt added to the mixture) were used for WMA mixture. A Superpave™ gyratory compaction was used to compact all the mixtures. For 50% RAP mixture (HMA and WMA), 74 gyrations were used; and for 75% RAP mixture, 13 gyrations were used to compact the sample to VMA value of 20. All samples were compacted in diameter of 100mm and cut to the desired size prior to the performance test.

5.3.1: Dynamic Modulus

HMA and WMA with high RAP content were evaluated using dynamic modulus testing. The master curve technique using the reference temperature of 4°C was used to analyze the |E*| of all RAP mixtures. The results of dynamic modulus testing for HMA contain 50% RAP ("50P RAP"), WMA contains 50% RAP made with Sasobit® ("50p Sasobit WMA RAP") and WMA contains 50% RAP using Advera® ("50p Advera WMA") are shown in Figure 5.3. In Figure 5.3, it is found that 50p Advera WMA has the lowest |E*| among all mixtures. The reason is mainly due to incomplete foaming of WMA made with Advera® in the mixing process. During the mixing process, part of the Advera® WMA additive evaporated as soon as contacted with superheated aggregate and before mixing with asphalt binder. Hence less foaming effect was created when mixed with binder and resulted in incomplete aggregate coating. For 50p Sasobit WMA RAP, it was found that the dynamic modulus is similar to control 50p RAP. The additional Sasobit® allow 50% RAP mixture to be produced at 33°C lower than traditional mixing temperature and does not affect the dynamic modulus.

For mixture contains 75% RAP, the dynamic modulus testing results are shown in Figure 5.4. In Figure 5.4, "75P RAP" is the control HMA with 75% RAP; "75p Advera WMA RAP" is the WMA contains 75% RAP using Advera®; and "75p Sasobit WMA RAP" is the WMA contains 75% RAP using Sasobit®. From Figure 5.4, it is found that the dynamic modulus for both WMA mixtures are similar with control 75p RAP. This indicated that mixture contains 75% RAP can be produced at a reduction of 33°C in mixing temperature using WMA technique. In general, the WMA technology shows the ability to reduce the mixing temperature of mixture containing high RAP content and did not affect the performance of asphalt mixture in terms of dynamic modulus.

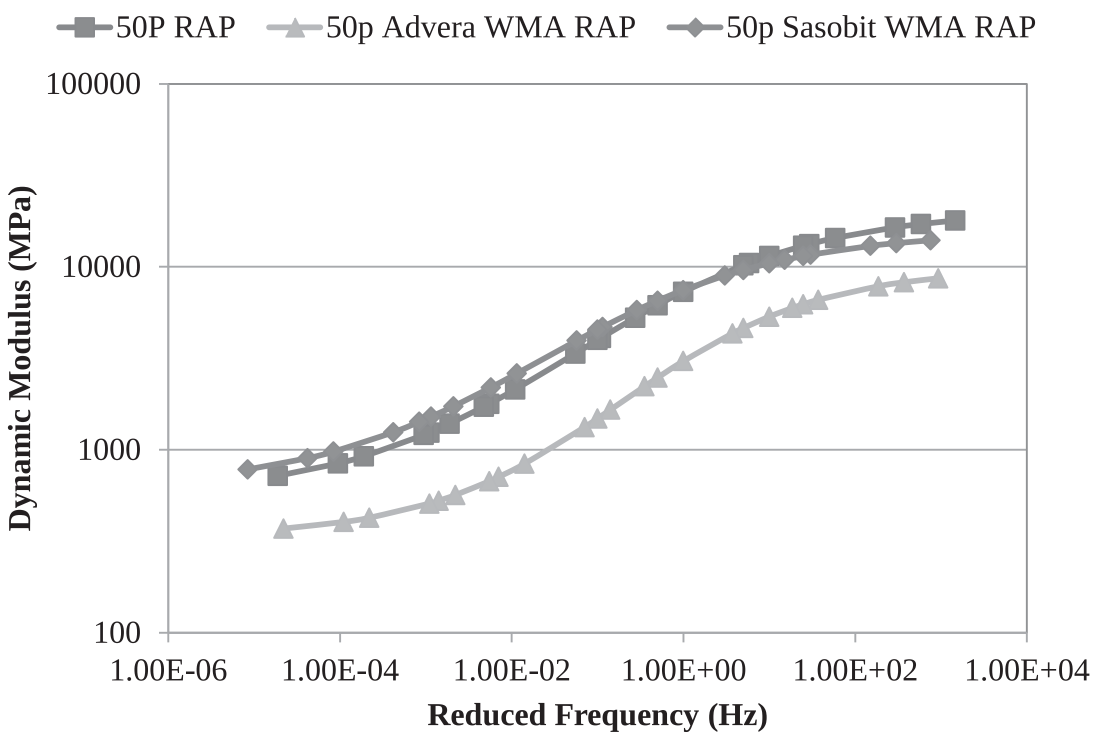


Figure 5.3 Comparison of Dynamic Modulus for HMA contains 75% RAP and WMA contains 75% made with Sasobit® and Advera®

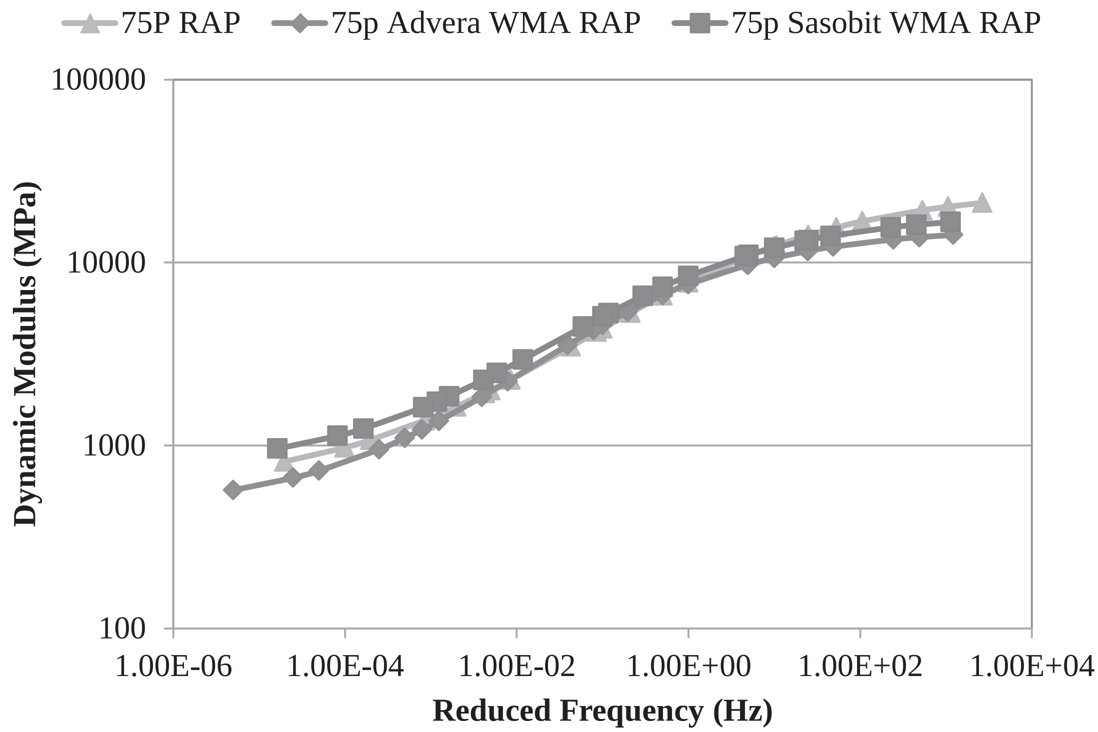


Figure 5.4 Comparison of Dynamic Modulus for HMA contains 75% RAP and WMA contains 75% made with Sasobit® and Advera®

5.3.2: Moisture Susceptibility using Tensile Strength Ratio (TSR)

The indirect tensile strength (ITS) and the tensile strength ratio (TSR) test were performed to evaluate the moisture susceptibility of HMA and WMA designed with 50% and 75% RAP. The test was conducted based on AASHTO T283 [63]. Figure 5.5 shows the ITS and TSR for HMA and WMA. From Figure 5.5, it is observed that 50p Advera WMA RAP has the lowest TSR and ITS. As mentioned in previous section, the main reason is due to incomplete coating during the mixing process. It is also found that HMA contains 50% and 75% RAP has a similar TSR and ITS value compare to control HMA. Generally, mixture with high RAP content has lower ITS and TSR due to highly aged of asphalt binder contained in RAP [146]. However, it was found that the additional RAP does not decrease the ITS value.

For RAP mixture made with Advera® and Sasobit®, it was found that the TSR value for WMA made with Sasobit® have TSR value higher than the control mixture. This indicated that the additional Sasobit® improve the moisture susceptibility of high RAP mixture. In addition, it is also observed that the ITS for high RAP mixture made with Sasobit® is slightly lower than the RAP mixture. However, the difference is not significant. It is also indicated that high RAP mixture made with Sasboit® has similar fatigue cracking potential compared to control high RAP mixture [64].

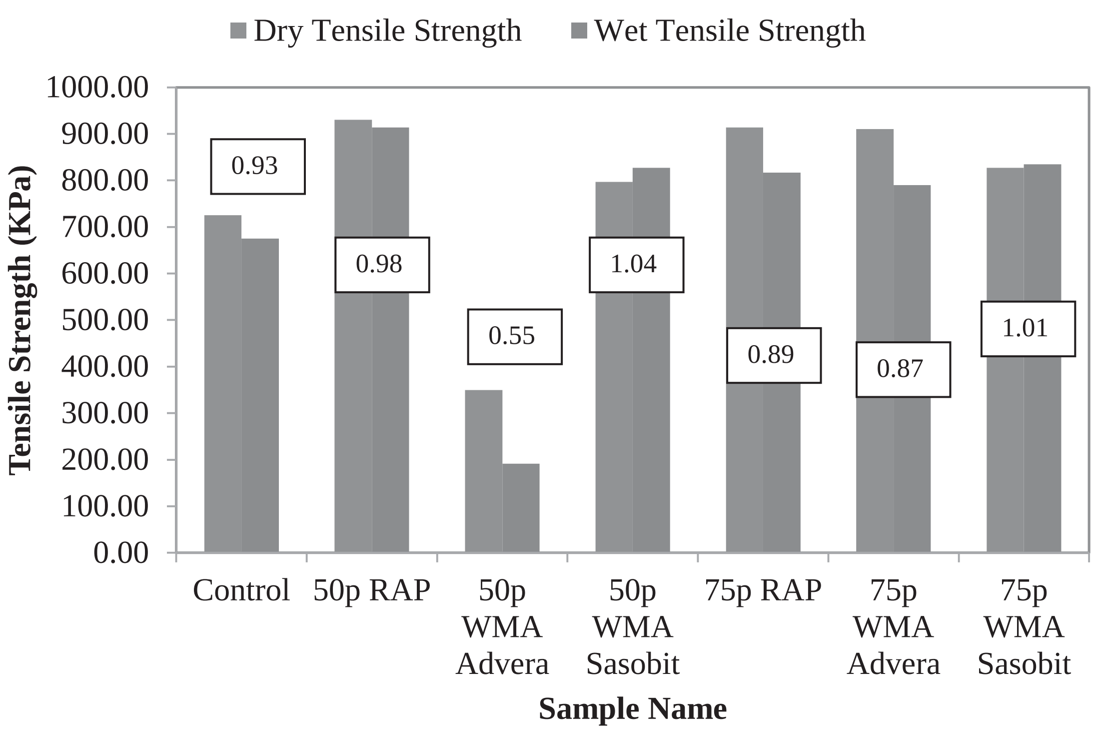


Figure 5.5 Tensile Strength of Control HMA, HMA contains 50% and 75% RAP, and WMA contains 50% and 75% RAP

5.3.3: Flow Number

Flow number testing was performed at 45°C based on NCHRP 9-29 [93]. HMA and WMA contains 50% and 75% RAP were compared and show in Figure 5.6 and Figure 5.7. In Figure 5.6, it shows that WMA contains 50% RAP made with Advera® has the lowest F_N. This result is in line with the testing result of dynamic modulus testing where the main reason was due to incomplete coating during the mixing process. Control HMA was also compared with HMA contains 50% RAP and 75% RAP in this study. It was found that both HMA contains RAP have higher F_N. This result was expected due to the aging of asphalt content. For WMA made with Sasobit®, the result is very interesting that the F_N value is found to be higher than the control 50% and 75% RAP mixture even it was produced at 33°C lower than the control mixture. This indicated that RAP mixture can be produced at 33°C lower using Sasobit® and will not affect the rutting potential of asphalt mixture.

