

Laboratory Evaluation of Warm Mix Asphalt

FINAL REPORT

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16. Abstract 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 generation of greenhouse gases. 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 is used compared to conventional HMA. 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: The main objectives of this study are: 1) review and synthesize information on the available WMA technologies; 2) measure the complex/dynamic modulus of WMA and the control mixtures (HMA) for comparison purpose and for use in mechanistic-empirical (ME) design comparison; 3) assess the rutting and fatigue potential of WMA mixtures; and 4) provide recommendation for the proper WMA for use in Michigan considering the aggregate, binder, and climatic factors. The testing results indicated 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. In addition, the WMA design framework was developed based on the testing results, and presented in this study to allow contractors and state agencies to successfully design WMA around the state of Michigan.					
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Executive Summary

Traditionally, asphalt mixtures were produced at high temperatures (between 150°C to 180°C) and thus 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, quite a few technologies were used to produce WMA 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 are used to produce asphalt mixtures, especially when it comes to environmental and energy savings. Past research indicates that both emissions and energy usage (fuel) were reduced significantly when the WMA concept was used. Some other potential benefits included cold weather paving, reduced thermal segregation of materials, extended paving window, improved workability, earlier traffic opening after construction, reduced worker exposure to asphalt fumes, and slowed binder aging potential.

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. Most of the current WMA laboratory test results are inconsistent and not compatible with field performance. Thus, the objectives of this project are to 1) review and synthesize information on the available WMA technologies; 2) measure the complex/dynamic modulus of WMA and the control mixtures (HMA) for comparison purpose and for use in mechanistic-empirical (ME) design comparison; 3) assess the rutting and fatigue potential of WMA mixtures; and 4) provide recommendation for the proper WMA for use in Michigan considering the aggregate, binder, and climatic factors.

Three main WMA technologies were used in this study, including foamed WMA, WMA using organic additive and WMA using chemical package. Aspha-min®, Advera® WMA, foamed WMA using free water system, Sasobit® and Cecabase RT® were used as the WMA technology in this study. For asphalt binder, rheological properties and aging factor of WMA modified asphalt were evaluated. For WMA mixture, a total of 696 asphalt mixtures were produced and evaluated using dynamic modulus ($|E^*|$), tensile

strength ratio (TSR), four point beam fatigue, flow number (F_N) and APA rutting. 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 11. A recommended WMA mix design framework was developed in this study to allow contractors and state agencies to successfully design WMA in Michigan.

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 generation of greenhouse gases. The asphalt industry has talked about energy savings and environmental benefits in cold or warm asphalt processes [1]. Additionally, environmental awareness has been increasing rapidly over the past years and extensive measures like air pollution reduction targets set by the European Union with the Kyoto Protocol have encouraged efforts to reduce pollution [2]. The hot-mix asphalt industry is constantly exploring technological improvements that will enhance the material's performance, increase construction efficiency, conserve resources, and advance environmental stewardship.

Warm Mix Asphalt (WMA), a new paving technology that originated in Europe and was reported by Harrison and Christodulaki [1] 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 CO₂ emissions of 30%, are realized when WMA is used compared to conventional HMA. These energy savings and emissions reductions could be greater if burner tuning was adjusted to allow the burners used in the WMA process to run 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 [3]. Figure 1 shows the typical mixing temperatures for asphalt mixtures.

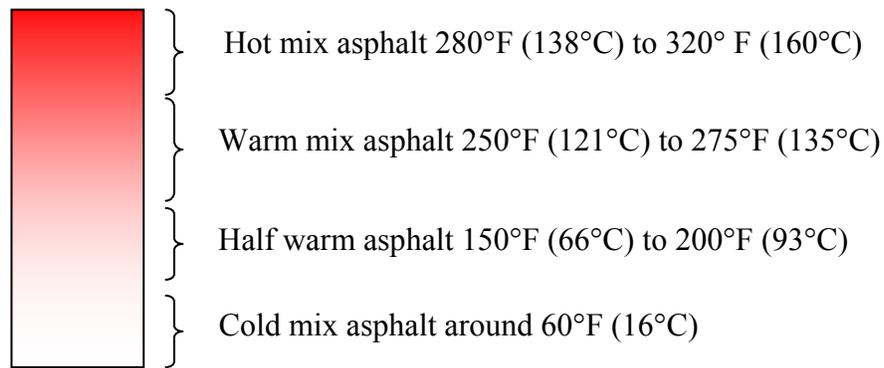


Figure 1 Typical Mixing Temperature Range for Asphalt Mixtures

Warm Mix Asphalt Technology

The technique of WMA was first invented by Professor Csanyi at Iowa State University in 1956 [4]. He found out that the foaming asphalt could be potential 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 [4]. This invention was later licensed to Conoco Inc. to promote foamed asphalt in United States and to further develop the product as a base stabilizer for both laboratory and field evaluation [5, 6].

Since 1970s, researchers have been trying to investigate a new method to reduce asphalt mixture production temperature [7]. 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 [3, 8]. As of today, three major 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 production process modification, or introduce a small amount of water to the asphalt mixture during the production using a hydrophilic material [3]. The water creates a volume expansion of the binder that results in asphalt foam, and allows increased workability and aggregate coating at lower temperature [9].

The organic additive for WMA 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 particular organic additive), allowing the asphalt mixture to be mixed and placed at lower temperatures [7, 10, 11]. It is important to ensure the selected organic material has a melting point above the expected service temperature to avoid permanent deformation [12].

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 are designed to enhance coating, adhesion, and workability of the asphalt mixture [12, 13]. Some of the chemical packages also act as the emulsification agent [14-16]. 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.

Table 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 weight of mixture
ADVERA® WMA	PQ Corporation	0.25% by total weight 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 directly 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

Benefits of Warm Mix Asphalt

The benefits of Warm Mix Asphalt (WMA) in terms of environmental aspects have been constantly identified by United States and European countries. Past research indicated that emissions and energy usage (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 [17-19]. The benefits of this research to Michigan are as follows:

Improved Mobility in Michigan

Identifying the use of WMA technology on asphalt pavement will allow for the development of an 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

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 a typical service life of 30 years [20]. The use of WMA techniques allow for the reduction in required mixing energy and subsequently allow for substantial savings in energy costs [21]. The use of additives in these WMA processes allowed the production temperatures to be 50°F to 100°F lower than the typical HMA production temperatures [22]. According to previous studies, this correlates to burner fuel savings with WMA processes ranging from 20 to 35 percent [3]. These energy savings and emissions reductions could be greater if burner tuning was adjusted to allow the burners used in the WMA process to run 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 [3]. Figure 2 shows the emission reduction results from

WMA European Practice Report conducted by WMA Technical Working Group (WMA TWG) [3].

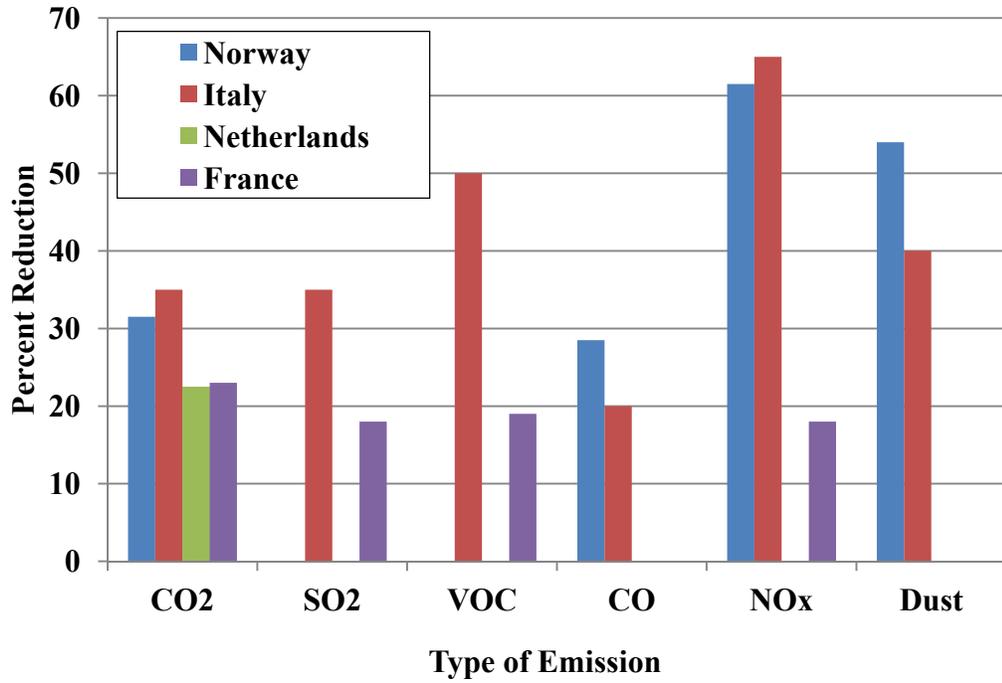


Figure 2 Reported Reduction in Plant Emission with the use of WMA for Selected EU Nations(data by WMA Technical Working Group[3])

Better Health to Contractors, Engineers, and Public

Hot asphalt fumes generated during asphalt mixing processes contain polycyclic aromatic hydrocarbon (PAH) compounds [20]. 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 [20]. The use of recycled asphalt in these processes can lead to additional asphalt related emissions and studies focuses on this topic have indicated that a distinct relationship exists between production temperatures and asphalt fume generation [3]. The use of Warm Mix Asphalt processes can effectively reduce the production of these fumes, consequently reducing exposure to workers. Monitoring of worker exposure to aerosol/fumes and PAHs within asphalt mixing plants

showed a viable decrease 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 [23]. 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 [3]. Therefore, the use of WMA will benefit many people including paving crews, contractors, MDOT engineers, and the public.

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 [24]. 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.

Extends Paving Window

Michigan is located at cold climate where the air temperature is usually low at all seasons. Hence, 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 [5]. 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 non-attainment areas [5, 25]. In the past, the research team evaluated the WMA using Sasobit® for cold region [26], 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 7.7°C (per Weather condition at Iron Mountain, Michigan on September 2007).

Problem Statement

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 [27, 28]. In addition, an evaluation of how the use of WMA impacts pavement design using the Mechanistic-Empirical Asphalt Pavement Guide (MEPDG) has not been done in past studies.

Objectives

The main objectives of this study are: 1) review and synthesize information on the available WMA technologies; 2) measure the complex/dynamic modulus of WMA and the control mixtures (HMA) for comparison purpose and for use in mechanistic-empirical (ME) design comparison; 3) assess the rutting and fatigue potential of WMA mixtures; and 4) provide recommendation for the proper WMA for use in Michigan considering the aggregate, binder, and climatic factors.

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. No extra additives are required 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 [12, 30].

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.

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 [9, 12, 31]. Technologies that use hydrophilic materials as foaming technique include Aspha-min® and ADVERA® WMA.

Damp Aggregate

WMA using damp aggregate as a foaming method have been used by many contractors especially in Europe [17, 21, 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 [17, 19, 33]. In the LEA WMA process, there are five phases shown in Figure 3 to produce WMA [21]:

- 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 aggregate was 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.

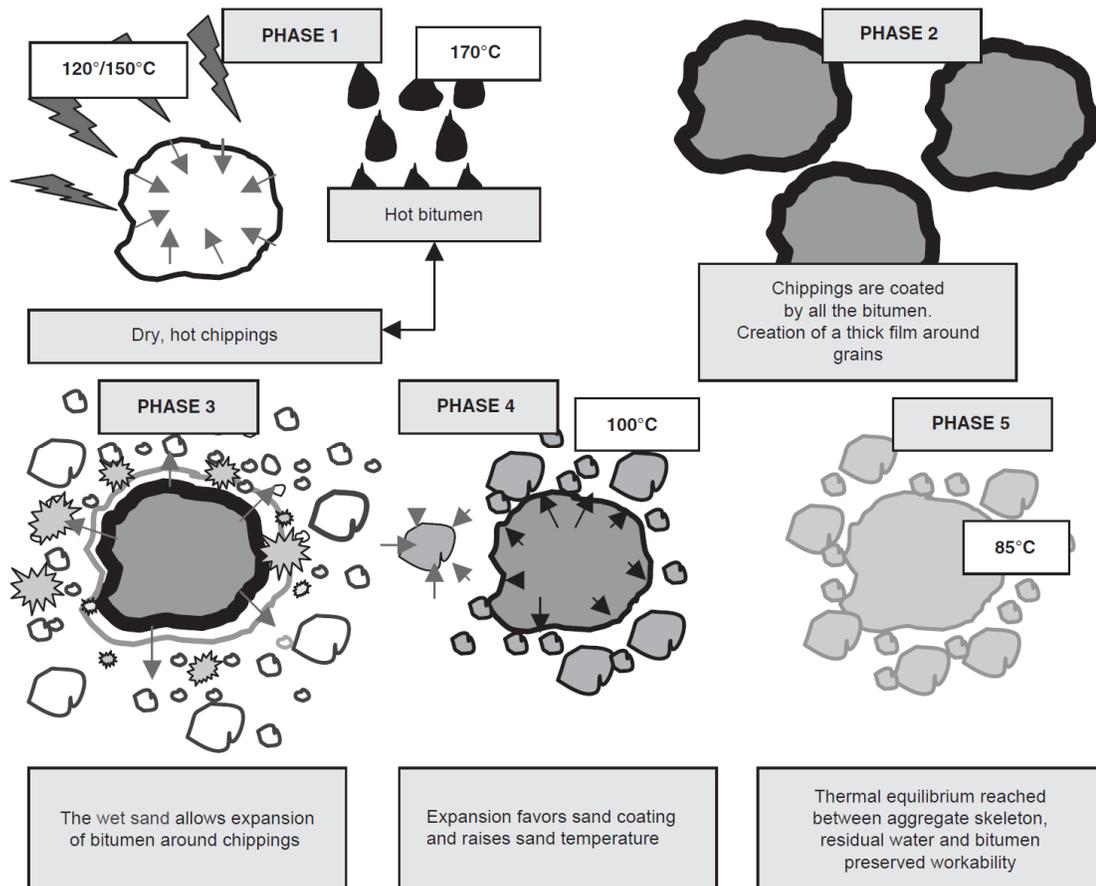


Figure 3 LEA Technique (from LEA-Co[21])

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 Standsteel [37], Double Barrel Green System from Astec Industries [41, 42] and Aquablack WMA from Maxam Equipment Inc. [43].