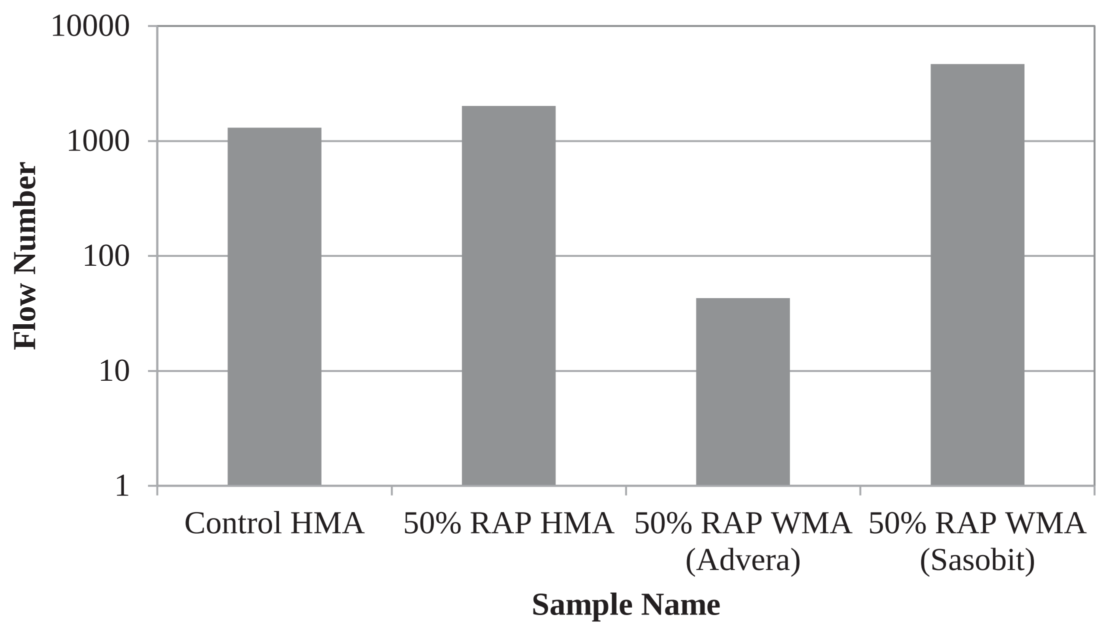


Figure 5.6 Comparison of Flow Number of HMA, and HMA and WMA contains 75% RAP

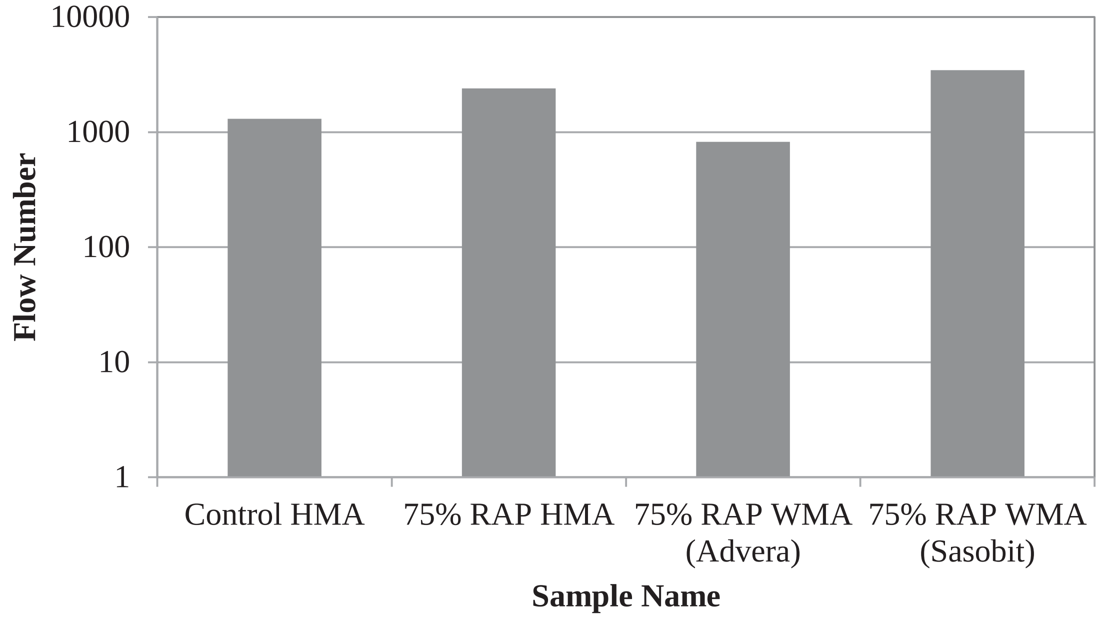


Figure 5.7 Comparison of Flow Number of HMA, and HMA and WMA contains 75% RAP

5.4: Summary Findings

This case study presented laboratory results of WMA made with high content recycle asphalt mixture (RAP) using two WMA technologies – Sasobit® and Advera®:

1. In this study, fractionating method was used to design high RAP mixture and all RAP was fractionated into eight different sizes. It was found that all RAP used in this study were mostly fine aggregates and were retained at 4.75mm and 2.36mm.
2. HMA and WMA with high RAP mixture were designed based on VMA and VMA for all mixtures was control at the value of 22. The main reason was to due to the "black rock" existed in the RAP mixture and hence controlling the VMA value in the high RAP mixture was relatively important.

3. Based on the |E*| and F_N testing, it was found that the WMA technology (Sasobit® and Advera®) able to reduce the production temperature of high RAP mixture (50% and 75% RAP) by as much as 33°C and did not affect the rutting potential of high RAP mixture. It was also found that WMA with 50% RAP made by Advera® has the highest rutting potential compared to the rest of the mixture. The main reason was found that during the mixing process, part of the Advera® WMA additive evaporated as soon as contacted with superheated aggregate and before mixing with asphalt binder. Hence less foaming effect was created when mixed with binder and resulted in incomplete aggregate coating.
4. Based on the ITS and TSR testing, it was found that the additional Sasobit® improve the moisture susceptibility of high RAP mixture. In addition, the finding also indicated the additional Sasobit® does not significantly affect the fatigue potential of high RAP mixture.

Chapter 6: WMA with Recycled Asphalt Shingles

6.1: Background and Introduction

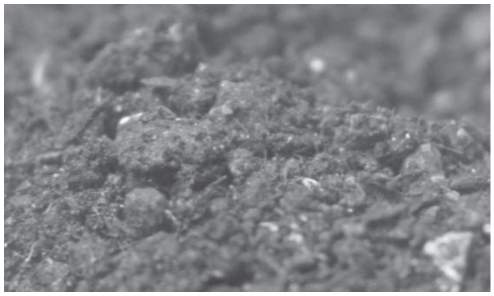
Every year, approximately eleven million tons of asphalt roofing shingles are disposed of in landfills. These shingles come from two sources, scraps and rejects from the manufacturing of new shingles and the shingles removed during reconstruction of existing roofs, also known as tear-offs [147]. One alternative to landfilling these shingles are to recycle them into hot mix asphalt (HMA) pavements.

There is strong evidence that asphalt roofing shingles can be recycled into HMA to reduce costs without causing detrimental effects on performance [121,148-150]. The composition of asphalt shingles is similar to that of HMA in that both contain asphalt binder, aggregates and mineral fines. In addition, shingles contain fibers that can serve as reinforcement of the HMA [151]. The binder used to make shingles is stiffer than the binder typically used in HMA; and the aggregates used to surface the shingles are of a higher quality than those used in HMA. Approximately 10 million tons of tear-off shingle waste and 1 million tons of manufacturer scrap are produced each year in the US. These shingles must be processed to reduce their size and also to remove contaminants from the tear-off shingles. All of the waste shingles could be disposed of if two percent recycled shingles were used in all HMA produced in the US, which is less than current applicable specifications allow. The cost savings of using recycled shingles in HMA has been estimated to range from $0.50 to $2.80 per ton depending on virgin material costs and whether tear-off or manufacturer scrap shingles are used [152]. At the same time, there are concerns about the presence of asbestos and polycyclic aromatic hydrocarbons in recycling shingles and studies have found that these concerns are minimal. The addition of shingles to HMA has been found to improve the rut resistance of the mixture and make the HMA easier to compact during construction [153]. Although large amounts of shingles have been found to increase the moisture susceptibility of the mix, small amounts have been found to have an insignificant impact on the mix. There have been several field trials of HMA pavements containing shingles performed by different states. The field trials have generally proved that the addition of shingles to HMA has been successful as the performance of these sections has been similar to that of the control sections [154,155].

6.1.1: Recycle asphalt shingles (RAS)

In this study, the recycled asphalt shingles (RAS) were obtained from Grand Rapid Asphalt, a paving firm in the State of Michigan. The RAS received were collected and processed at Crutchall Resource Recycling, a resource recycler located in Grand Rapids, Lansing, Kalamazoo, Warren, and Flint. Tear off shingles - shingles that has been removed from existing building - were used in this study. One of the differences between manufacturer scrap shingles and tear off shingles is the fact that tear offs usually contain other construction debris while manufacturer scrap shingles do not. This debris can be plastic, fiberglass or asbestos, chunks of wood, nails, or other debris that might be found on the roof. Thus, shingles that are tear offs need to be thoroughly processed to remove this debris.

In order to thoroughly investigate the composition of RAS received, the asphalt binder in the shingles was extracted and recovered using the procedure described in the ASTM D2172 standard specification, which is the procedure typically used in recovering binders from asphalt mixtures. Figure 6.1 (a) and (b) show the shingles before and after it was extracted.



(a)

(b)

Figure 6.1 Shingles (a) before and (b) after the process of extraction and recovery

From Figure 6.1, it is observed that the remaining shingles contain a fair amount of debris, mainly chunks of wood, fiberglass and pieces of plastic. The gradation testing of the shingles in this study was performed by Grand Rapids Asphalt. A total of four replicates gradation tests, each test contain approximately 1000g RAS sample, were conducted and these results are shown in Table 6.1.

Table 6.1 Gradation Test for Recycled Asphalt Shingles

Sieves size	**% Passed**				**AVERAGE**
	Sample 1	**Sample 2**	**Sample 3**	**Sample 4**	
3/4	100.0	100.0	100.0	100.0	100.0
1/2	98.5	99.3	98.4	99.1	98.8
3/8	93.9	96.9	95.0	98.6	96.1
4	81.4	89.9	88.2	95.5	88.8
8	77.6	87.0	83.4	93.1	85.3
16	65.5	71.7	70.7	74.7	70.7
30	47.8	50.2	48.0	51.1	49.3
50	37.8	41.7	39.9	43.3	40.7
100	31.7	35.3	34.0	35.4	34.1
200	25.4	29.1	27.8	27.7	27.5
Asphalt Content	30.26%	36.25%	39.21%	44.23%	37.49%

Based on the test results, it was observed that the sample sizes varied; however, a consistent result is observed among the four replicates. It is observed that a lot of dust (aggregate passing 200 sieve size) was in the RAS collected. For the asphalt binder content, it was found that RAS contains high binder content, which is around 37.49% based on the sample weight. These asphalt binders were highly aged and they were stiffer compared to the neat binder.

6.2: RAS Mixture Design

Similar to RAP, fractionation technique was used to design HMA with RAS content. In this study, only fine RAS was used to design the RAS mixture. The main reason is that it was found that RAS with the size larger than 2.36mm were very fragile and easily breaking apart and this could affecting the durability of asphalt mixture. Hence, in order to maintain the quality of HMA, only RAS smaller or same size as 0.3mm was used in this study. Table 6.2 and Table 6.3 shows the gradation design for HMA contains 5% and 10% RAS, respectively.

Table 6.2 Gradation Design for HMA contains 5% RAS

Size	Percent Passing	HMA (% Retained)	RAS (% Retained)
1/2" (12.5mm)	100	0	0
3/8" (9.5mm)	99.1	0.9	0
#4 (4.75mm)	75	24.1	0
#8 (2.36mm)	55.9	19.1	0
#16 (1.18mm)	41.3	14.6	0
#30 (0.6mm)	27.5	13.8	0
#50 (0.3mm)	14.5	10.035	2.965
#100 (0.015mm)	7.5	6.67	0.33
#200 (0.0075mm)	5.5	1.67	0.33
Pan		4.125	1.375
Sum		95.00	5.00

Table 6.3 Gradation Design for HMA contains 10% RAS

Size	Percent Passing	HMA (% Retained)	RAS (% Retained)
1/2" (12.5mm)	100	0	0
3/8" (9.5mm)	99.1	0.9	0
#4 (4.75mm)	75	24.1	0
#8 (2.36mm)	55.9	19.1	0
#16 (1.18mm)	41.3	14.6	0
#30 (0.6mm)	27.5	13.8	0
#50 (0.3mm)	14.5	7.07	5.93
#100 (0.015mm)	7.5	6.34	0.66
#200 (0.0075mm)	5.5	1.34	0.66
Pan		2.75	2.75
Sum		90.00	10.00

In this study, HMA contains 5% and 10% RAS was produced and served as control mixture. For WMA, 0.25% Advera® based on mixture weight and 3.0% Sasobit® based on new binder weight was used to produce the RAS WMA mixture. The mixing and compacting temperature used for RAS HMA was 165°C; and for WMA, the temperature used was 130°C for both RAS WMA made with Advera® and Sasobit®. A total of 100 gyrations was used for all 5% RAS mixture (HMA and WMA) and a total of 61 gyrations was used for mixture contains 10% RAS.

When designing the RAS mixture, there is uncertainty of the exact amount of asphalt from RAS will contribute to final blended binder. Similar to RAP, the concern of “black rock” existed in the RAS is one of the factors that will affect the optimum binder content used in RAS mixture. Hence in this study, the optimum binder content for RAS mixture were determined using Superpave™ mix design method [145]. Figure 6.2 and Figure 6.3 shows the optimum binder for mixture containing 5% and 10% RAS, respectively. It was found that the optimum binder content for 5% RAS mixture is 5.19% and 5.13% for mixture contains 10% RAS.

Since the existing of "black rock" would affect the amount of new binder used in final blended binder, the calculation of void in mineral is relatively important in this case [143]. Thus, the VMA was controlled to the value of 20 for all RAS mixture design during the production.