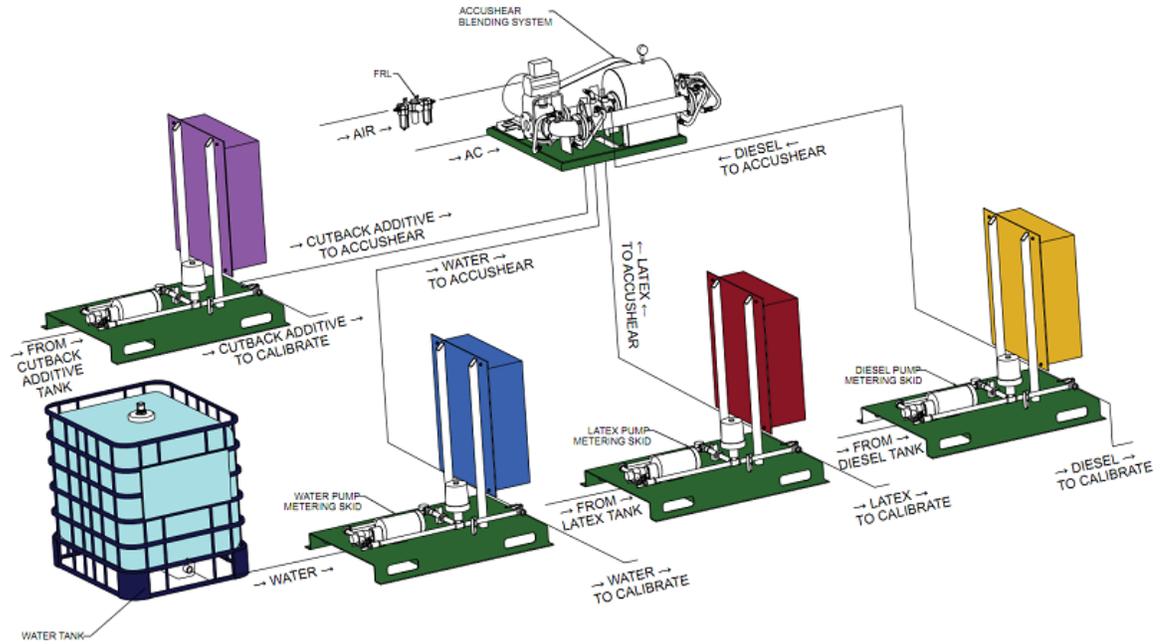


Figure 4 Accu-Shear Dual Warm-Mix Additive system (from Standsteel)



Figure 5 Double Barrel Green System (from Astec Industries)



Figure 6 Aquablack WMA (from Maxam Equipment Inc.)

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.

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 CO₂ emissions by 15%. Aspha-min® (a.k.a. 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 [5, 15, 44].

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 mixture for the volumetric analysis) and PG52-34. For the PG64-28 binder, a 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 un-aged condition were 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[47].

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 [48-50]. 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[48-50] was followed in the mix preparation. For the WMA mixture, the 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[48-50].

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.

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 10. On the other hand, four types of PG52-34 binder (i.e., control, 0.3%, 0.4% and 0.5% Aspha-min®) were used in the viscosity test. The results are shown in Figure 11.

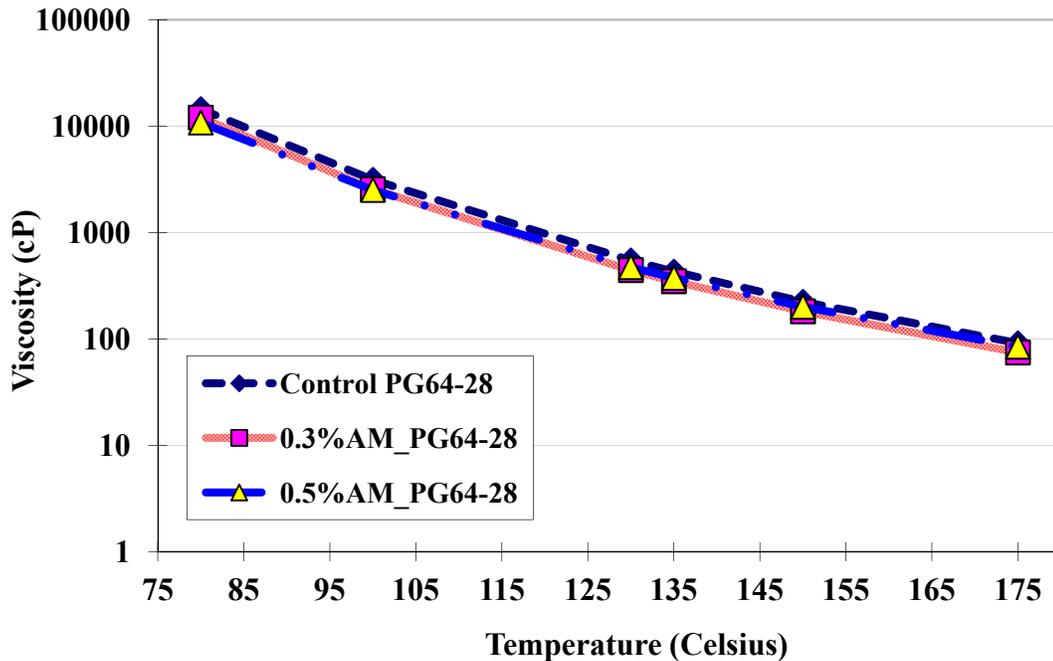


Figure 10 Comparing Viscosity Test Results for PG64-28 Control and WMA binders

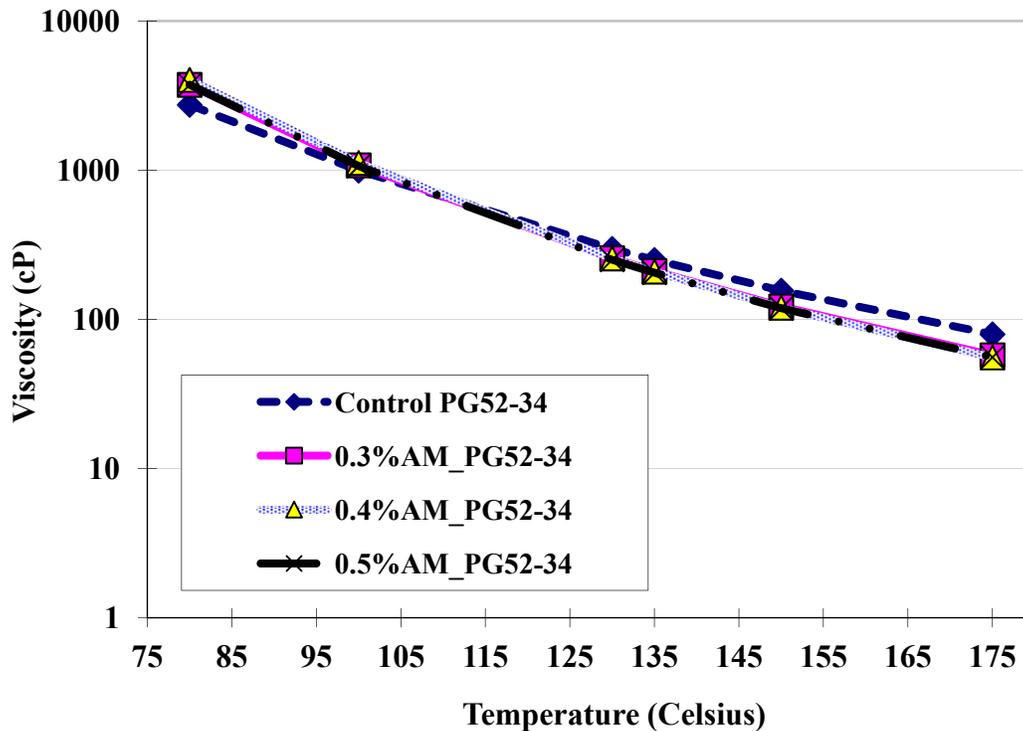


Figure 11 Comparing Viscosity Test Results for PG52-34 Control and WMA Binders

From Figure 10 and Figure 11, 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 ± 0.03 Pa·s, respectively. For binder PG64-28, the mixing and compacting temperatures increase when more Aspha-min® was used (i.e. 0.5%). However, the results of PG52-34 didn't 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 0.5%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[47, 51] 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.

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 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 $G^*/\sin(\delta)$ 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 [5, 15]; the additional Aspha-min® may decrease the production temperature by bumping one grade down on high temperature.

Table 2 Dynamic Shear Modulus Test Results for High and Low Temperatures

Asphalt Binder	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
	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)

For the DSR results of PG64-28 binder after the short-term aging process, as expected, the 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 $G^*/\sin(\delta)$ of un-aged and short term aging [11]. Due to the limited availability of current test results, only the aging factor of PG64-28 was evaluated. Table 3 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 [11]. Thus, this finding concluded that WMA has a shorter pavement life compared to the HMA.

Table 3 Aging factor (the ratio of $G^*/\sin(\delta)$ RTFO to $G^*/\sin(\delta)$ 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

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.

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 12 shows the IDT results tested at 4°C, 21.1°C, 37.8°C, and 54.4°C. Observation of Figure 12 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.

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 [15]. 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 [52-54]. 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.

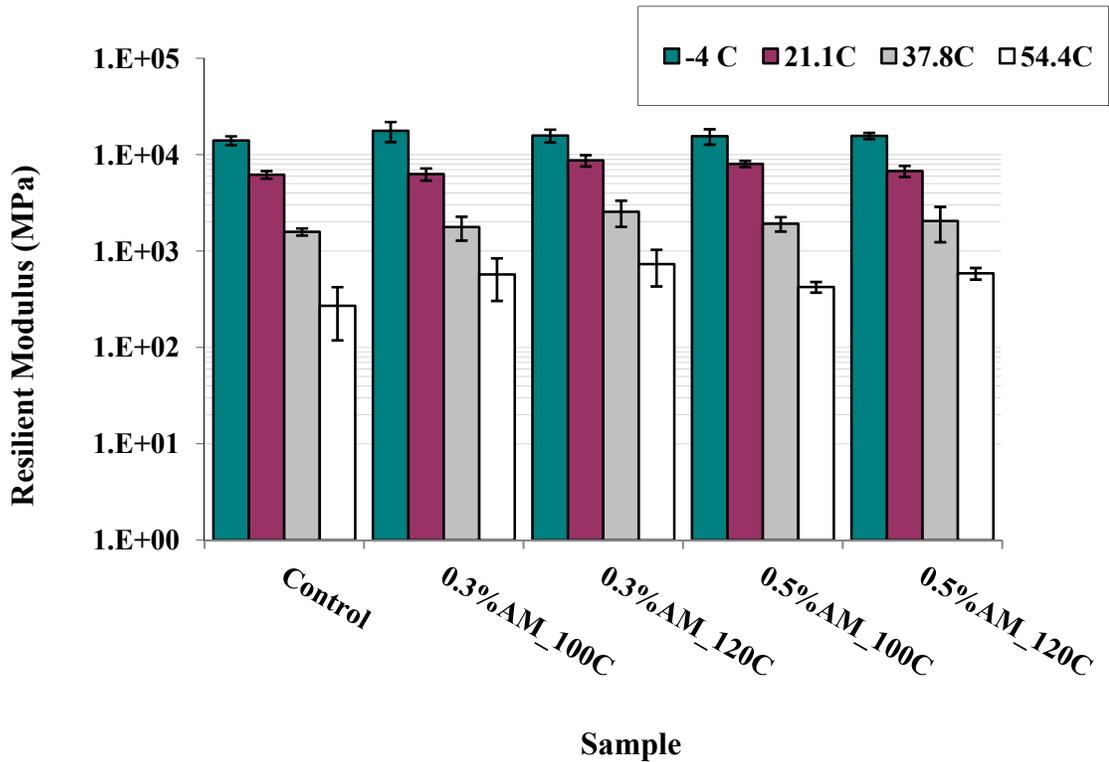


Figure 12 Resilient Modulus tested at 4°C, 21.1°C, 37.8°C and 54.4°C for control mixture compacted at 140°C and WMA mixture compacted at 100°C and 120°C

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 13. 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 12, 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[11]. 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.

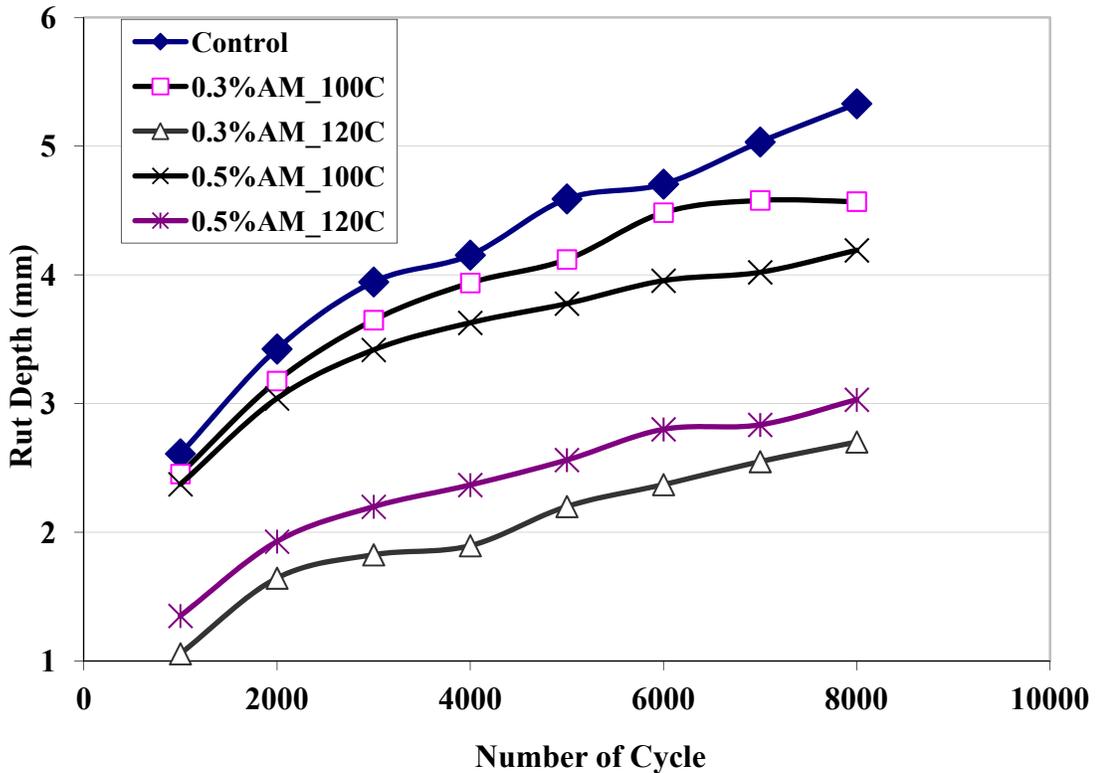


Figure 13 APA rutting test results for the control mixture and the WMA at 64°C

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[55]. Figure 14 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 is 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 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 mixture 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 [56].

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 15. During the formation of the sigmoidal master curve, -5°C was used as the reference temperature.