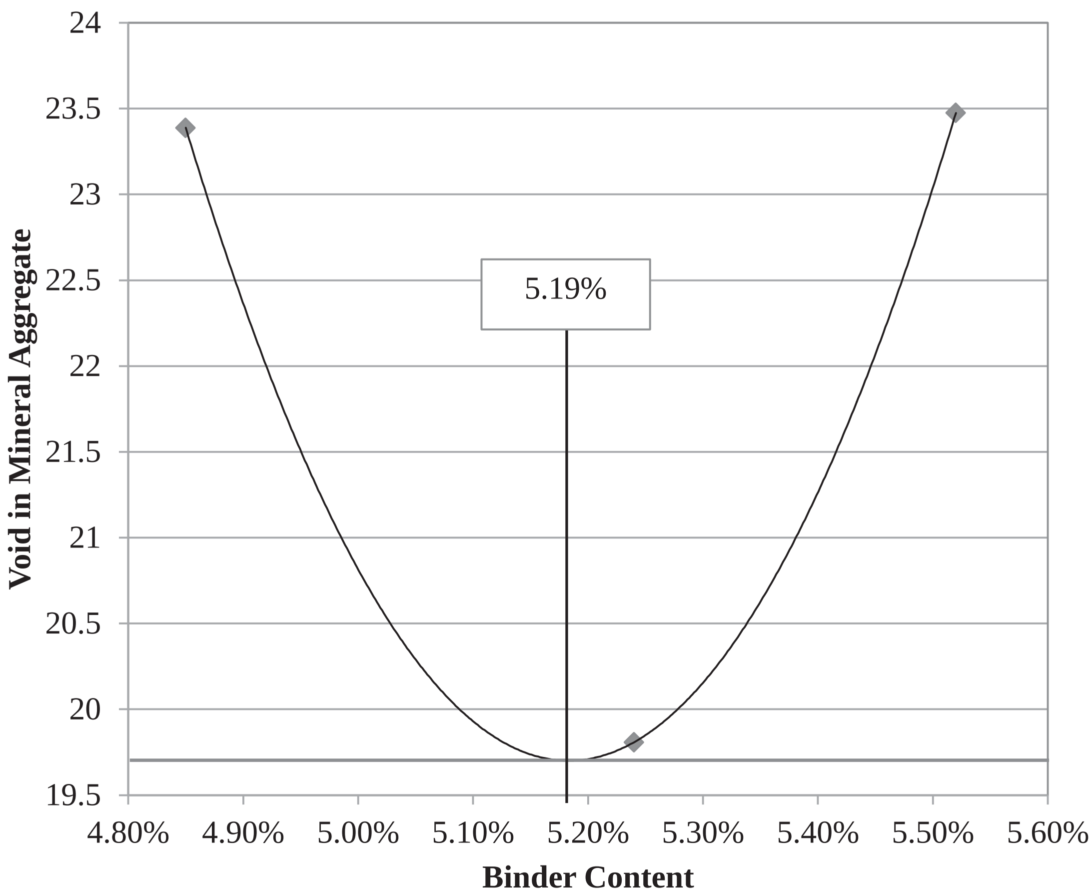


Figure 6.2 VMA of HMA contains 5% of RAS at Different Binder Contents

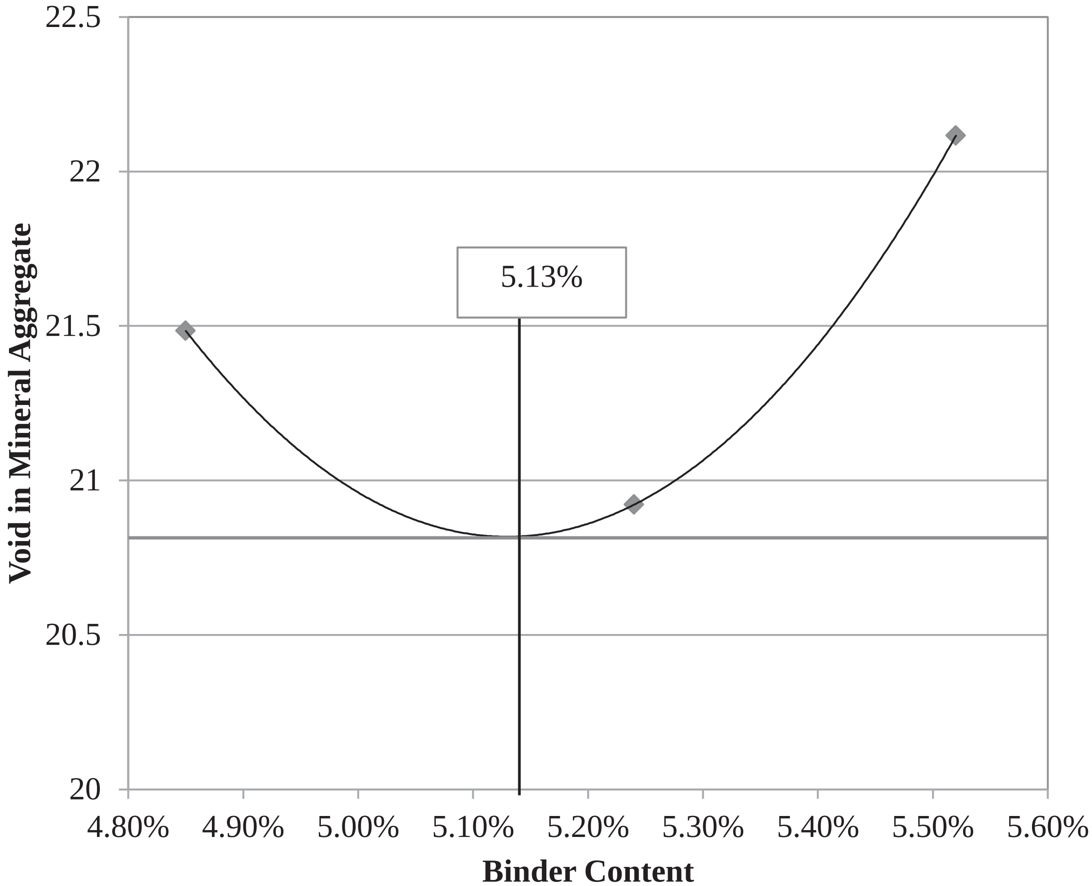


Figure 6.3 VMA of HMA contains 10% of RAS at Different Binder Contents

6.3: Performance of RAS Mixture

In this study, dynamic modulus (|E*|), flow number (F_N) and indirect tensile strength (ITS) testing was used to access the performance of RAS mixture. A total six type of RAS mixture were used in this study – HMA with 5% RAS, WMA with 5% RAP using Advera®, WMA with 5% RAS using Sasobit®, HMA with 10% RAS, WMA with 10% RAS using Advera® and WMA with 10% RAP using Sasobit®. For WMA mixture, 0.25% Advera® was added to all RAS WMA made with Advera® based on mixture weight, and 3.0% Sasobit® was added to all RAS WMA made with Sasobit® based on binder weight. A total of three replicates samples were used for each testing and the results were shown in the following sections.

6.3.1: Dynamic Modulus Testing

The dynamic modulus (|E*|) testing based on AASHTO TP62-03 was performed at temperature of -10°C, 4°C, 21.3°C and 39.2°C, and frequencies ranged from 0.1Hz to 25Hz. The sample used in this testing was cut into 100mm in diameter and 150mm in height and all tests were completed within two months after produced. The recoverable axial micro-strain in this test was controlled within 75 and 125 micro strains so that the material is in a visco-elastic range [54,55].

In order to have a better comparison between HMA and WMA RAS mixtures throughout all the temperatures and frequencies, a sigmoidal master curve was constructed with reference temperature of 4˚C. Figure 6.4 and Figure 6.5 show the results of |E*| for 5% and 10% RAP mixture made with and without WMA additives. Based on Figure 6.4, it was found that WMA contains 5% RAS and 0.25% Advera® (5p Advera RAS) has the slightly lower |E*| compared to control 5% RAS mixture ("5P RAS) and 5% RAS mixture made with Sasobit® ("5p Sasobit RAS"). It was also found that the additional Sasobit® does not significantly affect the RAS mixture and this indicated that WMA produce at a reduced temperature of 35°C using Sasobit® does not affect the rutting potential of RAS mixture.

From Figure 6.5, it was found that the |E*| for both control 10% RAS mixture ("10P RAS) and 10% WMA made with Advera® and Sasobit® ("10p Advera RAS" and "10p Sasobit RAS", respectively) are comparable high temperature. However, the |E*| for 10p Advera RAS has slightly lower |E*| at lower temperature. A higher value of |E*| at a high temperature (i.e. 39.2°C) indicated that the asphalt mixture has higher rutting resistant; and a lower |E*| value at low temperature (i.e -5°C) indicated that the asphalt mixture has lower fatigue cracking potential [55,156]. In this study, the 10p Advera RAS mixtures favored both fatigue cracking and rutting resistant of asphalt mixture compared to the control mixtures. The main reason is that the higher fatigue cracking resistant of RAS mixture was due to the fiberglass in RAS mixture [157]; and the higher rutting resistant was due to the highly aged of the asphalt shingles.

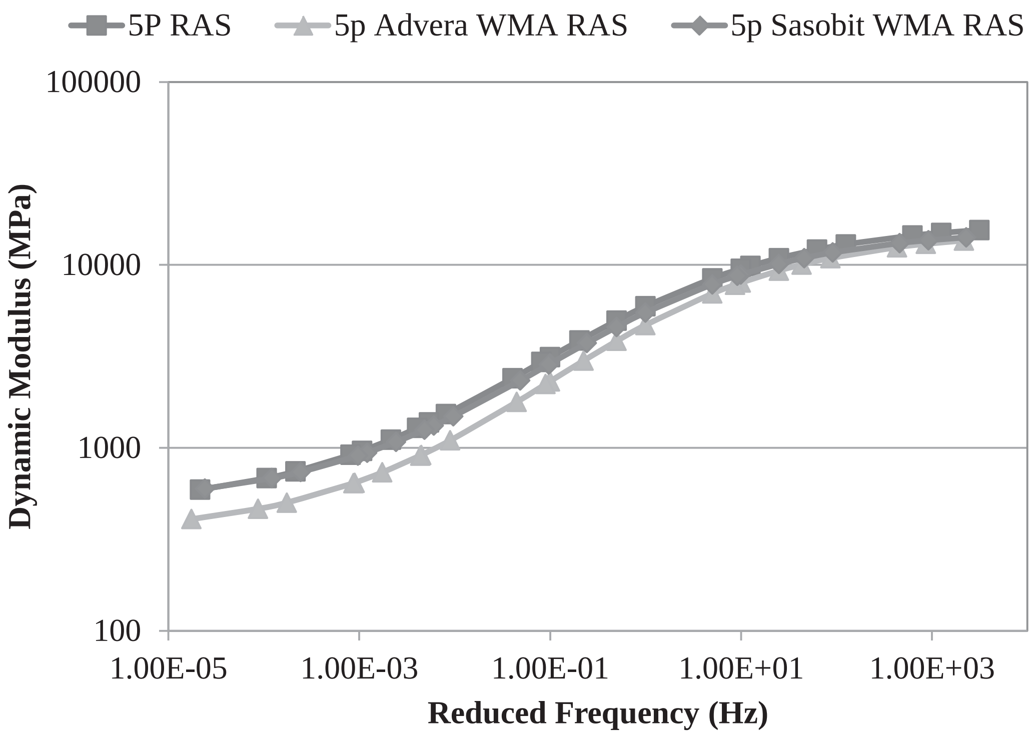


Figure 6.4 Comparison of Dynamic Modulus for HMA contains 5% RAP and WMA contains 5% made with Sasobit® and Advera®

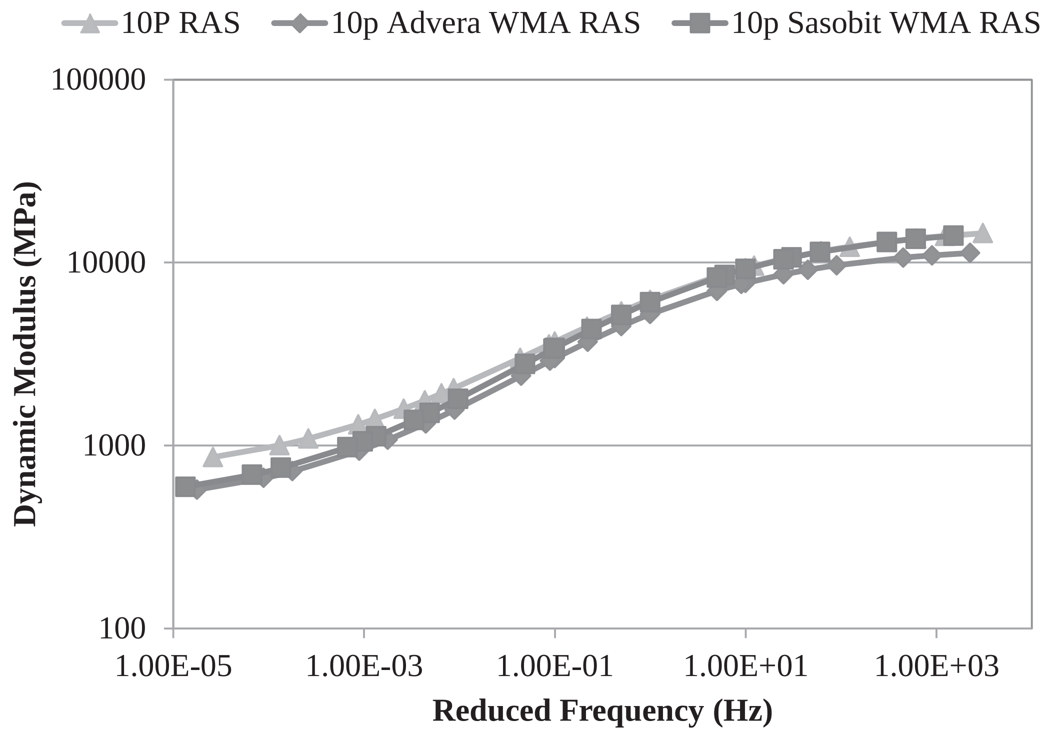


Figure 6.5 Comparison of Dynamic Modulus for HMA contains 10% RAP and WMA contains 10% made with Sasobit® and Advera®

6.3.2: Flow Number Testing

Flow number testing was performed at 45°C [158] based on NCHRP 9-29 [93]. HMA and WMA contains 5% and 10% RAS were compared and show in Figure 6.6 and Figure 6.7. From Figure 6.6, it was found that the additional 3.0% Sasobit® (based on binder weight) does not affect the F_N of mixture containing 5% RAP. Study in the past indicated that F_N could be used to compare the quality of the mixture s in terms of rutting performance [69,78], hence this showed that 5% RAS mixture produced at a lower temperature (35°C lower) using Sasobit® has similar rutting performance compare to control 5% RAS. In addition, it was found that 5% RAS mixture made with Advera® and Sasobit® has similar or higher F_N compare to control HMA without RAS.