Figure 14 Dynamic Modulus Test Setup

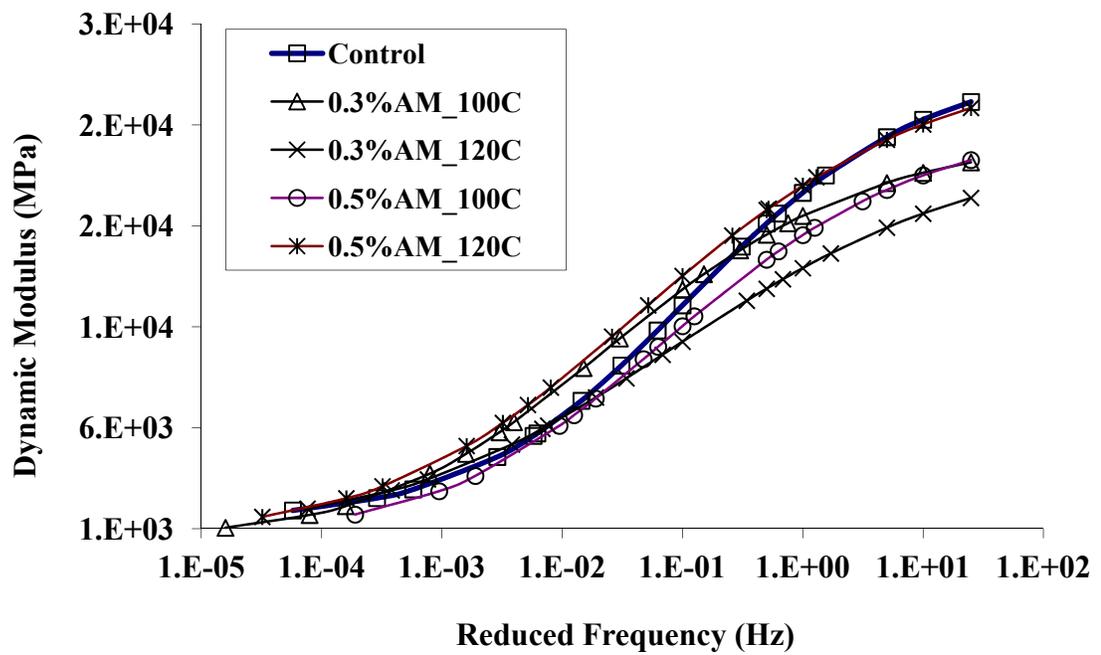


Figure 15 Sigmoidal Master Curve of Dynamic Modulus Test Results for Control and WMA Mixtures

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 [57]. 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).

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 [58, 59]. 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 [60].

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 [52, 61]. 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 16 and the MEPDG analysis results are shown in Figure 17. The results indicated that the difference in predicted permanent deformation for both HMA and WMA is insignificant.

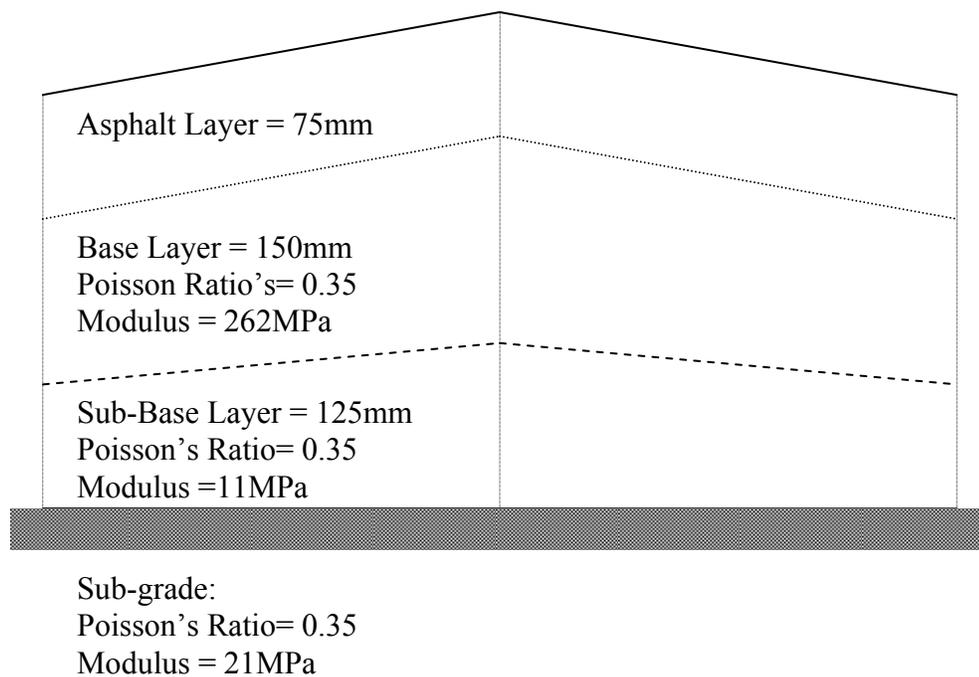


Figure 16 Pavement Structure for the Control and WMA in MEPDG Study

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.

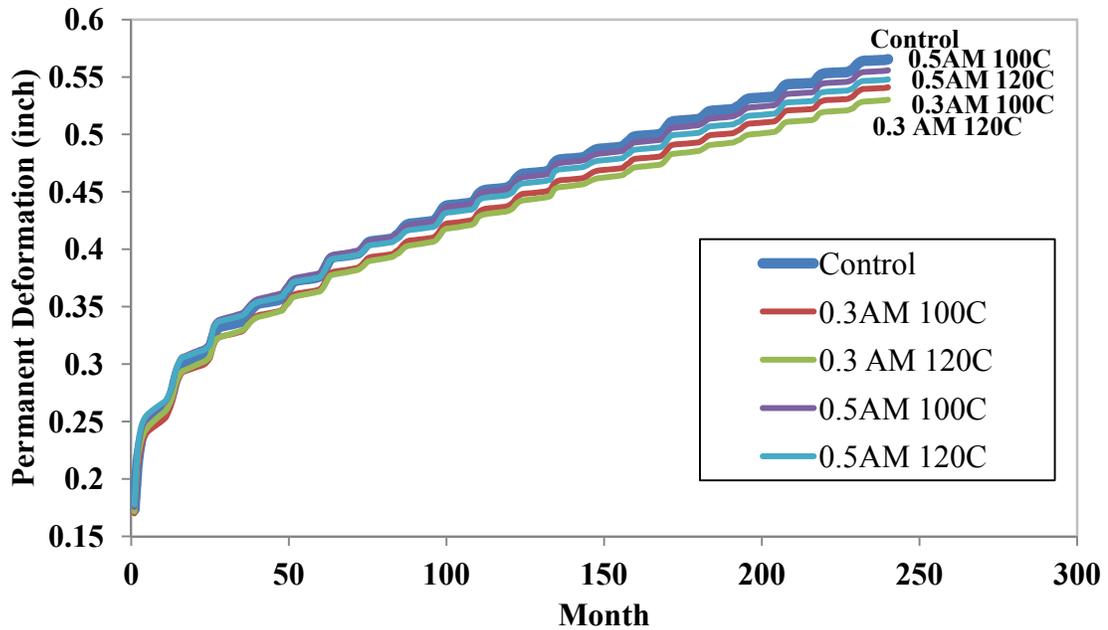


Figure 17 Predicted rutting depth over 20 years using MEPDG analysis

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 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 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 terms of 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.

Case Study 2: WMA using ADVERA® WMA

ADVERA® WMA is similar to Aspha-min®, which is also an aluminosilicate or hydrated zeolite powder [62]. 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 temperature above 210°F. Figure 18 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 19 was recommended.



Figure 18 ADVERA® WMA

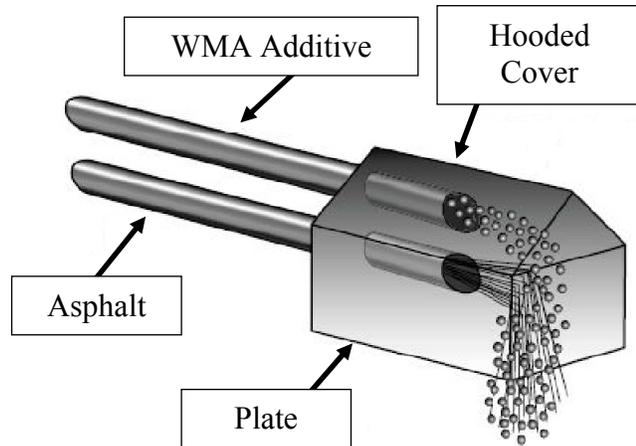


Figure 19 ADVERA® WMA Mixing Box (from PQ Corp)

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 [62]; 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 12.5mm and the designed traffic level is less than 3 million ESALs based on the current Superpave™ asphalt mixture design procedure [48-50]. 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 mixtures reached the compaction temperatures (153°C). The Superpave™ specification [48-50] 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.

For the 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.

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.

For DSR testing, temperature of 58C and frequency of 10 rad/s were used in this testing. Table 4 shows the testing results for DSR and the aging factor of WMA aged at different temperatures. Based on Table 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[11]. This finding from Table 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.

Table 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

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 [56, 57].

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 20. 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 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 [57]. 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).

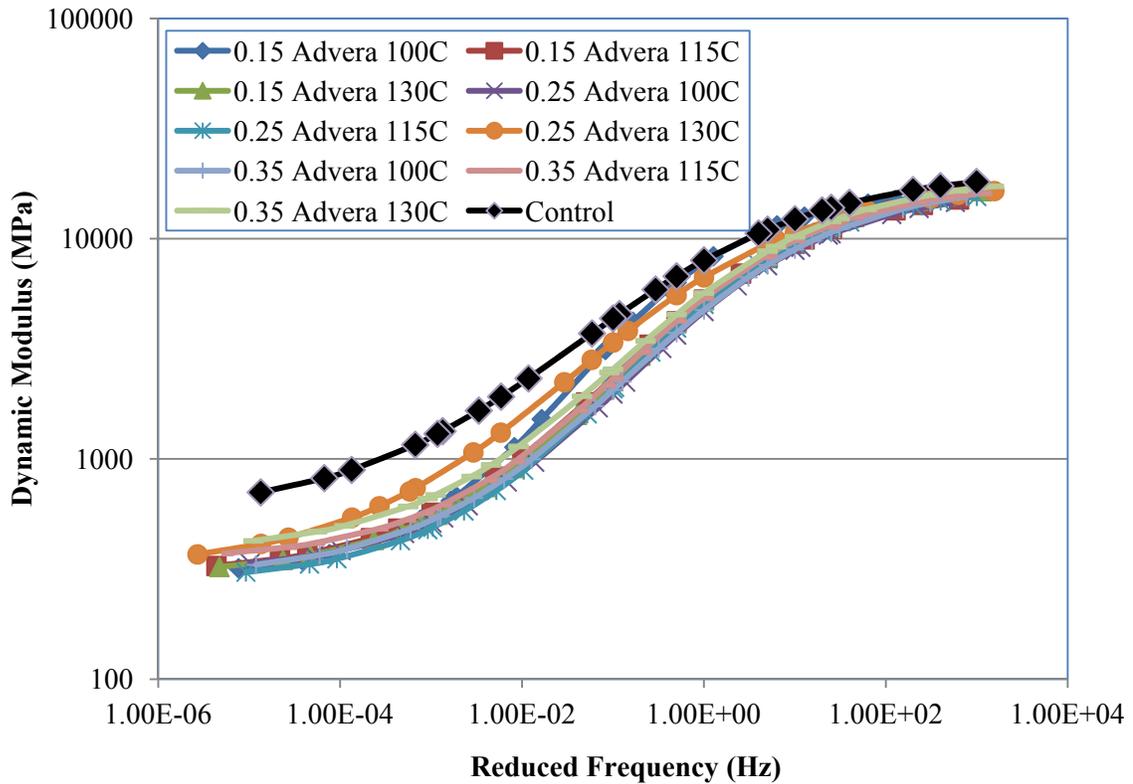


Figure 20 Sigmoidal Master Curve of Dynamic Modulus Test Results for Control HMA and WMA Mixtures

Table 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)

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 [63]. 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 [64]. 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 25°C and 0.085mm/s. Figure 21 shows the tensile strength testing setup, and Figure 22 shows a typical result from the indirect tensile strength test.

Figure 23 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 [65] 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 23, 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 21 Indirect Tensile Strength Testing Setup

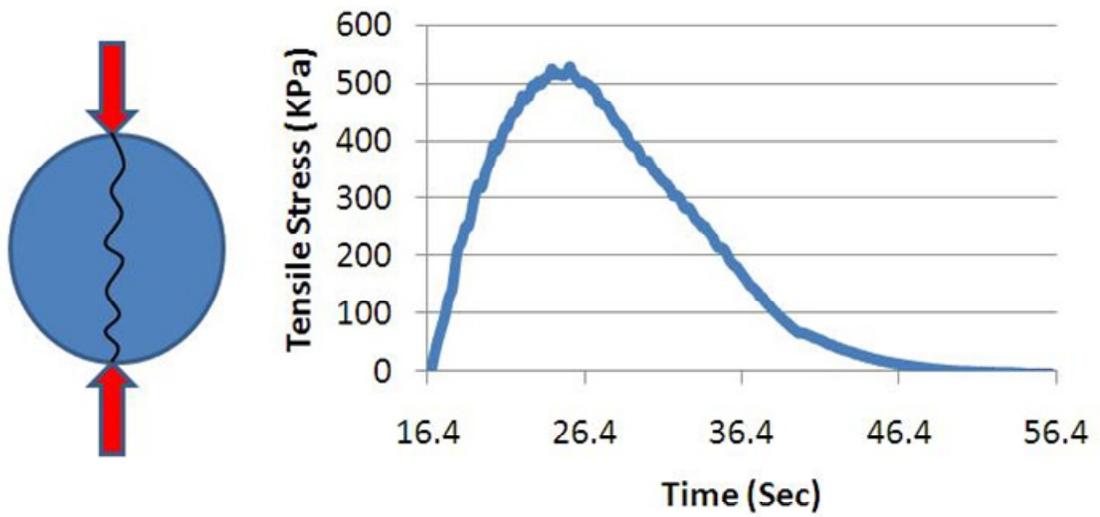


Figure 22 Typical Result for Indirect Tensile Strength

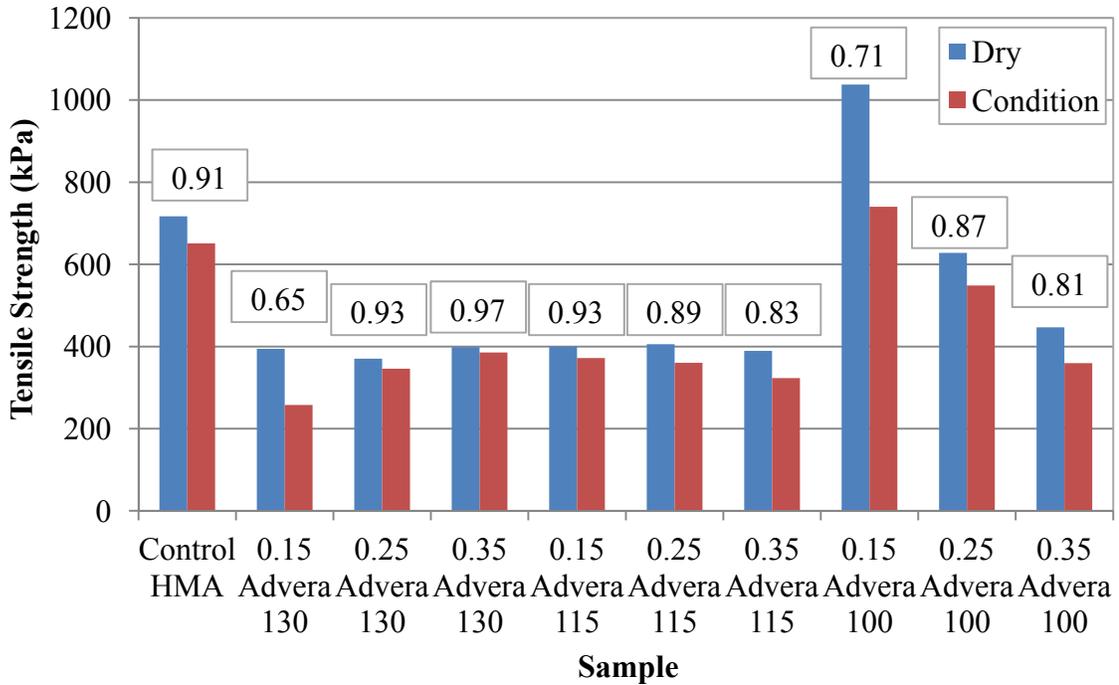


Figure 23 Tensile Strength Testing Results for Control HMA and WMA made with ADVERA® WMA

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 [66]. In this test, a frequency of 10 Hz and 400 micro-strain (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 24.

From Figure 24, 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 24.

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 [4] and; 2) aging of the asphalt binder – lower mixing temperature of WMA will reduce binder’s aging and thus improve workability of asphalt mixture.

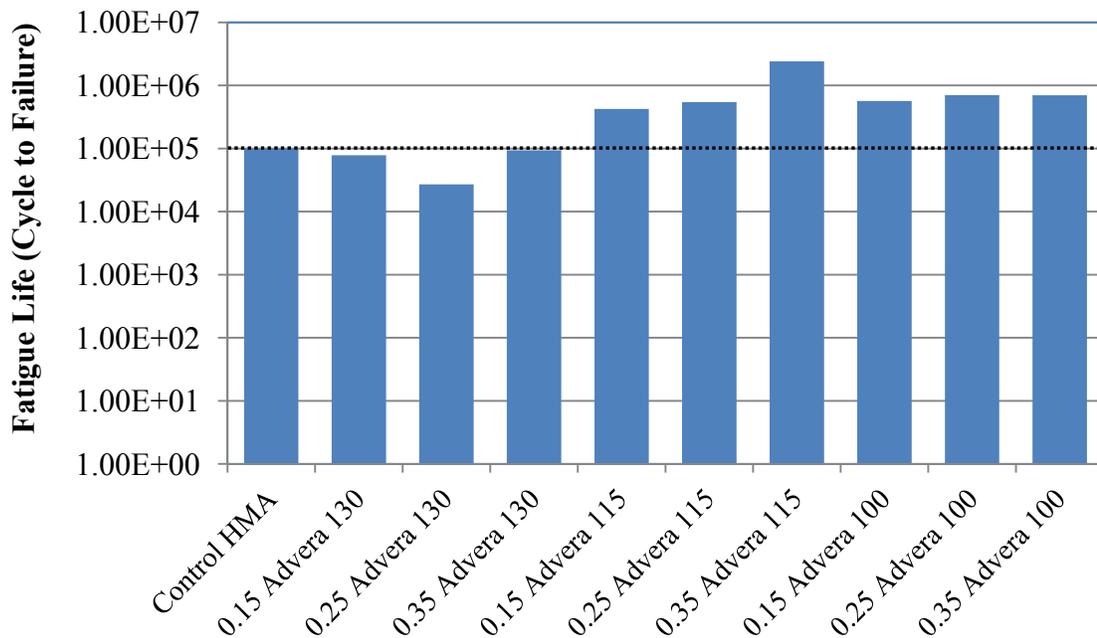


Figure 24 Results of Four Point Beam Fatigue Testing for Control HMA and WMA made with ADVERA® WMA

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 [67, 68]. During the mid-70s, Brown and Snaith [69] 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 [70] indicates that F_N is better when distinguishing the performance and quality of asphalt mixtures in terms of rutting distress

when compared with the $|E^*|$ [70, 71]. Faheem et. al. [72] 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 [72]. More recently, studies conducted by Witzak [73] and Dongre et al. [74] 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) [75, 76]. Additionally, an effective temperature of 45°C, often referred to as rutting temperature, is used in this test [77, 78].

There are three stages of flow that occurred during the test: primary, secondary and tertiary flow [77]. 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 [79]. Tertiary flow indicates that the specimen begins to deform significantly and the individual aggregates that makes up the skeleton of the mix moves past each other [80-82]. 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 [77] as shown in Figure 1(c). In addition, the flow number has been recommended as a rutting indicator for asphalt mixtures [67, 73, 79].

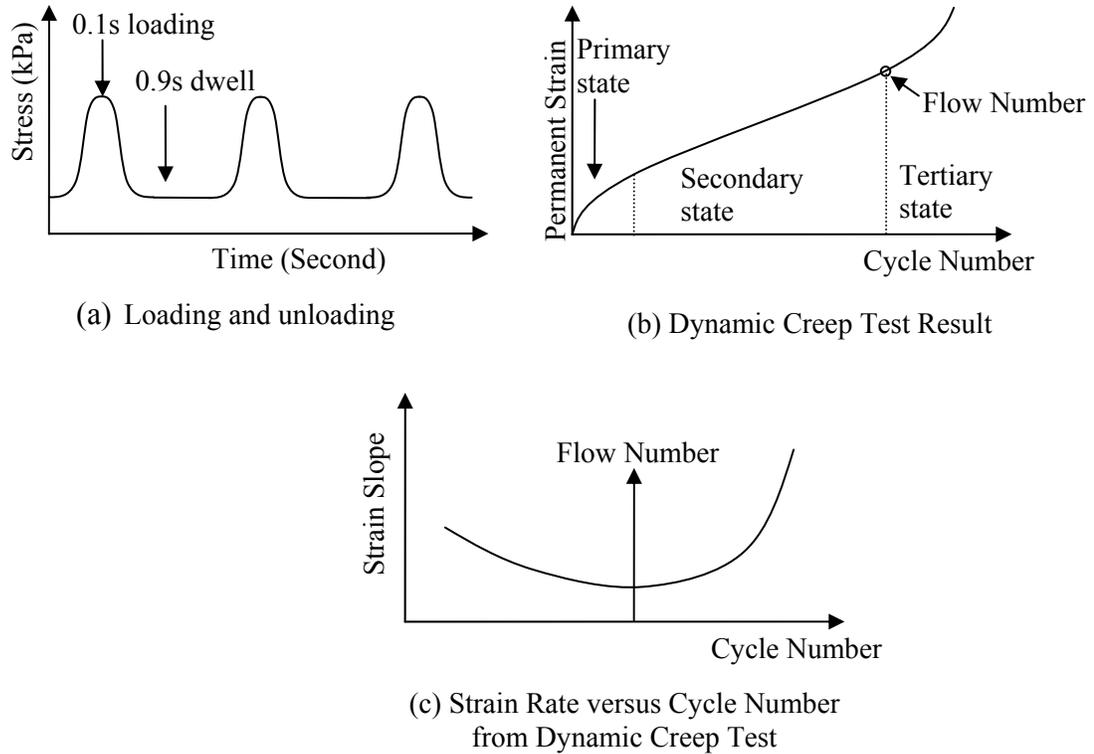
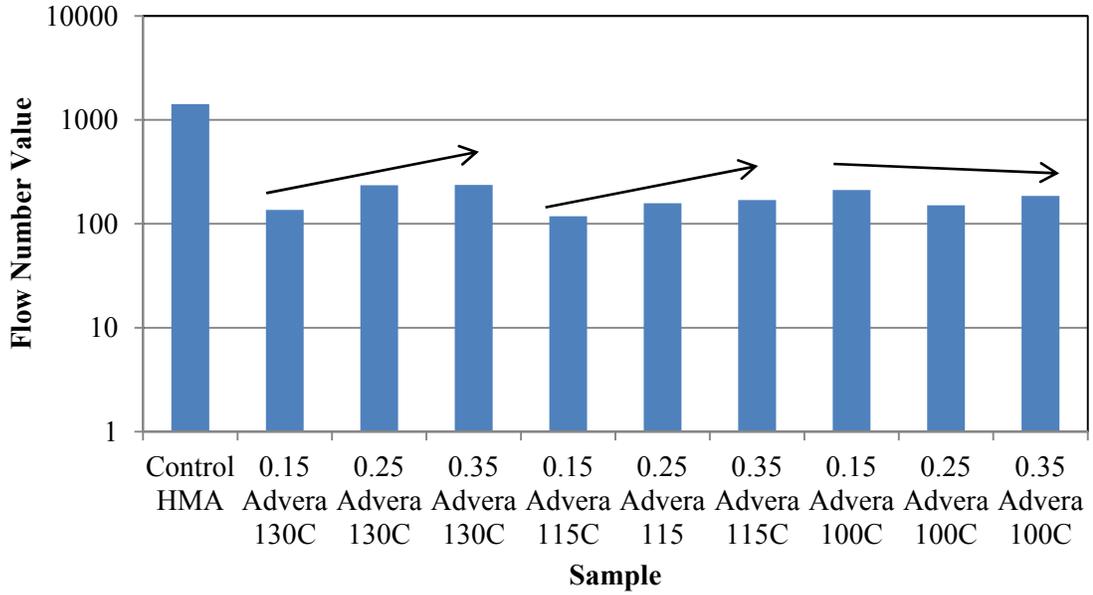


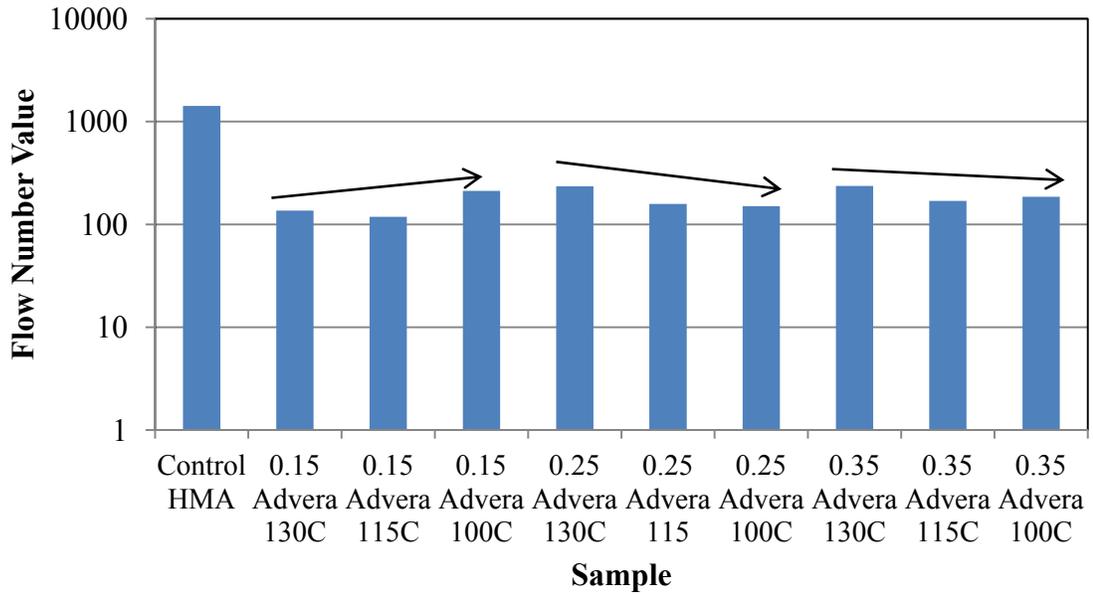
Figure 25 Flow Number Testing and the Flow Number Value

Figure 26 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 26 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.

From Figure 26, 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 26 Flow Number Test Results for Control HMA and WMA Made with ADVERA® WMA

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 27. Based on the results conducted, it was found that most of the WMA has higher rutting depth compared to the control HMA mixture. Figure 27 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 finding in this study is similar to $|E^*|$ and F_N testing where rutting potential for WMA is higher in general which is mainly due to aging.

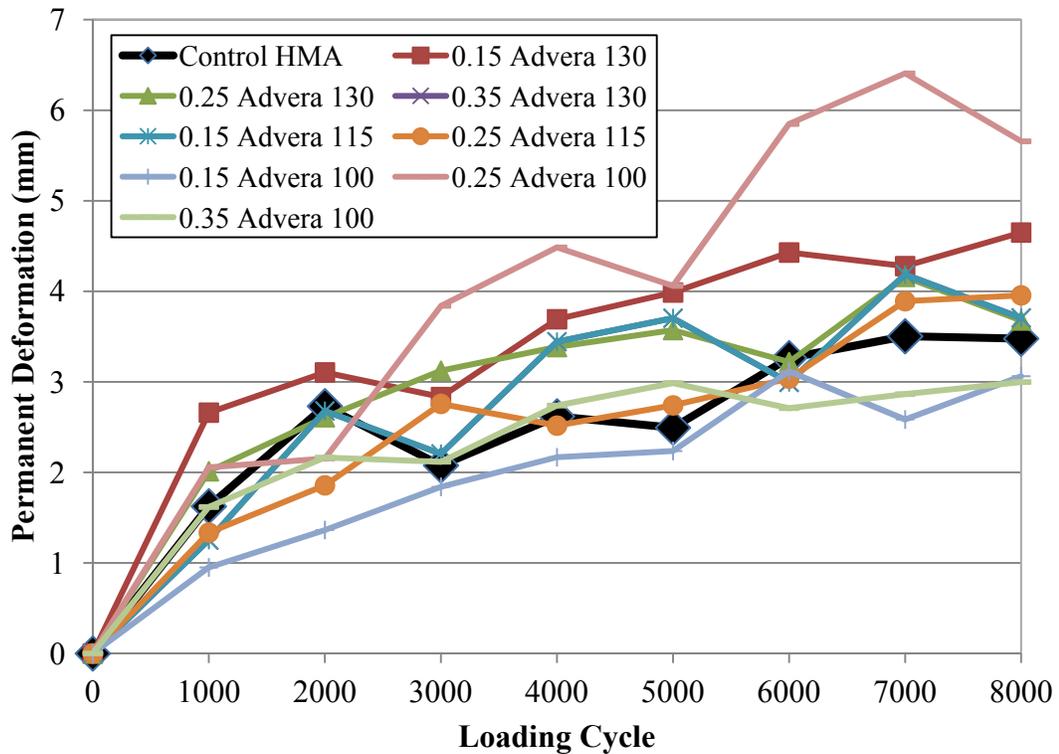


Figure 27 APA Rutting Test Results for Control HMA and WMA made with ADVERA® WMA

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. 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 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).
3. 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.
4. 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 affected by the amount ADVERA® added.
5. 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.

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 28 shows an example of foaming nozzle and Figure 29

shows the foaming device for laboratory scale produced by Wirtgen Inc. [83] . From Figure 29, it is observed that a typical foaming device consists of a heated asphalt binder, water tank, and pressure pump (foaming nozzle).