Figure 6.6 shows the comparison of HMA with and without RAS, and WMA with 10% RAS made with Advera® and Sasobit®. It was found that both 10% RAS WMA made with Advera ® and Sasobit® are lower have lower F_N compare to control 10% RAS. However, when compared to HMA without RAS, the results show that the F_N values for all 10% RAS mixture are higher. This is mainly due to the highly aged binder in RAS and resulted in stiffer binder. In addition, the results also indicated that the additional 10% RAS increase the rutting resistant of asphalt mixture; and 10% RAS mixture produced using Advera® and Sasobit® at a reduced temperature (35°C lower) has a slightly lower rutting resistant compared to unmodified 10% RAS mixture.

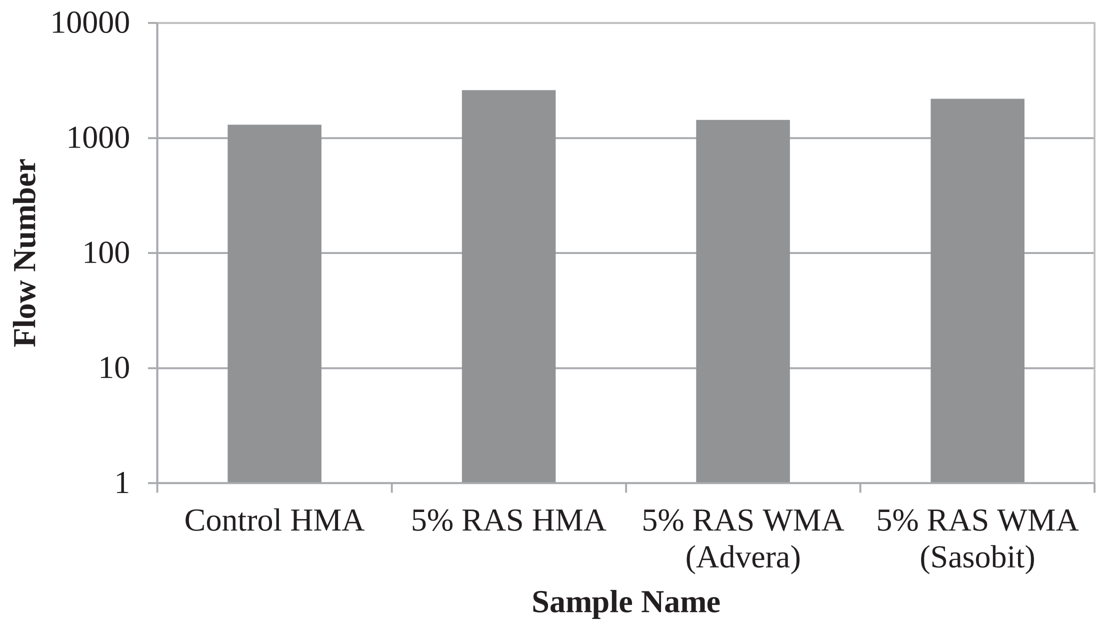


Figure 6.6 Comparison of Flow Number of HMA, and HMA and WMA contains 5% RAS

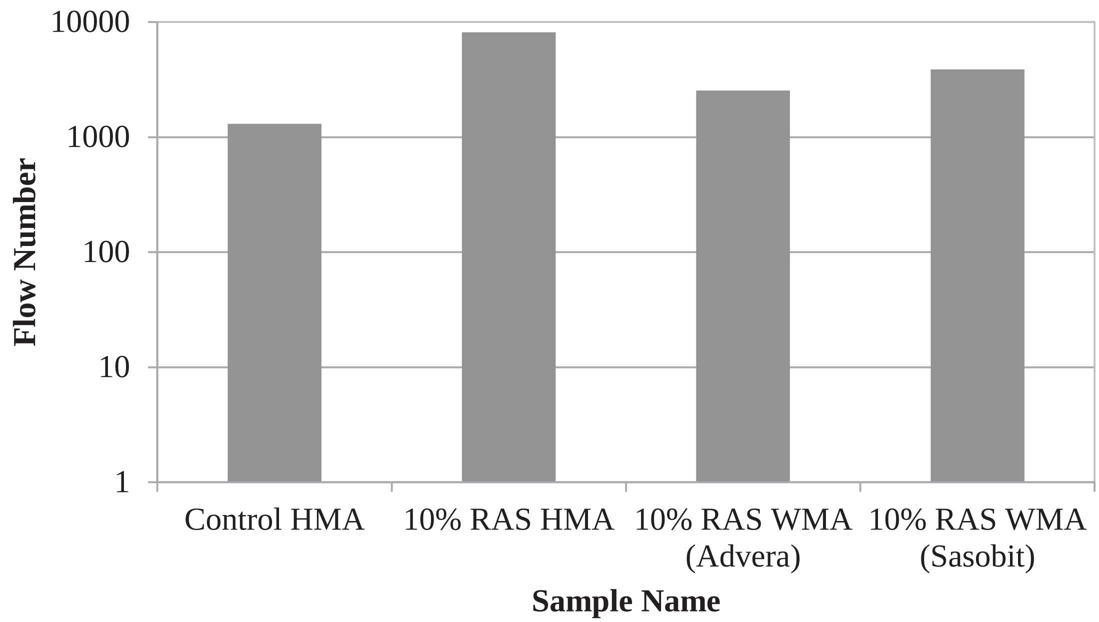


Figure 6.7 Comparison of Flow Number of HMA, and HMA and WMA contains 10% RAS

6.3.3: Moisture Susceptibility using Tensile Strength Ratio (TSR) Testing

In this section, the indirect tensile strength (ITS) and tensile strength ratio (TSR) tests were conducted based on AASHTO T283 [63]. The results of ITS and TSR testing were shown in Figure 6.8. For mixture contains 5% RAS, the results show that the value of TSR for WMA (made with both Advera® and Sasobit®) are higher than control 5% RAS mixture. However, it was found that the ITS value are lower and this is mainly due to lower adhesion value resulted from less binder absorption into the aggregate during the lower temperature mixing process. Similar results were also observed in mixture contains 10% RAS where the RAS made with Adera® and Sasobit® have lower ITS value. These indicate that the RAS mixtures produced using Advera® and Sasobit® have slightly higher fatigue potential [64]. The results show that the additional Advera® and Sasobit® do not affect the moisture susceptibility of mixture containing 5% and 10% RAS.

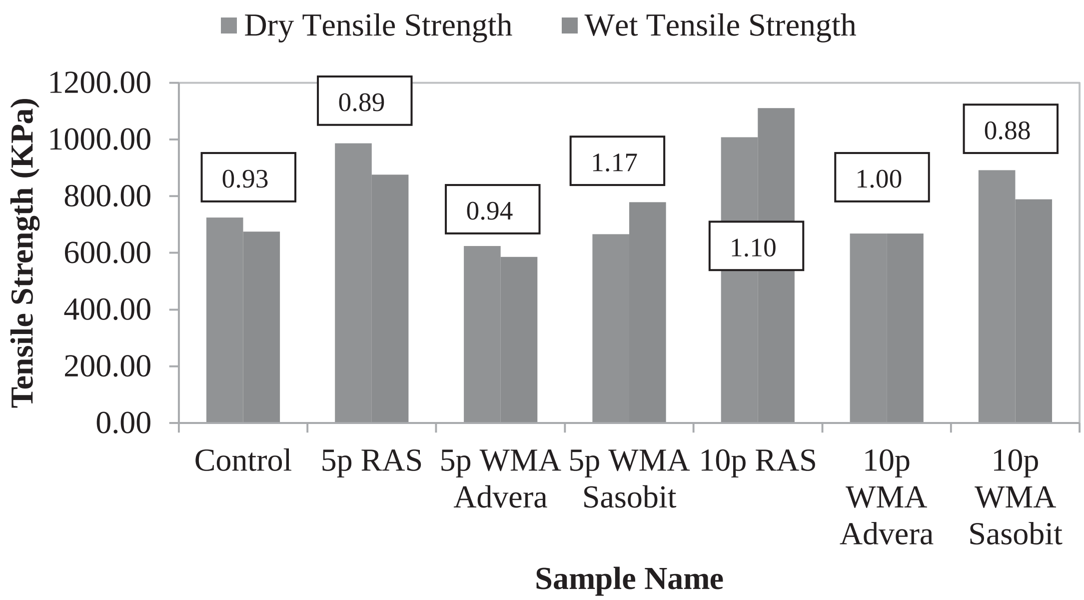


Figure 6.8 Tensile Strength of Control HMA, HMA contains 5% and 10% RAS, and WMA contains 5% and 10% RAS

6.4: Summary Findings

This case study presented laboratory results of WMA made with recycle asphalt shingles (RAS) using two WMA technologies – Sasobit® and Advera®:

1. In this study, fractionating method was used to design high RAS mixture. Only fine RAS was used in designing the RAS mixture due to the reason that the RAS with size larger than 2.36mm were very fragile.

2. HMA and WMA with high RAS mixture were designed based on VMA. The value of VMA was control to be 20 for all RAS mixture design and the main reason is because of the existing “black rock” in the RAS.
3. Based on the |E*| testing, it was found that the additional Sasobit® does not significantly affect the RAS mixture and this indicated that WMA produce at a reduced temperature of 35°C using Sasobit® does not affect the rutting potential of RAS mixture. For mixture contains 10% RAS, it was found that the additional Advera® improve the fatigue cracking and does not affect the rutting potential of the mixture containing 10% RAS. The main reason is that the higher fatigue cracking resistant of RAS mixture was due to the fiberglass in RAS mixture and the higher rutting resistant was due to the highly aged of the asphalt shingles.
4. From F_N testing, , the results show that the F_N values for all 10% RAS mixture are higher due to the highly aged asphalt binder in RAS. For mixture contains 5% RAS, it was found that the additional Advera® and Sasobit® has similar or higher F_N compare to control HMA without RAS. For mixture contains 10%, the results show that 10% RAS mixture produced using Advera® and Sasobit® at a reduced temperature (35°C lower) has a slightly lower rutting resistant compared to unmodified 10% RAS mixture.
5. Based on the ITS and TSR testing, the results show that the RAS mixtures produced using Advera® an Sasobit® have slightly higher fatigue potential. However, the TSR results show that the additional Advera® and Sasobit® do not affect the moisture susceptibility of mixture containing 5% and 10% RAS.

Chapter 7: Moisture Sensitivity of WMA

Moisture damage in the asphalt mixture is the results of loss of adhesion between asphalt binder and aggregate [159-161]. It consists of physical, chemical and mechanical process, and involve two mechanism – moisture transport and system response [162]. The moisture transport is the moisture in either liquid or gas form that penetrated into the asphalt pavement and contact with the asphalt binder and binder-aggregate-system. The system responses include the adhesion and cohesive failures within asphalt and aggregate, and freezing [162,163].

Moisture damage occurred in asphalt pavement can resulted in rutting [164] and fatigue cracking [160]. WMA has been producing at a lower temperature and the recent concern of WMA is the incomplete drying of aggregate during the mixing process. Incomplete drying of aggregate during WMA production may increase the potential of moisture damage. Moisture damage

The current major problem of WMA is the moisture damage that is caused by the water trapped inside the aggregate. Figure 7.1 illustrated the moisture trapped inside aggregate due to incomplete drying. Moisture damage occurs when aggregates are not completely dry during the low temperature mixing process. The result from moisture damage could affect its long-term performance due to decrease of strength and durability in the asphalt mixture, and thus resulted in increased maintenance and rehabilitation costs to highway agencies. The main objective of this chapter is to evaluate the moisture sensitivity of WMA through laboratory setup.