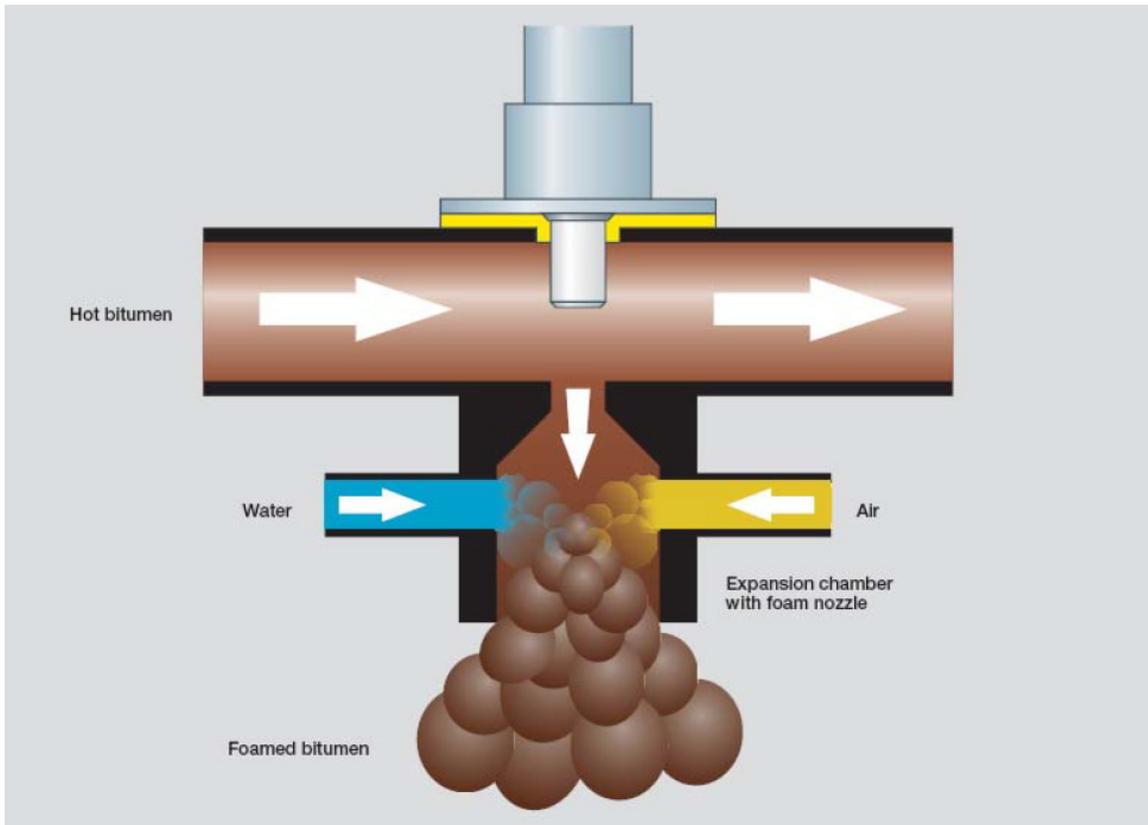


Figure 28 Wirtgen WLB 10 Foaming Nozzle



Figure 29 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 [84].

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 [84, 85]. In terms of asphalt binder type, researchers [86] 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 [85, 87, 88]. This can be easily achieved by conducting a series of foaming tests using different water content. Figure 30 shows an example of foaming properties of asphalt binder in terms of E_r and λ [85].

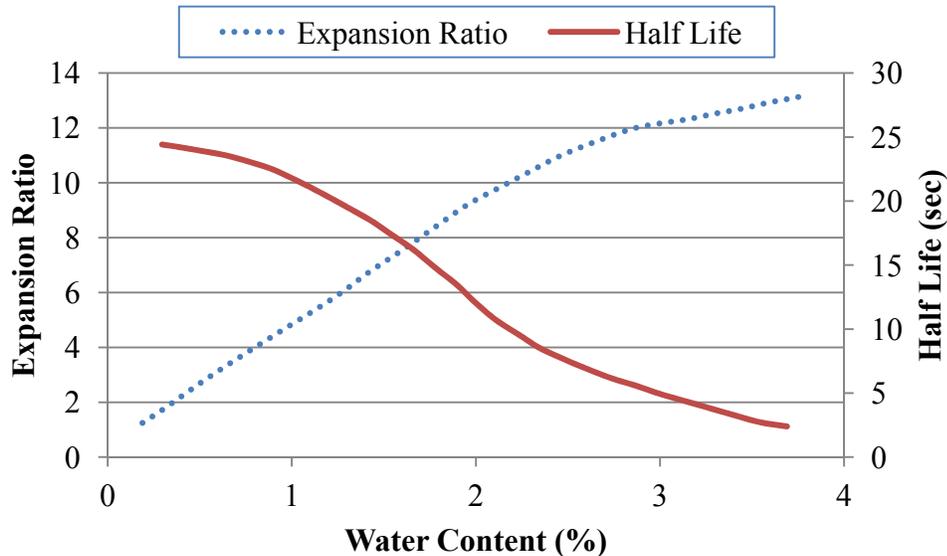


Figure 30 Example of Foaming Properties of Asphalt Binder

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 Table 4. 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.

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 SuperpaveTM 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 31 shows the procedure for producing the foamed asphalt binder.

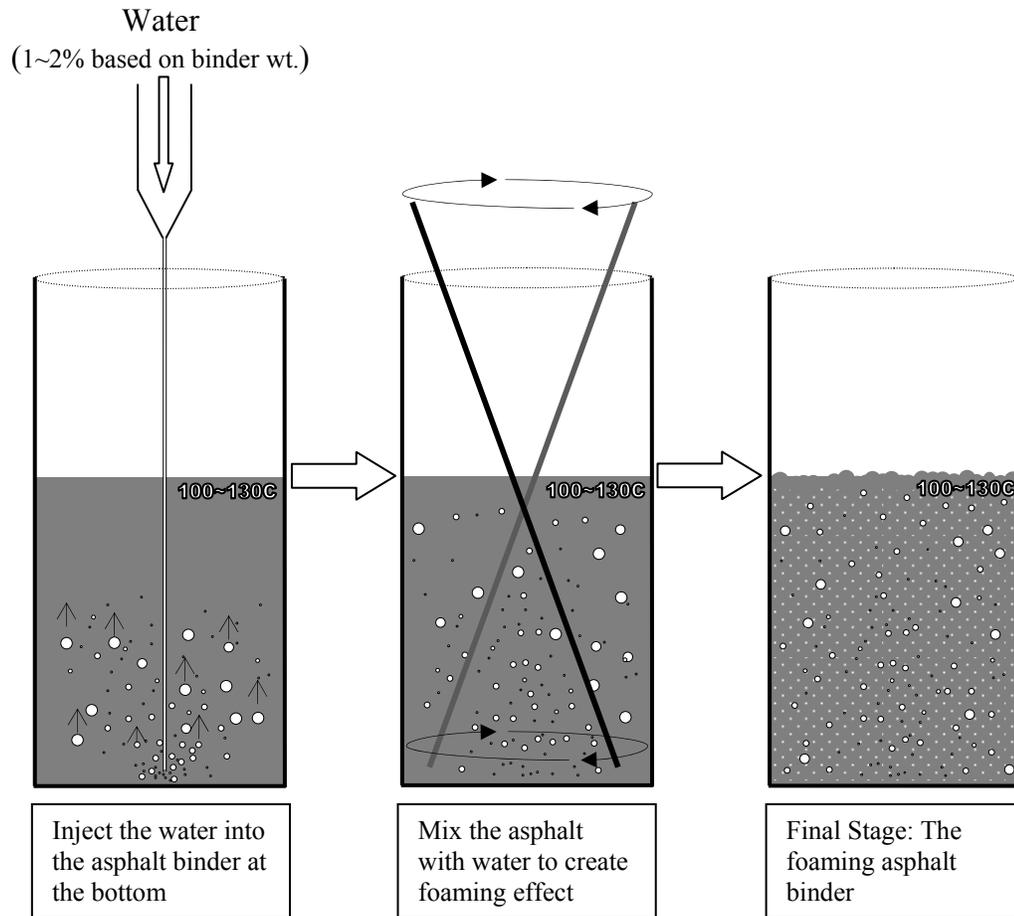


Figure 31 Procedure to Produce Foamed Asphalt Binder

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 SuperpaveTM gyratory compactor. Figure 32 shows the procedure of mixing and compaction of foamed WMA in this study; and Figure 33 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 SuperpaveTM 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%.

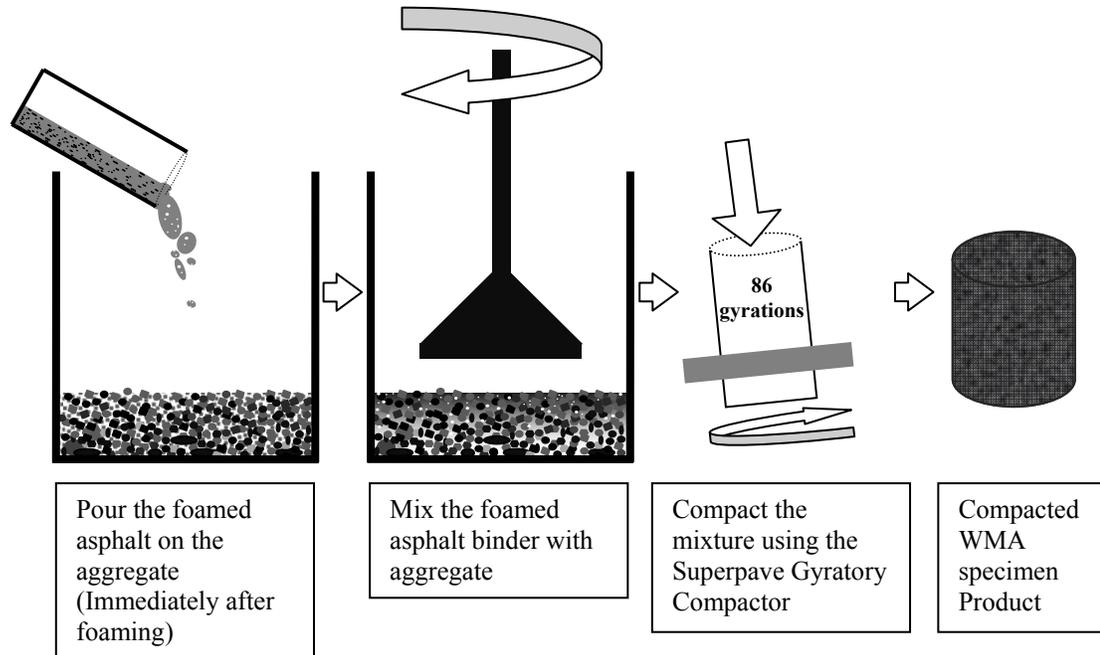


Figure 32 Mixing and Compacting the Foamed Asphalt with Aggregate



Figure 33 Warm Asphalt Mixture Produced using the Water Foaming Method

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™ 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 6.

Table 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

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 curves 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 34. 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).

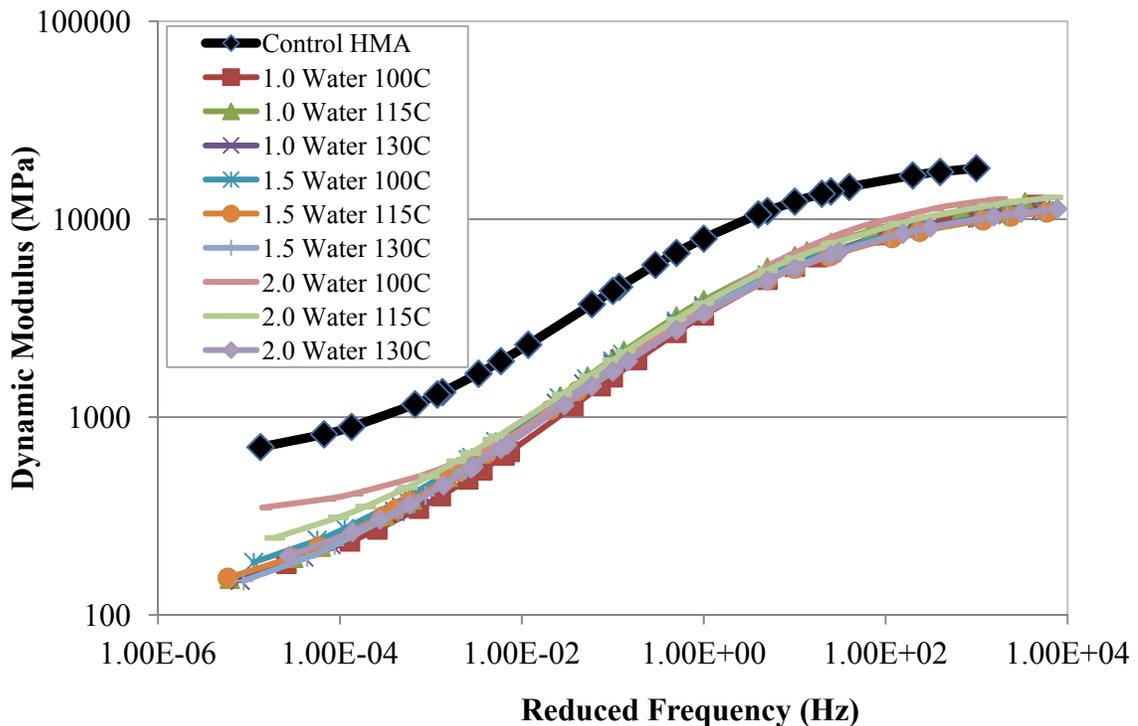


Figure 34 Dynamic Modulus Test Results for Control HMA and WMA produced using Water Foaming

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[63] 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 [64] 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 35 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.

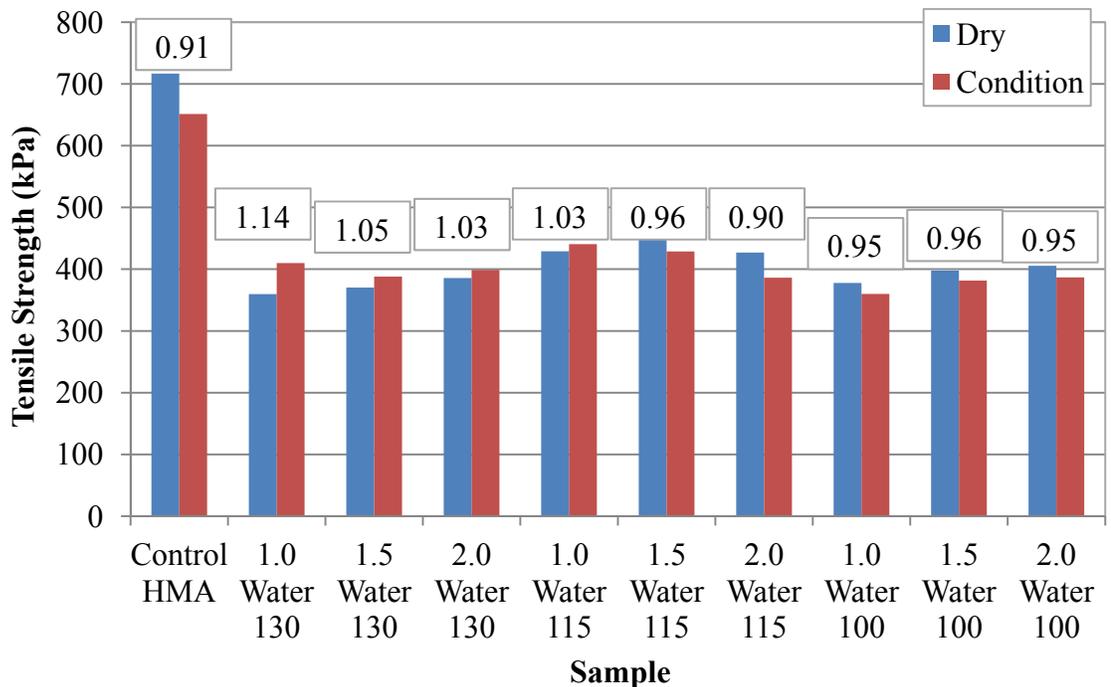


Figure 35 Comparison of Indirect Tensile Strength and TSR for the Control Mixture, and WMA using 1%, 1.5% and 2% Water at 100°C, 115°C and 130°C

In this study, the TSR testing results are shown in Figure 35 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. 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.