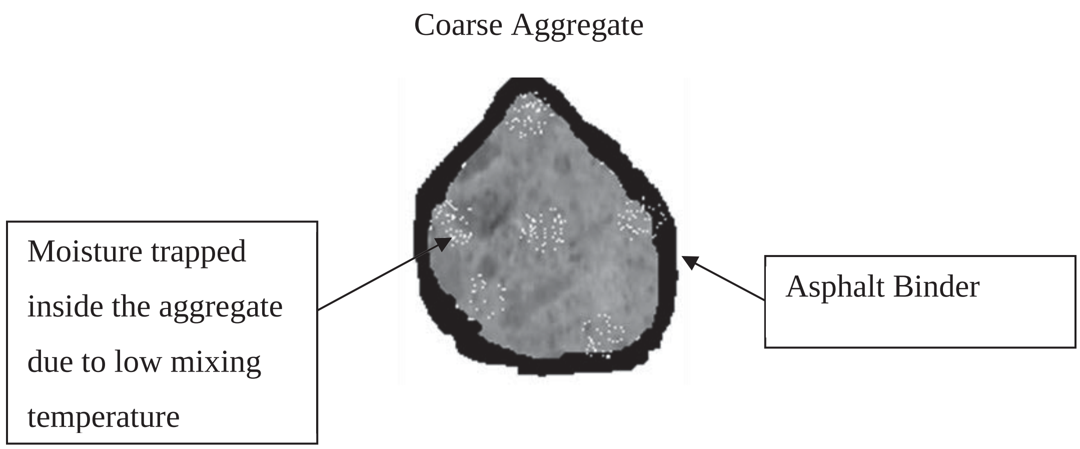


Figure 7.1 Moisture Trapped inside Aggregate due to Incomplete Drying

7.1: Incomplete Aggregate Drying during the Construction of WMA

7.1.1: Moisture Content in Aggregate and RAP Stockpile

Incomplete drying of aggregate during WMA production may increase the potential of moisture damage. The FHWA International Scanning Tour on WMA indicated that this concern was not significant in European countries because the aggregates used have low water absorptions [5]. According to contractors' experiences, it was reported that a moisture content drop from 10 to 6 percent, in fine aggregates would result in 9.2 percent of fuel saving [165]; and another report shows that the moisture content reduction from 6 to 4 percent would bring 25% (about 0.48 gallon/ ton) of fuel saving [27]. Additionally, the reduction of fuel usage would reduce plant emissions. The RAP stockpile may have similar issues as the aggregate stockpile.

Based on the literature reviews, there are two practical methods that were widely used to reduce moisture damage: pave the area under the stockpile, or cover the aggregate storage areas [27]. The first option is paving under the stockpile and it prevents the "bathtub" created underneath the stockpile that would trap water. The second option is covering the aggregate storage areas. It keeps aggregates entering the plant dry and also reduces the wind-blow dust.

7.1.2: Complete Fuel Combustion of Burner

Some contractors reported that there were some operational challenges for WMA production because a plant system that is not properly tuned will exacerbate deficiencies when operating at lower temperature [166]. The efficiency of combustion is affected by 1) time where the fuel has to combust or resides in the flame; 2) turbulence of the fuel, air and the heat source that provides complete combustion; and 3) the differences of temperature between the source of the heat and the material being heated[166]. Prowell and Hurley [27] indicated that the damage due to uncombusted fuel is possibly greater for WMA compared to HMA due to improper burner adjustment. Asphalt mixture that contaminated by uncombusted fuel will have higher rutting potential and higher levels of carbon monoxide (CO) during the production. Currently, at least one uncombusted fuel was observed from all the WMA demonstrations. It was suggested to have an experienced burner technician available when inspecting and adjusting the burner to produce WMA [27].

7.1.3: Balance between Aggregate Drying and Maintaining Adequate Bag house Temperature

Balance between adequately drying the aggregate and maintaining a proper bag house temperature to prevent condensation is probably one of the biggest challenges in WMA production. Using lower temperature might cause incomplete aggregate drying, especially for the aggregate internal moisture at the aggregate bed (aggregate at the bottom of the drum). A best practice guideline to minimize the condensation in the bag house and preventing damage from corrosion was provided by Young [167]. This guide is of importance when large quantity of WMA was produced. Some general bag house operation best practices when producing WMA was provided by Prowell and Hurley [27] as well. In general, they indicated that the condensation could be removed by preheating the bag house for 15–20 minutes; pressure drops across the bags that have to be monitored to prevent caking of the bags; and the fines return line has to be inspected regularly to ensure that there is no build-up due to moisture. In order to balance between the aggregate drying and maintaining the bag house temperature, it was suggested to reduce drum slope, remove flights (to increase heat penetration), increase the combustion air, and add RAP to WMA [27].

7.2: Scope and Experiment Design

Several challenges were found to mimic the occurrence of moisture damage in the field and to ensure the moisture trapped inside the aggregate will not evaporate during the evaluation. The critical part in this evaluation is the determination of the appropriate moisture that should be added to the WMA due to different absorption values of aggregate. In this study, moisture was added to the HMA and WMA based on coarse aggregate surface saturated dry (SSD) condition. Figure 7.2 shows the SSD condition of coarse aggregate used in this study. Three WMA additives were used in this study – Advera®, Sasobit® and Cecabase® RT. For WMA, Advera® was added to the mixture at the rate of 0.25% based on mixture weight; 3.0% Sasobit® was added based on the asphalt binder weight; and 0.35% Cecabase® RT was added based on the asphalt binder weight. The mixing and compacting temperatures used for the control HMA are 163°C and 153°C, respectively; and for WMA, 130°C was used for both compacting and mixing temperatures.

In this study, hydrated lime was used as an anti-stripping agent to evaluate if it can improve the moisture susceptibility of the HMA and WMA where their coarse aggregates were conditioned with SSD. In the past, researcher found that hydrated lime would act as mineral filler and it could stiffen the asphalt binder and HMA, and it could alter the plastic properties of clay fines to improve moisture stability and durability[168-170]. In this study, the hydrated lime was added to the HMA and WMA at the rate of 1% based on the mixture weight[32,168]. All samples were cut into 100mm diameter and 63.5mm height prior to the ITS and TSR testing.

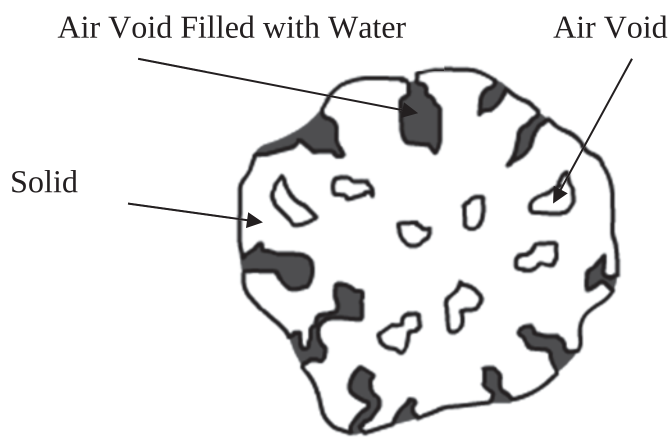


Figure 7.2 Coarse Aggregate in SSD Condition

7.3: Moisture Susceptibility of WMA

Indirect tensile strength (ITS) and tensile strength ratio (TSR) tests were conducted to evaluate the moisture susceptibility of the HMA and WMA contains moist aggregate. The testing was conducted based on AASHTO T283 [63] and the results were shown in Figure 7.3. From Figure 7.3, it is observed that the TSR for all HMA and WMA were relatively low. The lowest value among all the mixtures was found to be 0.30 where the mixture was made by Advera® WMA. This result was expected because Advera® is the hydrophilic material where it will gradually release water and turns into steam during the mixing process, and thus increase the moisture susceptibility. The results from Figure 7.3

indicated that all mixtures contain moist aggregate do not meet the minimum requirement of 0.80 by AASHTO T283 [63]. This indicated incomplete drying of aggregate during WMA production would result in severe moisture damage. However, when hydrated lime was introduced to the mixture, the TSR value increase dramatically and all mixtures modified by the hydrated lime passed the minimum requirement of 0.80. This indicated that by adding the hydrated lime, the moisture susceptibility of the WMA can be improved.

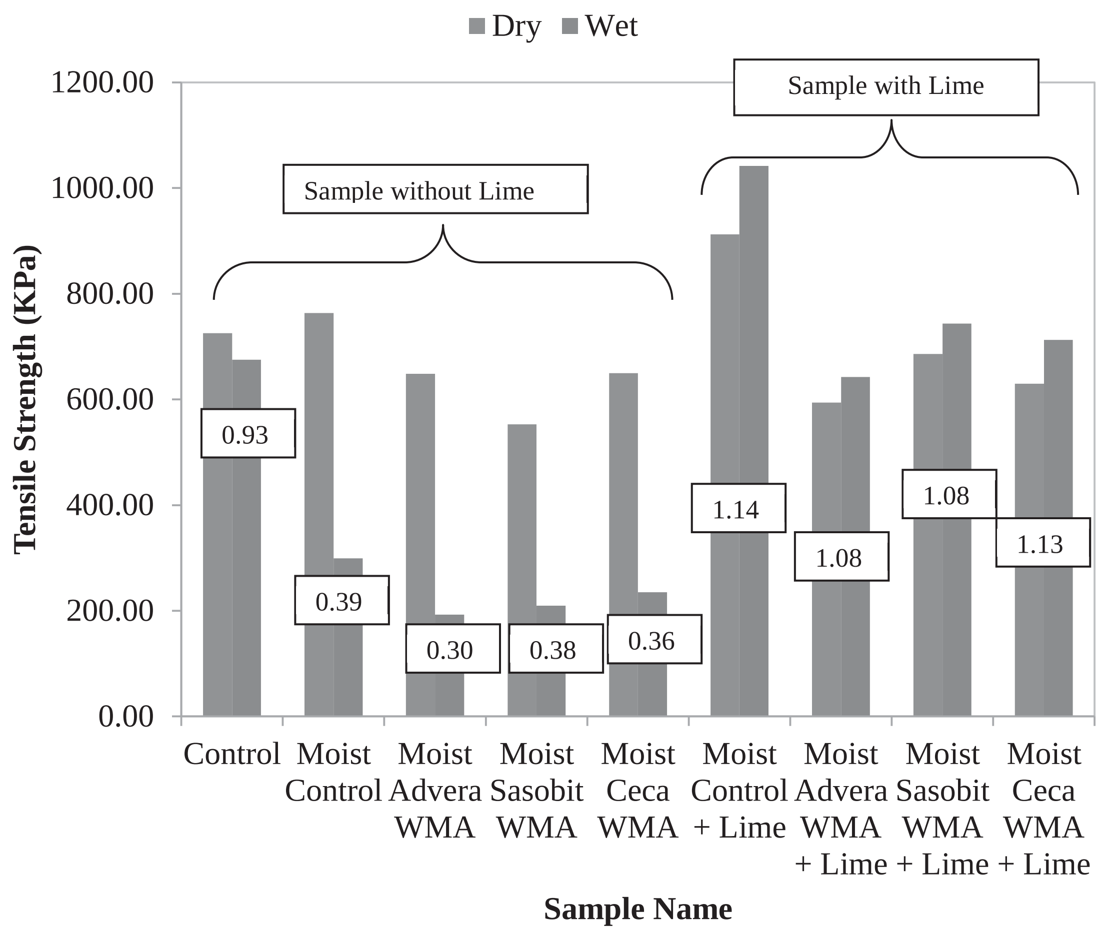


Figure 7.3 Tensile Strength of Control HMA, HMA and WMA with and without Lime Conditioned with contains SSD Moist Aggregate

Chapter 8: Summary, Conclusions and Recommendations

8.1: Summary and Conclusions

The results of past studies on WMA indicated significant promise in economic savings and reduction in emissions. Although numerous studies have been conducted on WMA, only limited laboratory experiments are available and most of the current WMA laboratory test results are inconsistent and not compatible with field performance. The main objectives of this study are:

1. To develop a mix design framework for WMA by evaluating its mechanical properties
2. To evaluate performance of WMA containing high percentage of recycled asphalt material
3. To evaluate the moisture sensitivity in WMA

In this study, three main WMA technologies – foamed WMA, WMA using organic Additive and WMA using chemical package were discussed and evaluated. Aspha-min®, Advera® WMA, foamed WMA using free water system, Sasobit® and Cecabase® RT were used as the WMA technology in this study. Rheological properties, aging factor, and performance tests including complex/ dynamic modulus (|E*|), tensile strength ratio (TSR), four point beam fatigue, flow number (F_N) and APA rutting were used to access WMA rutting, fatigue and moisture susceptibility. Based on the testing results, most of the WMA has higher fatigue life and TSR which indicated WMA has better fatigue cracking and moisture damage resistant; however, the rutting potential of most of the WMA tested were higher than the control HMA. A summary of the findings from all testing result was summarized in Table 4.1.

In this study, a recommended WMA mix design framework was developed as well. The WMA design framework was presented in this study to allow contractors and state agencies to successfully design WMA. In addition, five main sections include WMA technology selection, asphalt binder, WMA mixing and compacting, aggregate gradation, WMA technology handling and critical WMA performance testing were discuss and recommendation were provided based on the literature reviews and testing results from the laboratory evaluation.