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 [66]. 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 36.

From Figure 36, 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 [4] and; 2) aging of the asphalt binder – lower mixing temperature of WMA will reduce binder's aging and thus improve workability of asphalt mixture.

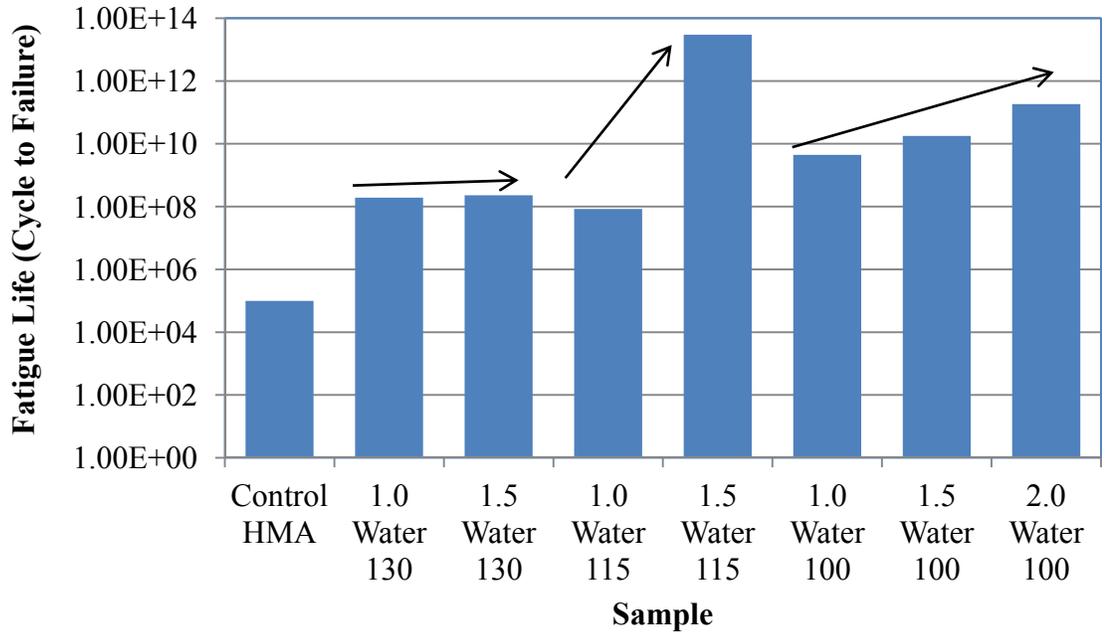


Figure 36 Comparing the Fatigue Life of Control HMA and Foamed WMA

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 [89]. The testing results for control HMA and foamed WMA are shown in Figure 37. Generally, Figure 37 shows that the F_N for all WMA samples are 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. From Figure 37, 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.

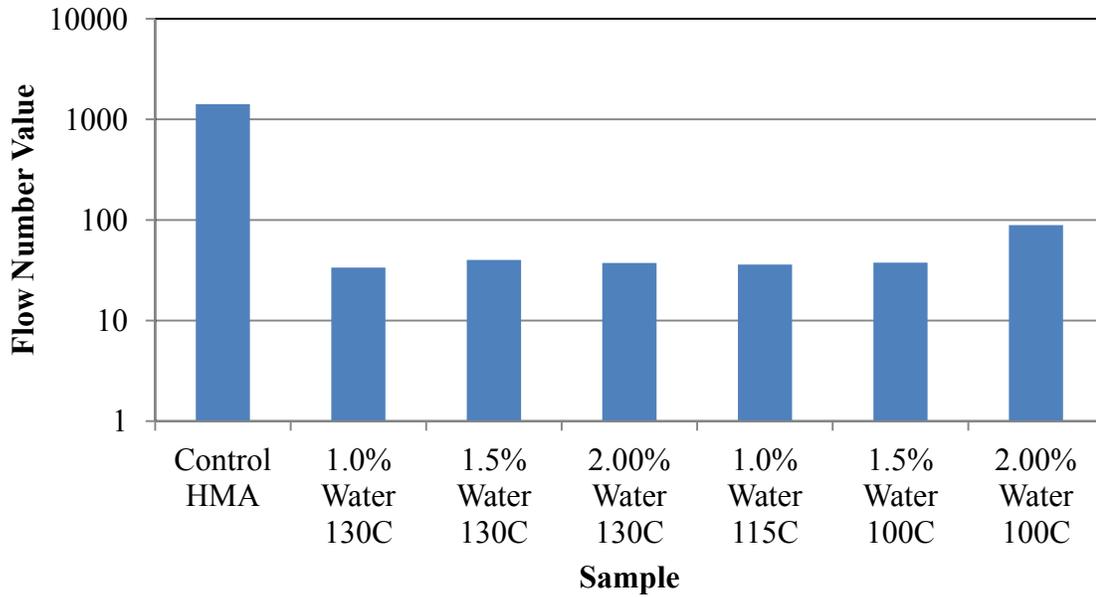


Figure 37 Flow Number Test Results for HMA control and Foamed WMA with Water

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 38. 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 38 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.

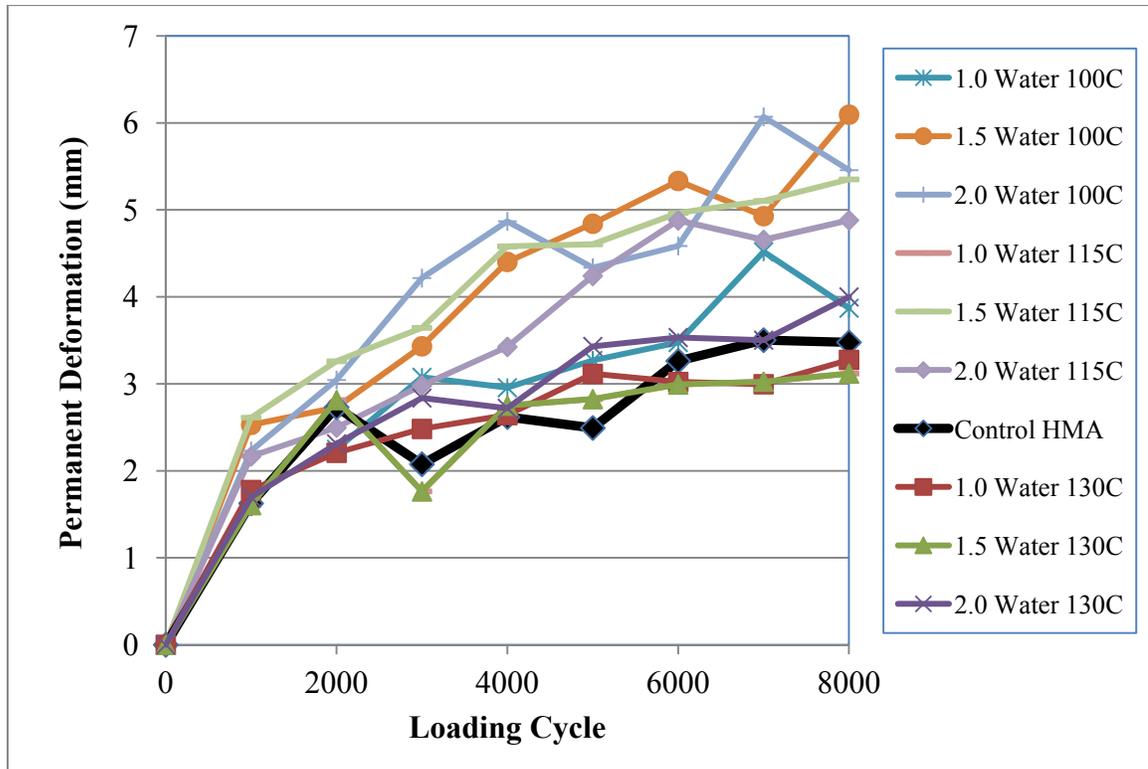


Figure 38 APA Rutting Results for HMA Control and Foamed WMA with Water

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.

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® [90] and Licomont BS-100[91].

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 39. 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 (H₂) under catalytic conditions producing a mixture of hydrocarbons having molecular chain lengths of carbon (C₅) to C₁₀₀ 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 C₄₅ to C₁₀₀ plus[92]. By comparison, macrocrystalline bituminous paraffin waxes have carbon chain lengths ranging from C₂₅ to C₅₀. 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.

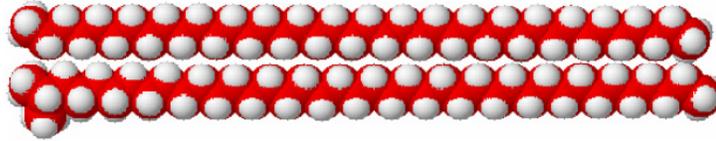


Figure 39 Chemical Structure Long Chain Aliphatic Polyethylene Hydrocarbon from Sasol Wax Americas[93]

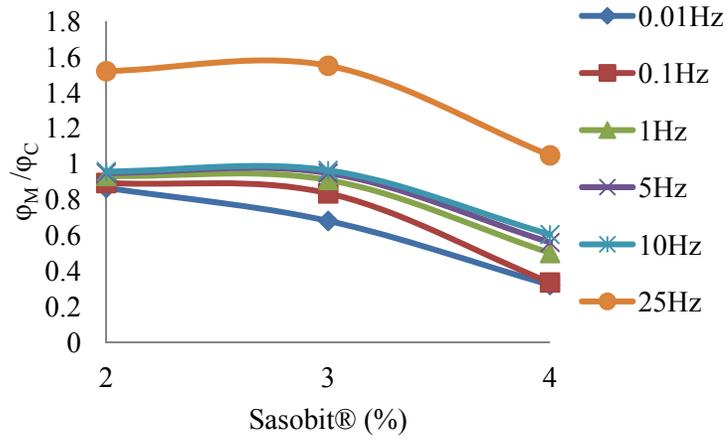
Asphalt Rheological Properties

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.

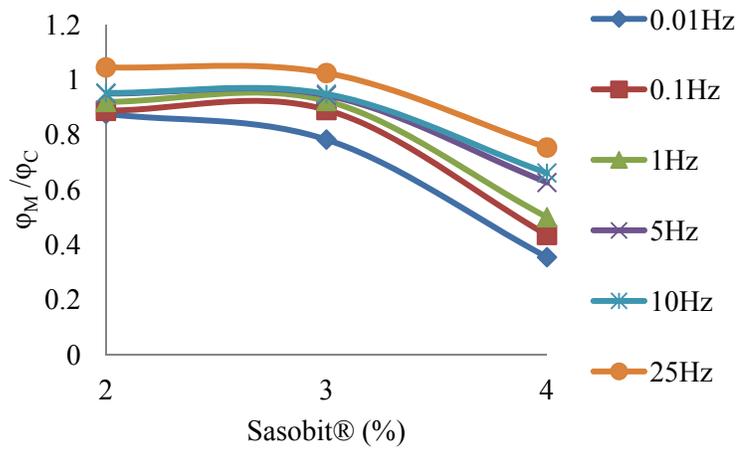
The results from the DSR for WMA and control binders were compared and shown in Figure 40 and Figure 41. Note ϕ_M and ϕ_C are phase angles of WMA and control binders, respectively; G_M and G_C are dynamic shear moduli for WMA and control binders, respectively. It was found that most of the ratios of 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 41, 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% 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.

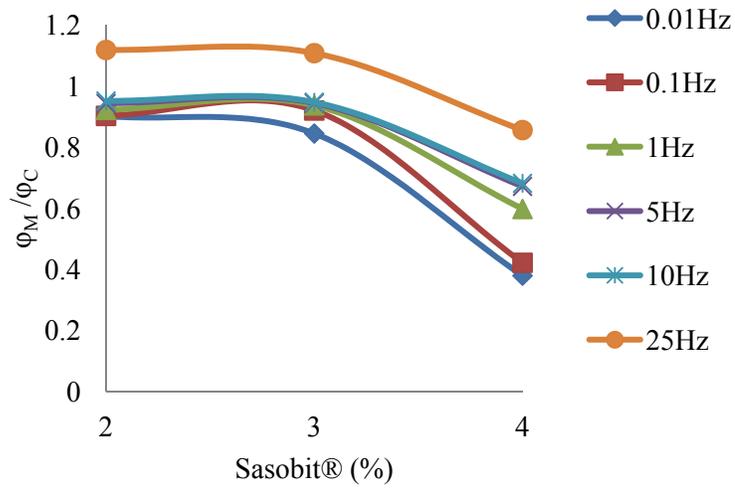
In general, the results indicated that when frequencies increase, dynamic shear modulus increase while phase angles decrease. It was observed that temperature affects the value of both the phase angle and dynamic shear modulus ratios.



(a) 46°C

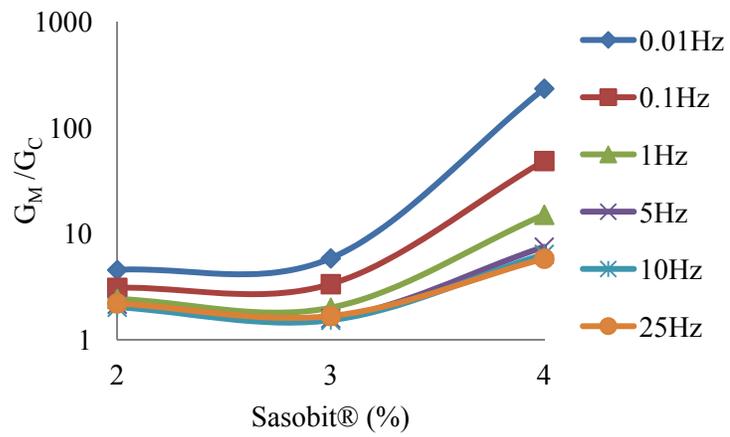


(b) 55°C

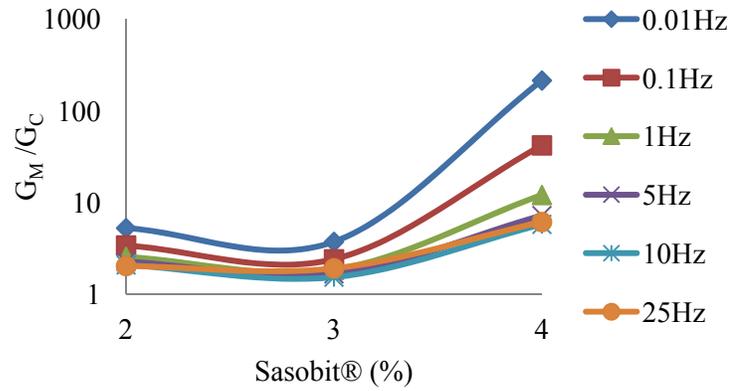


(c) 58°C

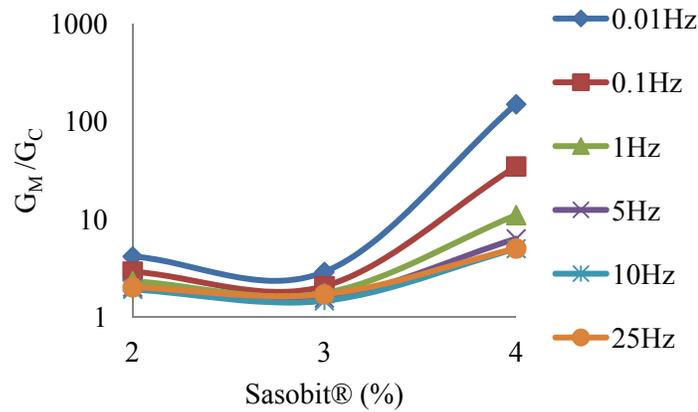
Figure 40 Ratios of Phase Angles for WMA and Control Binders over Different Percentages of Sasobit® Additive at (a) 46°C, (b) 55°C and (c) 58°C



(a) 46°C



(b) 55C



(c) 58C

Figure 41 Ratios of Dynamic Shear Modulus between modified and control binders over Different Percentages of Sasobit® Additive at (a) 46°C, (b) 55°C and (c) 58°C

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 $G^*/\sin(\delta)$ 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 7 shows $G^*/\sin(\delta)$ and aging factor of HMA and WMA aged at different temperatures. Based on Table 7, it shows the aging factors for Sasobit® aged at 130°C are higher than the control HMA. From Table 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 7 Aging Factor for HMA and WMA made with Sasobit®

Sample	$G^*/\sin(\delta)$		Aging Factor
	Unaged	12 hoursage	
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

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 42 shows the comparison of truck load out emissions between

HMA and WMA during the production. It was reported that a reduction of 14% in NO_x, 5% decrease in CO₂ and a slightly decrease in VOC when compared to HMA[94].



(a) Hot Mix Asphalt



(b) Warm Mix Asphalt

Figure 42 HMA versus WMA

The WMA was mixed and compacted at the temperature of 126.7°C. Table 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 gyrations 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 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%

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 9. The cool-down rate of HMA and WMA were then evaluated using MultiCool Program developed at the University of Minnesota [95]. It was assumed that the HMA was heated up to 18°C higher than its compaction temperature (i.e. 171°C) for cold weather paving. For WMA, it was assumed that the compacting temperature is similar to HMA, which is 171°C in order to compare the hauling and compacting time with HMA.

Table 9 Weather Condition at Iron Mountain on September 2007

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

Figure 43 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 °C

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.

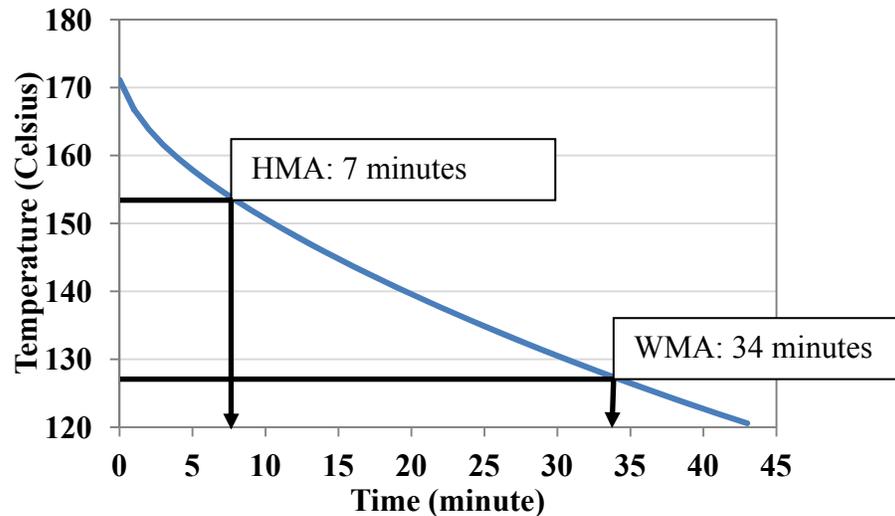


Figure 43 Mixture Cooling time calculated using MultiCool Program

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 44. 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.

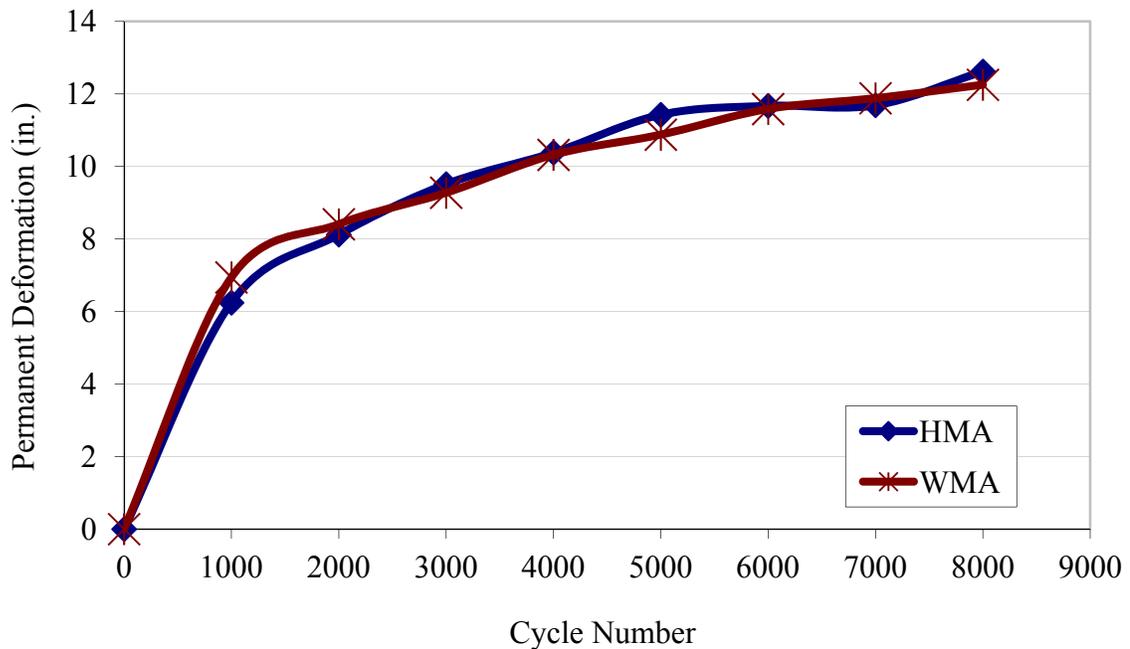


Figure 44 Comparison of APA Rutting for HMA and WMA collected from Field Trial

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 [48-50] 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. 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.

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 45. 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[89]. Thus, it can be concluded that WMA made with Sasobit® has similar rutting potential compared to the control HMA in this case.

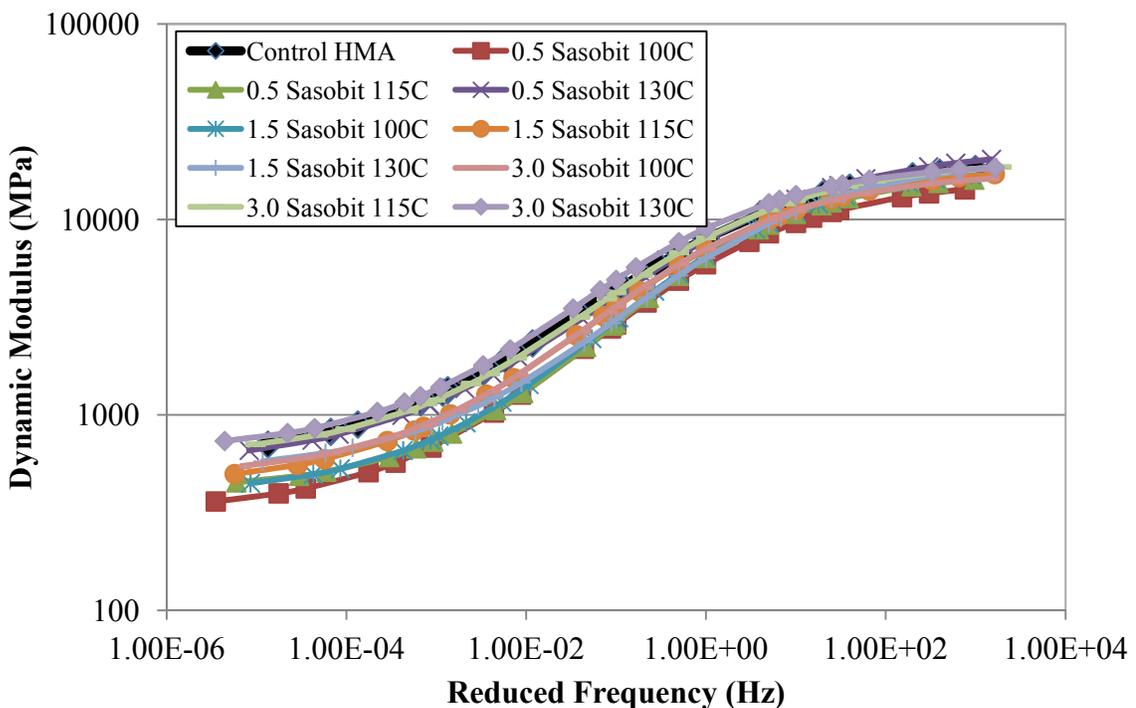


Figure 45 Dynamic Modulus Results for Control Mixture and WMA Mixture

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 [63]. 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 [64]. Samples were prepared at the size of 150mm in diameter and 95mm in height. The temperature and loading rate used in this study were 25°C and 0.085mm/s. Figure 46 shows the TSR testing results for control HMA and WMA mixtures made with Sasobit. The TSR result shows that 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. A lower tensile strength means that the fracture energy of WMA is lower than HMA. Wen and Kim [65] 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.

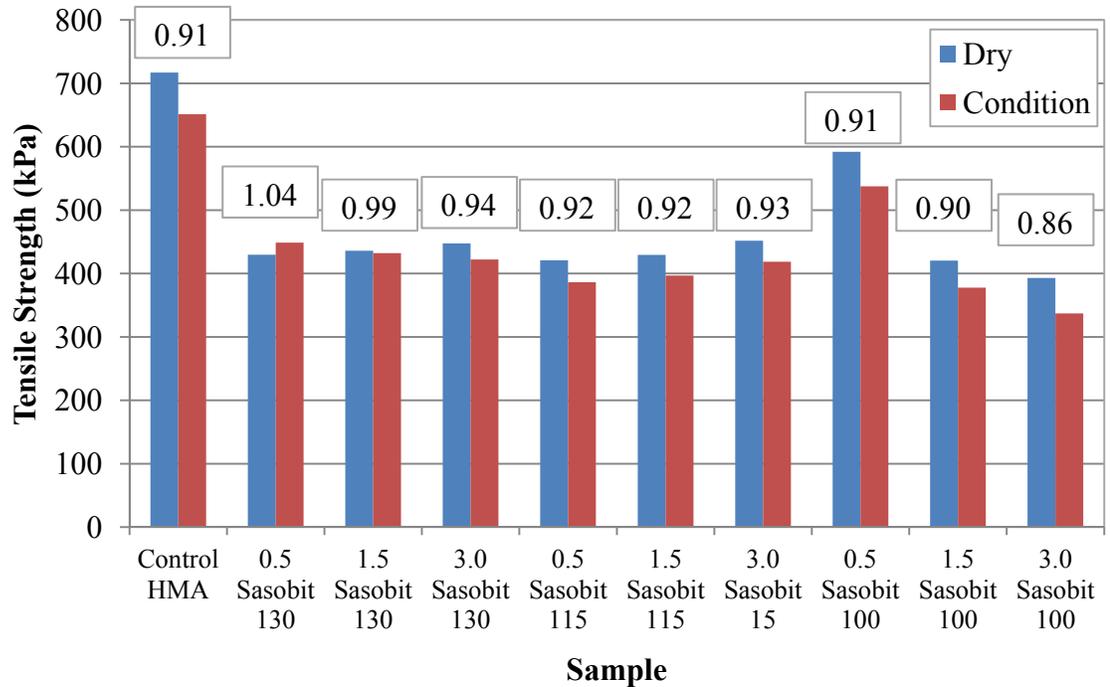


Figure 46 Tensile Strength Ratio Result for Control and WMA Mixtures

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 [66]. 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 47.

From Figure 47, 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.

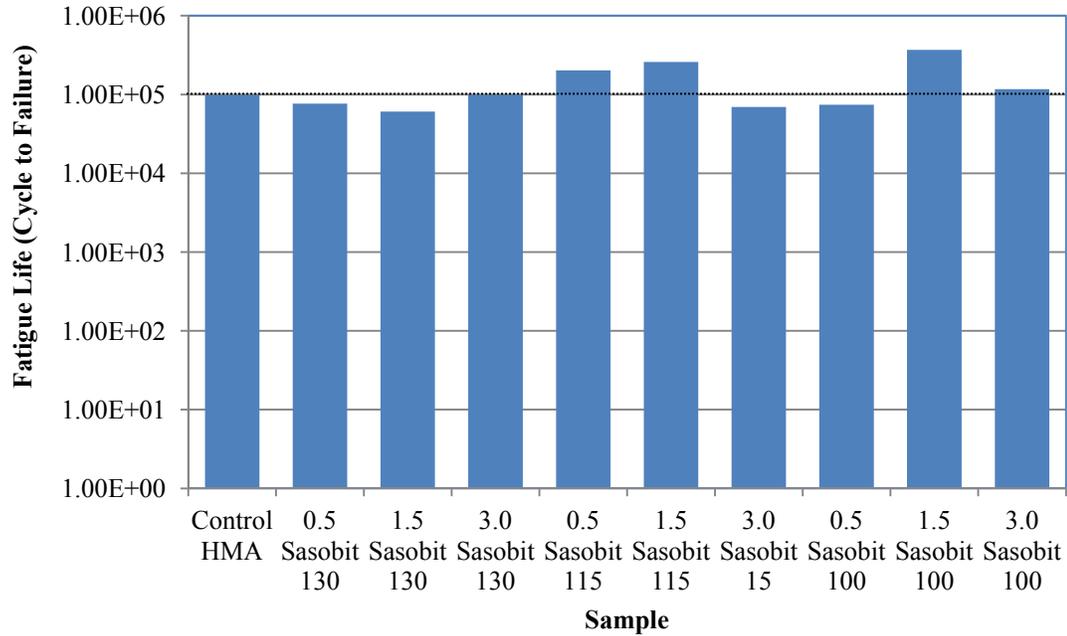
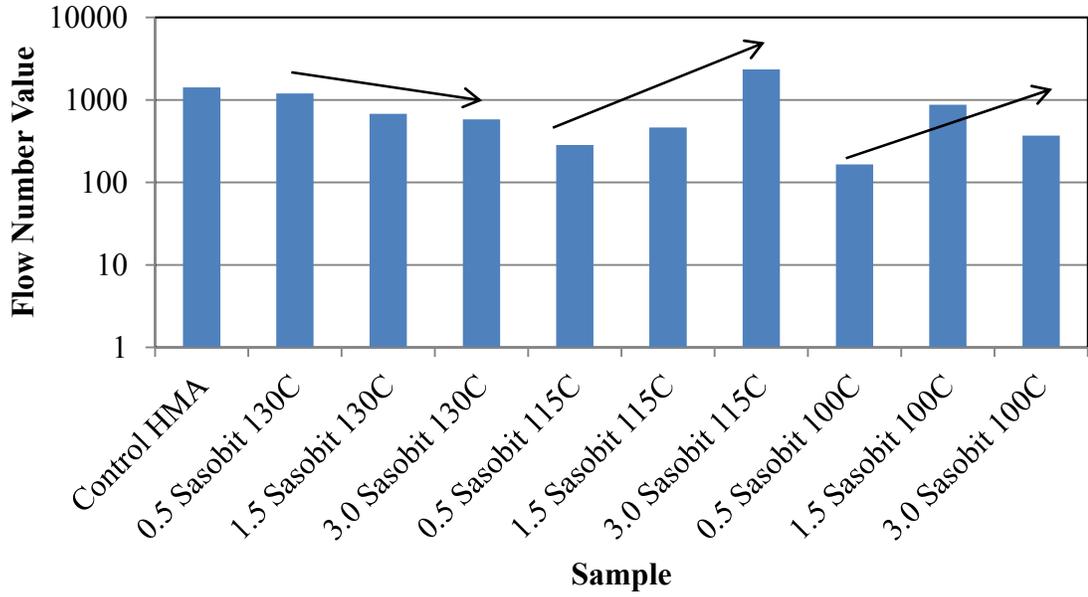