Mixtures contain high RAP content and RAS were studied as well. Fractionating method was used to design both high RAP content and RAS to allow a more uniformity of recycled materials to be incorporated in asphalt mixture. Both RAP and RAS mixture were designed based on VMA due to the existing of “black rock” in the RAP and RAS that not all the binder from RAP and RAS would contributed to the final blend of binder in the asphalt mixture. The results from $|E^*|$, F_N and TSR show that WMA technology allow the mixture containing high RAP content and RAS to be produced at lower temperature (up to 35°C lower) without significantly affect the performance of asphalt mixture in terms of rutting, fatigue and moisture susceptibility. However, it is noted that all WMA mixture should be examined in order to ensure all aggregate are fully coated.

This study also integrates three innovations in the pavement engineering field: permeable pavements (porous pavements), Warm Mix Asphalt (WMA), and recycled materials. A control porous asphalt mixture, porous asphalt mixture with Advera®, porous asphalt contains 15% RAP and porous WMA mixture contains 15% RAP were evaluated. Based on the test results, it was found that the energy used during construction by WMA with 0.25% Advera® WMA was lower compared to the control mixture (HMA). It was also found that the mixtures containing RAP have a higher CEI, which was expected. For the $|E^*|$ tests, it was found that WMA made with 0.25% Advera® WMA had significantly lower results than the control mixture (HMA). In addition, it is observed that the |E*| is higher for porous asphalt mixture containing RAP than the control mixture (HMA). When Advera® was added to the porous asphalt mixture containing RAP, only a slight decrease in E* was observed.

Lastly, the moisture susceptibility of WMA that contains moist aggregate was investigated in this study. The current major problem of WMA is the moisture damage that is caused by the water trapped inside the aggregate. The challenge of this evaluation is the determination of the appropriate moisture that should be added to the WMA due to different absorption values of aggregate. In this study, moisture was added to the HMA and WMA based on coarse aggregate surface saturated dry (SSD) condition. Hydrated lime was added to the asphalt mixture at the rate of 1% based on mixture to use as anti-stripping agent. Based on the ITS testing result, it was found that all mixtures contain moist aggregate do not meet the minimum requirement of 0.80 by AASHTO T283 [63] and this indicated that incomplete drying of aggregate during WMA production would result in severe moisture damage. By introducing the hydrated lime in the WMA, all mixtures modified by the hydrated lime passed the minimum requirement of 0.80. This indicated that by adding the hydrated lime, the moisture susceptibility of the WMA can be improved.

8.2: Recommendations for Future Research

Numerous studies were completed to evaluate WMA. This study is primary focus on laboratory testing of WMA and hence many construction, environmental and cost related issues are not very well investigated. The following summarize the knowledge gaps found in this study and were recommended for future/ ongoing research:

1. The performance of WMA in the laboratory setup compared to the field performance. Numerous of WMA field trial have been conducted to date, however, the laboratory procedure for introducing WMA technologies was not properly simulate the performance in the field.

2. The aging of the WMA in the asphalt plant. It is important to develop a standard procedure to mimic the WMA aging in the asphalt plant and at the time of placement.
3. The rutting potential of WMA in this study and studies conducted by other researchers was found be higher. However, to date, WMA field performance conducted around the United States were positive. Hence, there is a disconnection in laboratory setup which needs to be investigated.
4. Energy and emission of WMA need to be quantified as this would improve the life-cycle inventories of WMA compared with HMA.

References

1. AASHTO:R35. Standard Practice for Superpave Volumetric Mix Design for Hot-Mix Asphalt. American Association of State Highway and Transportation Officials 2011.

2. AASHTO:T195-67. Standard Method of Test for Determining Degree of Particle Coating of Bituminous-Aggregate Mixtures. American Association of State Highway and Transportation Officials 2005.

3. Harrison T, Christodulaki L. Innovative processes in asphalt production and application - strengthening asphalt's position in helping build a better world. First International Conference of Asphalt Pavement. Sydney2000.

4. McKeon B. Aspha-min in warm asphalt mixes. 51st Annual Convention of the National Asphalt Pavement Association. Lanham, Maryland2006.

5. D'Angelo J, Harm E, John Bartoszek, Baumgardner G, Matthew Corrigan, Cowsert J, Harman T, Mostafa Jamshidi, Jones W, Newcomb D and others. Warm Mix Asphalt: European Practice. Office of International Programs, Office of Policy, Federal Highway Administration, U.S. Department of Transportation, American Association of State Highway and Transportation Officials, National Cooperative Highway Research Program; 2008.

6. Button JW, Estakhri C, Wimsatt A. A Synthesis of Warm-Mix Asphalt. Austin, Texas: Texas Transportation Institute; 2007. Report nr Report 0-5597-1.

7. Kristjansdottir O. Warm Mix Asphalt for Cold Weather Paving. Seattle: University of Washington; 2006.

8. Little DN, Button JW, Epps JA. Structural Properties of Laboratory Mixtures Containing Foamed Asphalt and Marginal Aggregates. Transportation Research Record 1983;911.

9. Zettler R. Road manager: Warm mix stands up to its trials. Better Roads 2006;76(2):16-21.

10. Goh SW, You Z. Warm Mix Asphalt using Sasobit®: A Brief Field and Laboratory Experience. Mid-Continent Transportation Research Forum 2008. Wisconsin, Madison2008.

11. Barthel W, Marchand J-P, Devivere MV. Warm Asphalt Mixes By Adding A Synthetic Zeolite. 2004.

12. Hurley GC, Prowell B. Evaluation of Sasobit For Use in Warm Mix Asphalt. Auburn: National Center for Asphalt Technology; 2005.

13. Wasiuddin NM, Selvamohan S, Zaman MM, Guegan MLTA. A Comparative Laboratory Study of Sasobit® and Aspha-min® in Warm-Mix Asphalt. Transportation Research Board 86th Annual Meeting. Washington DC, United States2007.

14. Anderson RM, Baumgardner G, May R, Reinke G. Engineering Properties, Emissions, and Field Performance of Warm Mix Asphalt Technology. National Cooperative Highway Research Program (NCHRP); 2008.

15. Gonzalez Leon JA, Grampre L, Barreto G. Warm-Mix Asphalts with Low-Dosage Chemical Additives. Transportation Research Board; 2009. 12p p.

16. Daniel JS, Fowler J. Performance of Warm Mix Asphalt. 2006.

17. Hurley GC, Prowell BD, Reinke G, Joskowicz P, Davis R, Scherocman J, Brown S, Hongbin X, Bonte D. Evaluation of potential processes for use in warm mix asphalt. Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions; 2006; Savannah, GA, United States. Association of Asphalt Paving Technologist, White Bear Lake, MN 55110, United States. p 41-90. (Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions).

18. Davidson JK. Warm Asphalt Mix Technology: An Overview of the Process in Canada. Transportation Association of Canada; 2008. 15 p. p.

19. Ventura A, Moneron P, Jullien A, Tamagny P, Olard F, Zavan D. Environmental Comparison at Industrial Scale of Hot and Half-Warm Mix Asphalt Manufacturing Processes. Transportation Research Board; 2009. 12p p.

20. Hassan MM. Life-Cycle Assessment of Warm-Mix Asphalt: Environmental and Economic Perspectives. Transportation Research Board; 2009. 17p p.

21. Gaudefroy V, Olard F, Ridane M, Beduneau E, de La Roche C. Laboratory Environmental Assessment of Half-Warm Mix Asphalts by Factorial Experiment Design Approach. Transportation Research Board; 2009. 24p p.

22. Ventura A, Jullien A, Moneron P. Polycyclic aromatic hydrocarbons emitted from a hot-mix drum, asphalt plant: Study of the influence from use of recycled bitumen. Journal of Environmental Engineering and Science 2007;6(6):727-734.

23. Romier A, Audeen M, David J, Martineau Y, Olard F. Low-energy asphalt with performance of hot-mix asphalt. Transportation Research Record 2006(1962):101-112.

24. Brown DC. Warm Mix: The Lights Are Green. HMAT 2008;Vol. 13(No. 1):20-22,25,27,30,32.

25. Anderson EO. WAM-Foam- An Environmentally Friendly Alternative to Hot-Mix Asphalt. In: Team WS, editor. Oslo, Norway: Norwegian Public Roads Administration; 2007.

26. Prowell BD, Hurley GC, Crews E. Field Performance of Warm-Mix Asphalt at the NCAT Test Track. Transportation Research Board 86th Annual Meeting. Washington DC, United States2007.

27. Prowell BD, Hurley GC. Warm Mix Asphalt: Best Practice. National Asphalt Pavement Association; 2007.

28. Goh SW. Warm Mix Asphalt using Sasobit: Lab Evaluation for Cold Region. Houghton [Unpublished]: Michigan Technological University; 2009.

29. Abbas AR, Ali A. Mechanical Properties of Warm Mix Asphalt Prepard Using Foamed Asphalt Binders. Akron, Ohio: The University of Akron; 2011.

30. Warm Mix Asphalt Technologies and Research [Internet]. U.S. Department Of Transportation Federal Highway Administration. 2007 [updated cited Available from: http://www.fhwa.dot.gov/pavement/asphalt/wma.cfm

31. Brown DC. Warm Mix Picks Up Steam. James Informational Media, Incorporated; 2007. pp 62-64, 66-67 p.

32. Xiao F, Amirkhanian S. Laboratory Investigation of Moisture Damage in Warm-Mix Asphalt Containing Moist Aggregate. Transportation Research Board; 2009. 17p p.

33. Olard F, Heritier B, Beduneau E. Low energy asphalt LEA®: new half-warm mix asphalt for minimizing impacts from asphalt plant to job site. 2008; Zurich, Switzerland.

34. Middleton B, Forfylow B. Evaluation of Warm-Mix Asphalt Produced with Double Barrel Green Process. Transportation Research Board; 2009. 14p p.

35. Wielinski JC, Hand AJT, Rausch DM. Laboratory and Field Evaluations of Foamed Warm-Mix Asphalt Projects. Transportation Research Board; 2009. 18p p.

36. AESCO/Madsen. Eco Foam-II Static Inline Vortex Mixer. [Cited at March 2011: http://www.asphaltequipment.com] 2011.

37. Stansteel. Double Barrel Green System. [Cited at April 2011: http://www.stansteel.com] 2011.

38. Tarmc. Tri-Mix Warm Mix Injection. Tarmac International Inc. [CIted May 2011: http://www.tarmacinc.com] 2011.

39. Terex. Warm Mix Asphalt System. Terex Corporation {Cited March 2011: http://www.terexrb.com] 2011.

40. James R. Metering of steam - water two - phase flow by sharp - edged orifices. 1965. p 549-572.

41. Astec. Double Barrel Green System. [Cited at April 2011: http://www.astecinc.com] 2011.

42. Astec. A 138-Year-Old Company's New Technology. Hot-Mix Magazine [Cited at July 2011: http://www.hotmixmag.com/index.php?option=com_content&view=article&id=222&catid=50] 2011.

43. MAXAM. Aquablack Warm Mix Asphalt. MAXAM Inc. [Cited June 2011: http://maxamequipment.com/AQUABlackWMA.htm] 2011.

44. Goh SW, You Z. Mechanical Properties of Warm Mix Asphalt Using Aspha-min®. Transportation Research Board 87th Annual Meeting. Washington, D. C.: Transportation Research Board; 2008.

45. Von Devivere M, Barthel W, Marchand JP. Warm Asphalt Mixers by adding a synthetic zeolite. World Road Association - PIARC; 2003. 11p p.

46. Superpave Performance Graded Asphalt Binder Specification and Testing. Third Edition. Asphalt Institute; 2003. 69 p. p.

47. Superpave Performance Graded Asphalt Binder Specification and Testing. Asphalt Institute; 1995. 78 p. p.

48. Superpave. Asphalt Institute; 1996. 126 p. p.

49. M.W.Witczak, K.Kaloush, T.Pellinen, M.El-Basyouny, Quintus HV. Simple Performance Test for Superpave Mix Design. 2002.

50. Goh SW, You Z, Van Dam TJ. Laboratory Evaluation and Pavement Design for Warm Mix Asphalt. 2007 Mid-Continent Transportation Research Symposium. Center for Transportation Research and Education, Iowa State University, Ames, Iowa2007.

51. You Z, Buttlar WG, Dai Q. Aggregate Effect on Asphalt Mixture Properties by Modeling Particle-to-Particle Interaction. Symposium on the Mechanics of Flexible Pavements 2007(Geotechnical Special Publication No. 176).

52. You Z, Dai Q. Review of advances in micromechanical modeling of aggregate-aggregate interactions in asphalt mixtures. Canadian Journal of Civil Engineering 2007;34(2):239-252.

53. Shalaby A. Modelling short-term aging of asphalt binders using the rolling thin film oven test. Canadian Journal of Civil Engineering 2002;29(1):135-144.

54. Mallick RB, Brown ER. An evaluation of superpave binder aging methods. International Journal of Pavement Engineering 2004;5(1):9-18.

55. Witczak MW. Specification Criteria for Simple Performance Tests for Rutting. Tempe, Arizona: Arizona State University; 2007. Report nr NCHRP Report 580.

56. Priest AL, Timm DH, Solaimanian M, Gibson N, Marasteanu M. A full-scale pavement structural study for mechanistic-empirical pavement design. Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions; 2005; Long Beach, CA, United States. Association of Asphalt Paving Technologist, White Bear Lake, MN 55110, United States. p 519-556. (Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions).

57. Mulandi J, Khanum T, Hossain M, Schieber G. Comparison of pavement design using AASHTO 1993 and NCHRP Mechanistic- Empirical Pavement Design Guides. Proceedings of the 2006 Airfield and Highway Pavement Specialty Conference; 2006; Atlanta, GA, United States. American Society of Civil Engineers, Reston, VA 20191-4400, United States. p 912-923. (Proceedings of the 2006 Airfield and Highway Pavement Specialty Conference).

58. NCHRP. Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. National Cooperative Highway Research Program; March 2004.

59. Goh SW, You Z, Van Dam TJ. Laboratory Evaluation and Pavement Design for Warm Mix Asphalt. 2007 August 16-17, 2007; Center for Transportation Research and Education, Iowa State University, Ames, Iowa. p 1-11.

60. PQCorp. Advera® WMA Alumino Silicate PQ Corporation [Cited at January 2011: http://www.pqcorp.com/products/adverawma.asp] 2011.

61. Bahia HU, Faheem AF. Using the Superpave Gyratory Compactor to Estimate Rutting Resistance of Hot-Mix Asphalt. Transportation Research Board; 2007. pp 45-61 p.

62. Chapuis RP, Gatien A. Temperature dependent tensile strength of asphalt mixtures in relation to field cracking data. 1265 ed, ASTM Special Technical Publication. Philadelphia, PA, USA: ASTM; 1995. p 180-193.

63. AASHTO:T283-03. Standard Method of Test for Resistance of Compacted Asphalt Mixture to Moisture Induced Damage. American Association of State Highway and Transportation Officials; 2003.

64. Wen H, Kim YR. Simple performance test for fatigue cracking and validation with WesTrack mixtures. Transportation Research Record 2002(1789):66-72.

65. AASHTO:T321-07. Determining the Fatiuge Life of Compacted Hot-Mix Asphalt (HMA) Subjected to Repeated Flexural Bending. American Association of State Highway and Transportation Officials; 2007.

66. Zhou F, Scullion T, Sun L. Verification and Modeling of Three-Stage Permanent Deformation Behavior of Asphalt Mixes. American Society of Civil Engineers; 2004. p. 486-494 p.

67. Monismith CL, Ogawa N, Freeme CR. Permanent Deformation Characteristics of Subgrade Soils due to Repeated Loading. Transportation Research Record 1975(537):1-17.

68. Brown ER, Snaith MS. The Permanent Deformation Characteristic of a Dense Bitumen Macadam Subjected to Repeated Loading. Journal of the Association of Asphalt Paving Technologists 1974;43:224-252.

69. Zhou F, Scullion T. Preliminary Field Validation of Simple Performance Tests for Permanent Deformation: Case Study. Transportation Research Record 2003(1832):209-216.

70. Brown SF, Gibb JM. Validation Experiments for Permanent Deformation Testing of Bituminous Mixtures. Journal of the Association of Asphalt Paving Technologists 1996;65:255-299.

71. Faheem AF, Bahia HU, Ajideh H. Estimating results of a proposed simple performance test for hot-mix asphalt from superpave gyratory compactor results. Transportation Research Record 2005(1929):104-113.

72. Witczak MW. Specification Criteria for Simple Performance Tests for Rutting, NCHRP Report 580. NCHRP Report 580, National Cooperative Highway Research Program; 2007.

73. Dongre R, D'Angelo J, Copeland A. Refinement of Flow Number as Determined by Asphalt Mixture Performance. Journal of the Transportation Research Record 2009;2(2127):127-136.

74. Robinette C, Williams RC, Reinke G, Zhanping Y, Dukatz E. The effects of the testing history and preparation method on the superpave simple performance test. Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions; 2006; Savannah, GA, United States. Association of Asphalt Paving Technologist, White Bear Lake, MN 55110, United States. p 297-320. (Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions).

75. Bhasin A, Button JW, Chowdhury A. Evaluation of simple performance tests on hot-mix asphalt mixtures from south central United States. Transportation Research Record 2004(1891):174-181.

76. Witczak MW, Kaloush K, Pellinen T, El-Basyouny M, Quintus HV. Simple Performance Test for Superpave Mix Design. NCHRP Report 465, National Cooperative Highway Research Program; 2002.

77. Carpenter SH, Vavrik WR. Repeated triaxial testing during mix design for performance characterization. Transportation Research Record 2001(1767):76-84.

78. Kaloush KE, Roque R, Brown S, D'Angelo J, Marasteanu M, Masad E, Witczak MW. Tertiary flow characteristics of asphalt mixtures. Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions; 2002; Colorado Springs, CO, United States. Association of Asphalt Paving Technologist. p 248-280. (Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions).

79. Little DN, Button JW, Youssef H. Development of criteria to evaluate uniaxial creep data and asphalt concrete permanent deformation potential. Transportation Research Record 1993(1417):49-57.

80. Leahy RB, Witczak MW. Influence of test conditions and asphalt concete mix parameters on permanent deformation coefficients alpha and mu. Asphalt Paving Technology: Proceedings - Association of Asphalt Paving Technologists Technical Sessions; 1991; Seattle, WA, USA. Publ by Assoc of Asphalt Paving Technologists, St. Paul, MN, USA. p 333-363. (Asphalt Paving Technology: Proceedings - Association of Asphalt Paving Technologists Technical Sessions).

81. Kanitpong K, Bahia H. Relating adhesion and cohesion of asphalts to the effect of moisture on laboratory performance of asphalt mixtures. Transportation Research Record 2005(1901):33-43.

82. Wirtgen. Laboratory-scale plant WLB 10 S. Wirtgen Group [Cited at May 2011: http://www.wirtgen.de/en/produkte/kaltrecycler/wlb_10/WLB10_k_Bildergalerie.html] 2011.

83. Jenkins K, Ven Mvd, Groot Jd. Characterisation of Foamed Bitumen. 7th Conference on Asphalt Pavement for Southern Africa. South Africa1999.

84. Muthen KM. Foamed Asphalt Mixes - Mix Design Procedure. South Africa: CSIR Transportek Project TRA79; 1998.

85. Saleh MF. New Zealand Experiience with Foam Bitumen Stabilization. Transportation Research Record 2004(1868):pp40-49.

86. Ruckel PJ. Foamed-Asphalt Paving Mixtures: Preparation of Design MIxes and Treatment of Test Speciments. Transportation Research Record 1983(911):pp. 88-98.

87. Bissada AF. Structural Response of Foamed-Asphalt: Sand Mixtures in Hot Environments. Transportation Research Record 1987(1115):pp. 134-149.

88. Copeland A, Gibson N, Corrigan M. A Cross-Cutting Comparision between Hot Mix Asphalt and Warm Mix Asphalt. 2nd International WMA Conference, St. Louis, MO2011.

89. Bennert T, Brouse G. Influence of Initial Aggregate Moisture Content and Production Temperature on Mixture Performance of Plant Produced Warm Mix Asphalt. Piscataway: Center for Advanced Infrastructure and Transportation (CAIT); 2011.

90. Bhusal S. A Laboratory Study of Warm Mix Asphalt for Moisture Damage Potential and Performance Issues. Oklahoma State University 2004.

91. Gandhi T. Effects of Warm Mix Additives on Asphalt Binder and Mixtures Properties. Clemson University 2008.

92. Tsai J, Lai J. Evaluating Constructability and Properties of Warm Mix Asphalt. The Office of Materials and Research, The Georgia Department of Transportation 2010.

93. Witczak MW. Specification Criteria for Simple Performance Tests for Rutting, Volume I: Dynamic Modulus (E*) and Volume II: Flow Number and Flow Time 2008. Report nr NCHRP Report 580.

94. Sasol. Sasobit Asphalt Technology. Sasol Wax [Cited Jan 2010: http://www.sasolwax.us.com/sasobit.html] 2010.

95. Clariant. Licomont BS-100. Clariant [Cited May 2011: http://www.pigments.clariant.com/pa/ProductDataSheets.nsf/www/DS-OSTS-7SHE8V?open] 2011.

96. Damm K-W, Abraham J, Butz T, Hilderbrand G, Riebeschl G. Asphalt Flow Improvers as, Intelligent Fillers' for Hot Asphalts - A New Chapter in Asphalt Technology. Journal of Applied Asphalt Binder Technology 2002:pp. 36-69.

97. Naidoo P. "Sasobit in "Warm Mix Asphalt" Application, 9 Years of Global Success. Sasol Wax Americas, Inc. 2006.

98. Payne.&.Dolan. Warm Mix Asphalt with RAP. 2007.

99. MultiCool Software Version 3.0 [Internet]. [updated cited Available from: http://www.hotmix.org/index.php?option=com_content&task=view&id=178&Itemid=273

100. Wasiuddin NM, Zaman M, Rear EA. Effect of Sasobit and Aspha-min on Wettability and Adhesion Between Asphalt Binders and Aggregates. Transportation Research Board; 2008. 16p p.

101. Z. H, A. B, Zaman M, E. OR, S. C, S. L. Evaluation of the use of Warm Mix Asphalt as Viable Paving Material in the United States. Federal Highway Administration Turner-Fairbank Highway Research Center 2009.

102. Hurley GC, Prowell BD. Evaluation of Evotherm For Use in Warm Mix Asphalt. National Center for Asphalt Technology 2006.

103. Ceca. Cecabase RT. Ceca Arkema Group [Cited May 2010: http://www.ceca.fr/sites/ceca/en/business/bitumen_additives/warm_coated_material/warm_coated_material.page] 2009.

104. MWW. Evotherm Warm Mix Asphalt. MWW [Cited June 2009: http://www.meadwestvaco.com/SpecialtyChemicals/AsphaltAdditives/MWV002106] 2010.

105. AkzoNobel. Improved Performance at Lower Temperature. AkzoNobel Surface Chemistry [Cited May 2011: http://www.akzonobel.com/surface/markets/asphalt/new_developments/rediset.aspx] 2010.

106. Jorda E. Cecabase RT. Ceca Arkema Group. 2000 Market Street, Philadelphia, PA 19103.

107. Clements TM. The Effect of Loose Mix Aging on The Performance Properties of Warm Asphalts. University of Kentucky 2011.

108. Hurley GC, Powell BD, Kvaska AN. Wisconsin Field Trial of Warm Mix Asphalt Technology: Construction Summary. National Center for Asphalt Technology, Federal HIghway Administration 2010.

109. Bonaquist R. Mix Design Practices for Warm Mix Asphalt. National Cooperative Highway Research Program, Transportation Research Board 2011;NCHRP Report 691.

110. Hurley GC. Evaluation Of New Technologies For Use In Warm Mix Asphalt. Auburn: Auburn University; 2006. 231 p.

111. Kvasnak A, Prowell B, Hurley G, Smit AdF, Kim J. Alabama Warm Mix Asphalt Field Study: Final Report. Alabama Department of Transportation 2010.

112. AL-Qadi IL, Baek J, Leng Z, Wang H, Doyen M, Kern J, Gillen SL. Stone Matrix Asphalt (SMA) Produced with Warm Mix Additives. Illinois Center for Transportation 2012.

113. Sheth NM. Evaluation of Selected Warm Mix Asphalt. University of Iowa 2010.

114. Robjent L, Dosh W. Warm-Mix Asphalt for Rural County Roads. 41072 ed. Volume 359. Duluth, MN: ASCE; 2009. p 43-43.

115. Diefenderfer SD, McGhee KK, Donaldson BM. Installation of Warm Mix Project in Virginia. Virginia Transportation Research Council; 2007. Report nr VTRC 07-R25.

116. Kristjansdottir O, Muench ST, Michael L, Burke G. Assessing potential for warm-mix asphalt technology adoption. Transportation Research Record 2007:91-99.

117. Diefenderfer S, Hearon A. Laboratory Evaluation of a Warm Asphalt Technology for Use in Virginia. Virginia Transportation Research Council, Virginia Department of Transportation, Federal Highway Administration; 2008. 44p p.

118. Bonaquist R. Mix Design Practices for Warm Mix Asphalt. Interim Report, Project NCHRP 9-43, National Cooperative Highway Research Program 2008.

119. You Z, Goh SW, Williams RC. Development of Specification for the Superpave Simple Performance Test Michigan Department of Transportation 2009.

120. ARRA. Basic Asphalt Recycling Manual. Asphalt Recycling and Reclaiming Association; 2001.

121. Button JW, Estakhri CK, Little DN. Performance and cost of selected hot in-place recycling projects. Transportation Research Record 1995(1507):51-66.

122. Peterson RL, Soleymani HR, Anderson RM, McDaniel RS. Recovery and Testing of RAP Binders from Recycled Asphalt Pavements. Association of Asphalt Paving Technologists; 2000. p. 72-91 p.

123. Lewandowski LH, Graham R, Shoenberger J. Physicochemical and rheological properties of microwave recycled asphalt binders. 1992; Atlanta, GA, USA. Publ by ASCE, New York, NY, USA. p 449-461.

124. Peterson GD, Davison RR, Glover CJ, Bullin JA. Effect of composition on asphalt recycling agent performance. Transportation Research Record 1994(1436):38-46.

125. Chaffin JM, Liu M, Davison RR, Glover CJ, Bullin JA. Supercritical fractions as asphalt recycling agents and preliminary aging studies on recycled asphalts. Industrial & Engineering Chemistry Research 1997;36(3):656-666.

126. Terrel RL, Fritchen DR. Laboratory Performance of Recycle Asphalt Concrete. ASTM Special Technical Publication 1978:104-12.

127. Yamada M, Ninomiya T, Mise T. Recycled asphalt mixtures in Osaka and their performance. Memoirs of the Faculty of Engineering, Osaka City University 1987;28:197-201.

128. Yamada M. Characterization of Recycled Asphalt Mixes and their Pavement Performance. Doboku Gakkai Rombun-Hokokushu/Proceedings of the Japan Society of Civil Engineers 1984(348):51-60.

129. Daniel JS, Lachance A. Mechanistic and Volumetric Properties of Asphalt Mixtures with Recycled Asphalt Pavement. Transportation Research Board; 2005. p pp 28-36.

130. McDaniel RS, Shah A, Huber GA, Gallivan VL. Investigation of Properties of Plant-Produced RAP Mixtures. Transportation Research Board; 2007. 15p p.

131. Chehab GR, Daniel JS. Evaluating recycled asphalt pavement mixtures with mechanistic-empirical pavement design guide level 3 analysis. Transportation Research Record 2006(1962):90-100.

132. Kandhal PS, Foo KY. Designing recycled hot mix asphalt mixtures using Superpave technology. ASTM Special Technical Publication; 1997; New Orleans, LA, USA. ASTM, Conshohocken, PA, USA. p 101-117. (ASTM Special Technical Publication).

133. McDaniel RS, Soleymani H, Anderson RM, Turner P, Peterson R. Recommended use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method. National Cooperative Highway Research Program, North Central Superpave Center; 2000. 461 p. p.

134. McDaniel RS, Soleymani H. Superpave RAP Mixtures. University of Texas, Austin, Texas A&M University, College Station; 2000. 18p p.

135. McDaniel R, Anderson RM. Recommended use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual. Transportation Research Board, North Central Superpave Center; 2001. 55 p. p.

136. Kandhal PS, Rao SS, Watson DE, Young B. Performance of recycled hot-mix asphalt mixtures in Georgia. Transportation Research Record 1995(1507):67-77.

137. Hossain M, Scofield LA. Performance of Recycled Asphalt Concrete Materials in an Arid Climate. 1992; Atlanta, GA, USA. Publ by ASCE, New York, NY, USA. p 415-427.

138. Hossain M, Metcalf DG, Scofield LA. Performance of recycled asphalt concrete overlays in Southwestern Arizona. 1993. Report nr 0361-1981. 30-37 p.

139. Emery JJ. Asphalt concrete recycling in Canada. Transportation Research Record 1993(1427):38-46.

140. Paul HR. Evaluation of Recycled Projects for Performance. Louisiana Department of Transportation and Development, Louisiana Transportation Research Center, Federal Highway Administration; 1995. 75p p.

141. Hassan R. Feasibility of using high RAP Contents in Hot Mix Asphalt. Australian Asphalt Paving Association 13th International Flexible Pavements Conference, October, Queensland, Australia 2010.

142. Hansen K, Newcomb D. RAP Usage Survey. National Asphalt Pavement Association, Lanham, MD 2007.

143. Al-Qadi IL, Carpenter SH, Roberts GL, Ozer H, Aurangzeb Q, Elseifi MA, Trepanie J. Determination of Usable Residual Asphalt Binder in RAP. University of Illinois at Urbana-Champaign, Illinois Department of Transportation 2009;FHWA-ICT-09-031

144. Zhou F, Das G, Scullion T, Hu S. RAP Stockpile Management and Processing in Texas: State of the Practice and Proposed Guidelines. Texas Transportation Institute, Texas Department of Transportation 2010;FHWA/TX-10/0-6092-1.

145. Superpave Mix Design (SP-2). Asphalt Institute; 2001. 102 p. p.

146. Mogawer P.E WS, Austerman AJ, Engstrom B, Bonaquist R. Incorporating High Percentages of Recycled Asphalt Pavement and Warm-Mix Asphalt Technology into Thin Hot-Mix Asphalt Overlays as Pavement Preservation Strategy. Transportation Research Board; 2009. 21p p.

147. Asphalt Roofing Shingles Recycling [Internet]. 2008 [updated cited Available from: http://www.ciwmb.ca.gov/condemo/Shingles/

148. Asphalt Recycling & Reclaiming Product Focus. Asphalt Recycling and Reclaiming Special Report. Scranton Gillette Communications, Incorporated, PSA Group LLC; 1989. p. 56-57 p.

149. Button JW, Williams D, Scherocman JA. Roofing Shingles and Toner in Asphalt Pavements. Texas Transportation Institute, Texas Department of Transportation, Federal Highway Administration; 1996. 130 p. p.

150. Uses of Waste Asphalt Shingles in HMA. State-of-the-Practice. Virginia Department of Transportation; 1997. 19 p. p.

151. Abdulshafi O, Kedzierski B, Fitch M, Muhktar H. Evaluation of the Benefits of adding Waste Fiberglass Roofing Shingles to Hot-Mix-Asphalt. CTL Engineering, Incorporated, Ohio Department of Transportation, Federal Highway Administration; 1997. 181 p. p.

152. Foo KY, Hanson DI, Lynn TA. Evaluation of roofing shingles in hot mix asphalt. Journal of Materials in Civil Engineering 1999;11(1):15-20.

153. Hanson DI, Foo KY, Lynn TA. Evalution of Roofing Shingles in HMA. National Cetner for Asphatl Technology; 1997.

154. Amirkhanian SN, Vaughan KM. Field Evaluation of Use of Waste Shingles in Asphalt Mixtures. Clemson University, South Carolina Department of Transportation, Federal Highway Administration; 2001. 35 p. p.

155. Janisch DW, Turgeon CM. Minnesota's Experience with scrap Shingles in Bituminuous Pavements. Minnesota Department of Transportation; 1996. 43 p. p.

156. Witczak M. Simple Performance Tests: Summary of Recommended Methods and Database. Transportation Research Board; 2005. 23p p.

157. Abtahi SM, Sheikhzadeh M, Hejazi SM. Fiber-reinforced asphalt-concrete - A review. Construction and Building Materials;24(6):871-877.

158. Goh SW, You Z, Wang H, MIlls-Beale J, Ji J. Identify Flow Number for Asphalt Mixture using Flow Number Slope. Journal of Transportation Research Board 2011.

159. Copeland A. Reclaimed Asphalt Pavement in Asphalt Mixtures: State of The Practice. Federal Highway Administration 2011;FHWA-HRT-11-021.

160. Lu Q, Harvey JT. Inclusion of Moisture Effect in Fatigue Test for Asphalt Pavements. Proceedings of the 86th Annual Meeting of the Transportation Research Board (CD-ROM), Washington, D.C. 2007.

161. Bausano J, Williams RC. Transitioning from AASHTO T283 to the Simple Performance Test Using Moisture Conditioning. Journal of Materials in Civil Engineering 2009;21(2):73.

162. Caro S, Masad E, Bhasin A, Little DN. Moisture Susceptibility of Asphalt Mixture. International Journal of Pavement Engineering 2008;2:81-114.

163. Institute A. Best Practice to Minimize Sensitivity in Asphalt Mixture. 2007.

164. Roberts FL, Kandhal PS, Ray BE, Lee D-Y, Kennedy TW. Hot Mix Asphalt Materials, Mixture Design, and Construction. National Asphalt Pavement Association Research and Education Foundation, Lanham, Maryland 1996.

165. Prowell BD, West RC. Begin Reducing Production and Laydown Temperature - Today. Hot Mix Asphalt Technology, National Asphalt Pavement Association 2005;10(4):24-27, 30-31.

166. Hunt D. Overcoming Operating Challenges with Warm Mix Asphalt. 2007.

167. Young TJ. Saving Money through Effective Plant Maintenance. Hot Mix Asphalt Technology, National Asphalt Pavement Association 2007;12(6).

168. Little DN, Epps JA. The benefits of Hydrated Lime in Hot Mix Asphalt. National Lime Association 2001.

169. Button J. Maximizing the Beneficial Effects of Lime in Asphalt Paving Mixtures. Evaluation and Prevention of Water Damage of Asphalt Paving Materials, ASTM STP 89 1985.

170. Aragão FTS, Kim Y-R, Lee J. Research on Fatigue of Asphalt Mixtures and Pavements in Nebrask. University of Nebraska Lincoln, Nebraska Department of Roads 2008;NDOR Research Project Number P579.

Appendix 1: Copyright Permission Documentation

Email from Sasol for the permission to use Figure 2.33 Chemical Structure Long Chain Aliphatic Polyethylene Hydrocarbon

Reply | Reply All | Forward | Archive | Junk | Delet

From Honiball, William (WJ)
Subject **RE: Permission of using Sasobit picture**
11/22/2012 4:14 PM
To Me <sgoh@mtu.edu>
Cc Noelting, Matthias (M), Beigley, John (JR), Bessant, Guy (GA)
Other Actions

Good day,

Straight below this mail, I have copied into the text the permission granted by our IP & Branding Leader, as well as BU leader for the division. Please just follow the mentioned guideline [i.e. with permission ©Sasol Wax GmbH 2004].

Best of luck with your thesis! Needless to say, we would be very interested in receiving an electronic copy of the content once you have jumped through all the hoops and passed all the Examiner's criteria.

Regards,
William

From: Noelting, Matthias (M)
Sent: Thursday, November 22, 2012 10:05 AM
To: Beigley, John (JR); Honiball, William (WJ)
Cc: Bessant, Guy (GA)
Subject: AW: Permission of using Sasobit picture

Permission granted.

Mit Freundlichen Grüßen / Best Regards,

sasol
reaching new frontiers

Matthias Nölting Dipl.-Ing.
Global Business Unit Manager
Asphalt Additives
Sasol Wax GmbH

Tel +49 (0)40 78115731
Fax +49 (0)40 78115882
Mobile +49 (0)171 7298489
E-mail matthias.noelting@de.sasol.com

Worthdamm 13-27
20457 Hamburg
Germany
www.sasolwax.com

Sasol Wax GmbH
Gesellschaft mit beschränkter Haftung, Sitz Hamburg, Registergericht Hamburg HRB 73963
Geschäftsführer: Dr. Thomas Lüdemann

NOTICE: Please note that this eMail, and the contents thereof, is subject to the standard Sasol eMail legal notice which may be found at: http://www.sasol.com/legalnotices. If you cannot access the legal notice through the URL attached and you wish to receive a copy thereof please send an eMail to legalnotice@sasol.com

Environmental awareness starts with each of us – think before you print this page

Email from Stansteel for the permission to use Figure 2.1 Accu-Shear Dual Warm-Mix Additive system

Reply Forward Archive Junk Dele

From Dawn Kochert

Subject **RE: REQUEST - MICHIGAN TECH. UNIVERSITY - Contact request from stansteel.com** 11/20/2012 11:55 P

To Me <sgoh@mtu.edu>

Other Actions

Shu –
Thank you for the additional information. You are authorized to use the Accu-Shear image in the manner described in your email to me dated November 19, 2012.
Good luck with your dissertation and Happy Thanksgiving!
Dawn

From: Shu Wei Goh [mailto:sgoh@mtu.edu]
Sent: Monday, November 19, 2012 11:14 PM
To: Dawn Kochert
Subject: Re: REQUEST - MICHIGAN TECH. UNIVERSITY - Contact request from stansteel.com

Hi Dawn,

Yup sure, here is the pic I am using: http://www.stansteel.com/accuinstall.asp
I am using the first photo in my dissertation to explain and shows different type of available WMA.

Thanks and let me know as soon as possible

Regards,
Shu Wei

On 11/20/2012 3:50 AM, Dawn Kochert wrote:

> Good Afternoon Shu –
> In regards to your request. Is it possible to email me in what context the image would be used. I am consulting with our attorney on staff and we would need to have this information before he can approve.
> Thanks Shu, looking forward to hearing from you.
> Dawn

Email from PQCorp for the permission to use Figure 2.13 ADVERA® WMA Mixing Box

File Edit View Go Message Events and Tasks Tools Help

Get Mail | Write | Chat | Address Book | Tag | Quick Filter | Search... <Ctrl+K>

Reply | Forward | Archive | Junk | Delet

From PQ Web Customer Service <PQWeb.CustomerService@pqcorp.com>

Subject **RE: PQ Customer Service Contact Form** 11/22/2012 4:03 AI

To Me <sgoh@mtu.edu> Other Actions

Dear Shu:

It should not be a problem using the zeolite picture in your dissertation.

Tel: 800-944-7411
Fax: 610-251-5249

From: sgoh@mtu.edu [mailto:sgoh@mtu.edu]
Sent: Monday, November 19, 2012 11:32 AM
To: PQ Web Customer Service
Subject: PQ Customer Service Contact Form

Company Name:	MIchigan Technological University
Contact Name:	Shu Wei Goh
Product Line:	Zeolites
Street:	1110 College Ave., APT B
City:	Houghton
State:	MI
Postal Code:	49931
Country:	United States
Telephone:	9063704269
Fax:	
Email:	sgoh@mtu.edu

Email from Maxam Equipment for the permission to use Figure 2.2 Aquablack WMA

From Lonnie Greene

Subject **RE: Permission of using Aquablack WMA Picture**

To Me <sgoh@mtu.edu>

Reply | Forward | Archive | Junk | Dele

1:02 A

Other Actions

This email constitutes permission from Maxam Equipment Inc. for use of our AquaBlack photos, logos and descriptive language and literature for the sole purpose of inclusion in your thesis entitled "Development and Improvement of Warm-Mix Asphalt (WMA) Technology".

Good luck.

Lonnie Greene
Research Manager
Maxam Equipment Inc.
1575 Universal Ave
Kansas City, MO 641`20