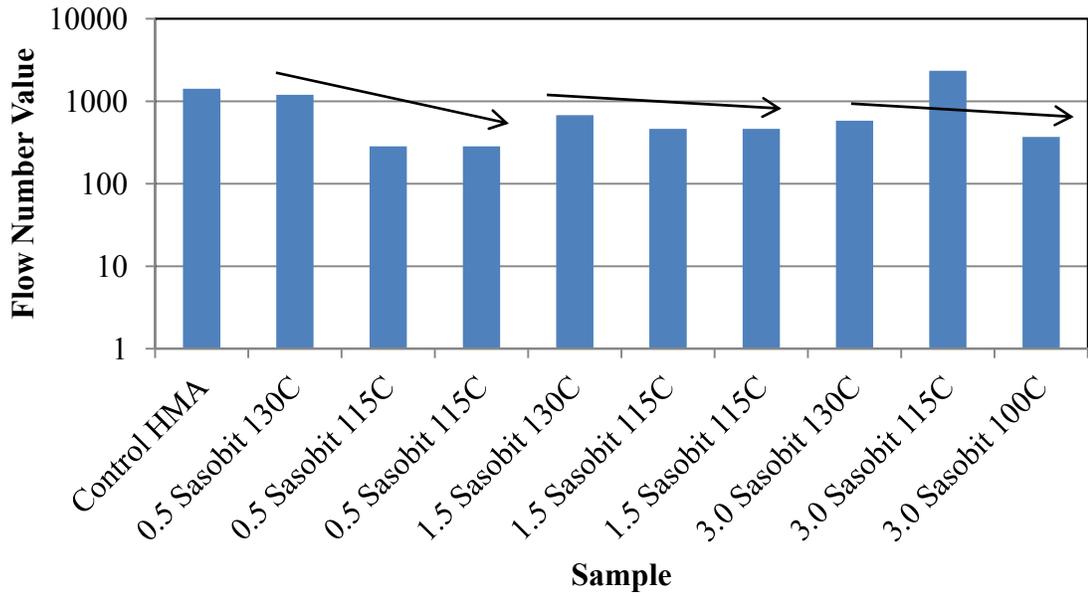
Figure 47 Four Point Beam Fatigue Testing Results for Control HMA and WMA made with Sasobit®

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 [89]. The testing results for control HMA and foamed WMA are shown in Figure 48. Generally, Figure 48 shows 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 48, it is also observed that the F_N increase when more Sasobit® was added and/ or the production temperature was increased.



(a)



(b)

Figure 48 Flow Number Results for HMA Control and WMA made with Sasobit®

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 49. 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.

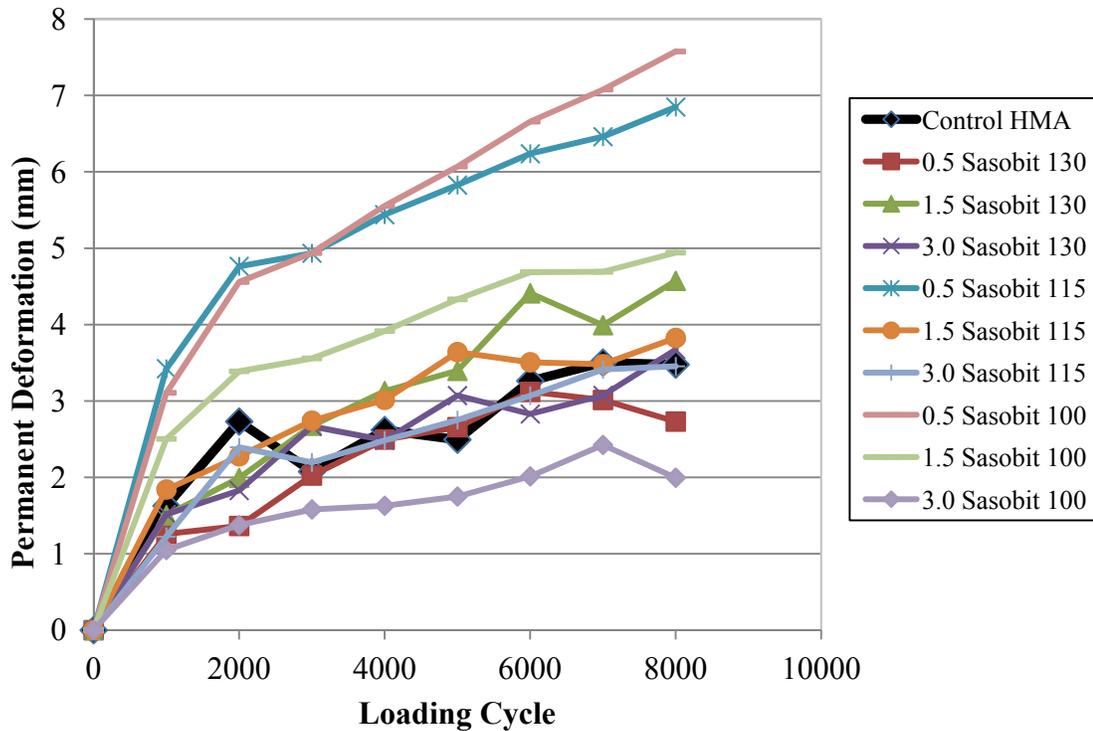


Figure 49 APA Rutting Results for Control HMA and WMA made with Sasobit®

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. And both mixtures were produced 18°C higher than the conventional temperature (171°C 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 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®.
2. 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.
3. 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.
4. 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.

5. 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.
6. 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.

WMA Using Chemical Package

The chemical package often includes anti-stripping agents and does not change asphalt viscosity [24, 96]. The chemical additive that used surfactant acted as “lubricant” and work at the microscopic interface of aggregate and the asphalt [12]. 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® [97], Evotherm [98] and Rediset™ WMX [99].

Case Study: WMA Using Cecabase RT®

Cecabase RT® is a patented chemical package developed by CECA, a division of Arkema Group [13, 97]. It was made up by 50% of renewable raw materials that produce increased workability to the asphalt mixture a lower temperature [97]. The Cecabase RT® is available in liquid form and can be injected directly into the asphalt. Figure 50 shows the Cecabase RT® used in this study.



Figure 50 Cecabase RT®

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 [48-50] 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. 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.

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 10 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 10 shows that all the binders meet the Superpave™ specification requirement (i.e., minimum 1.00KPa).

Table 10 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

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 [56, 57].

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 51.

Figure 51 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[57]. The $|E^*|$ test results indicate that the WMA made with Cecabase RT® has higher rutting potential compared to HMA (i.e. control mixture).

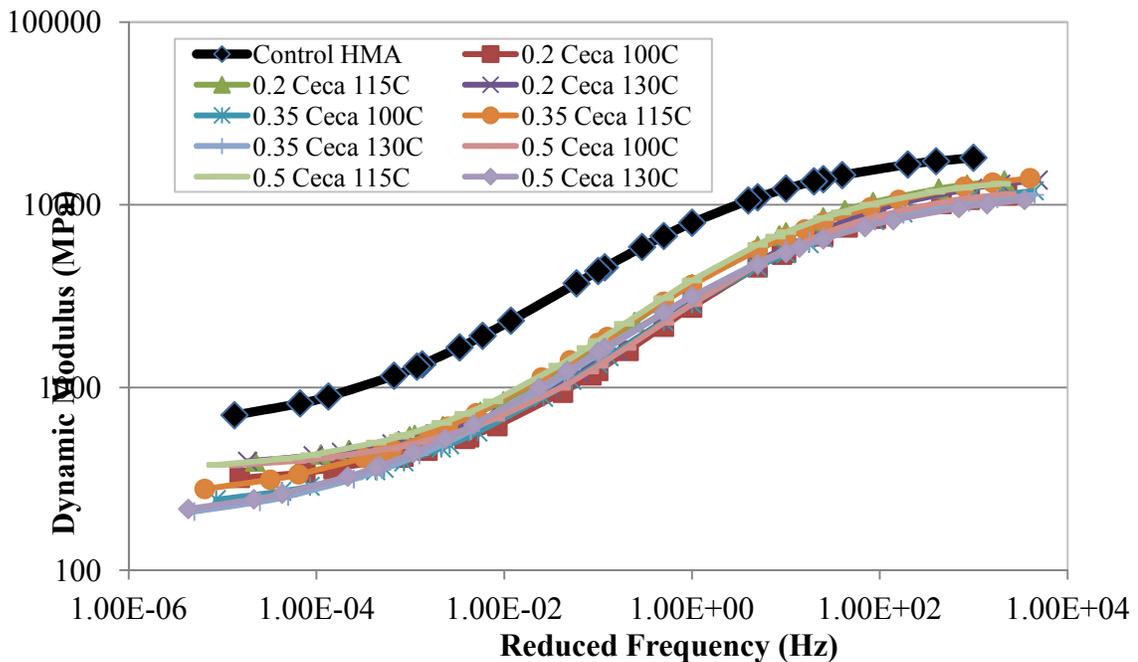


Figure 51 Master Curve of Dynamic Modulus of Control HMA and WMA made with Cecabase RT®

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 [64]. 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 [63], 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 25°C and 0.085mm/s.

Figure 52 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). However, 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.

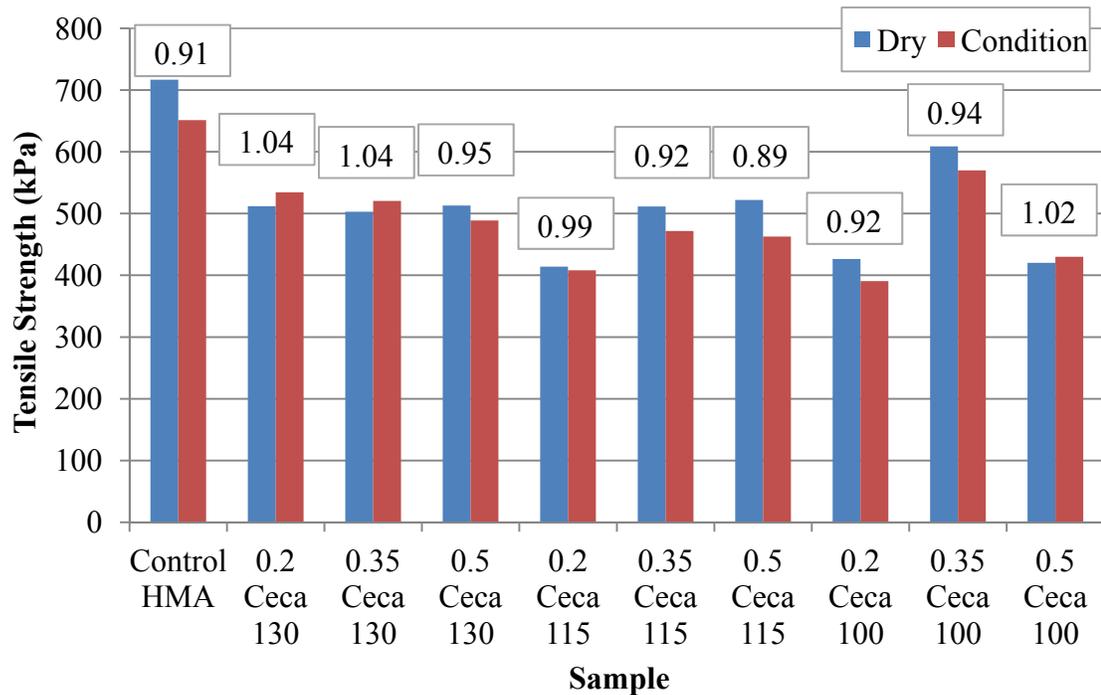


Figure 52 TSR Results of Control HMA and WMA made with Cecabase RT®

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 [66]. A frequency of 10 Hz and 400 micro-strain (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 53. 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.

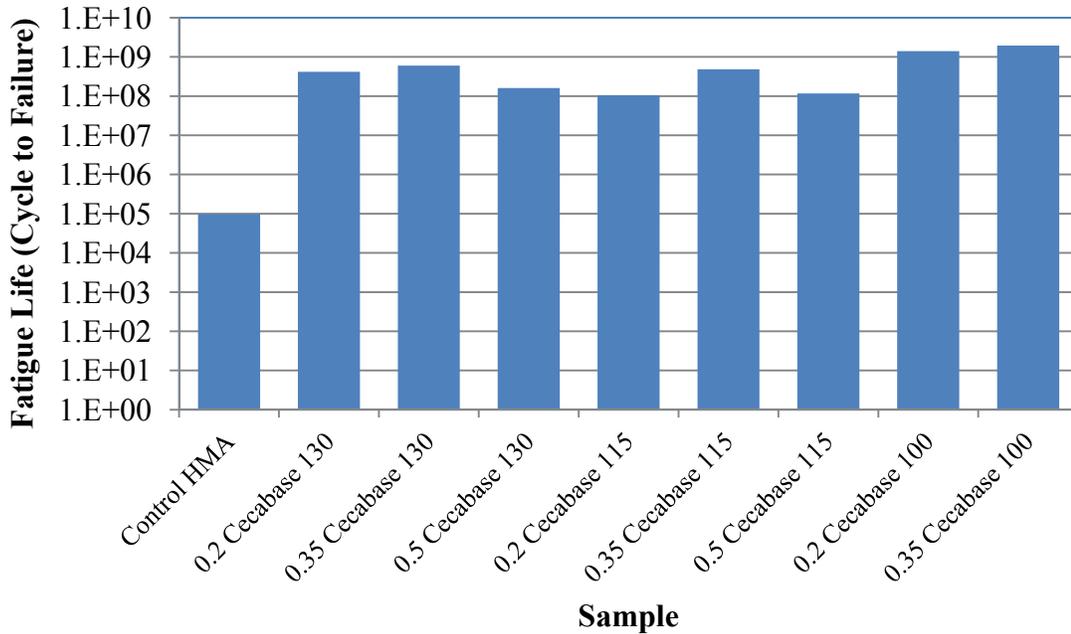


Figure 53 Four Point Beam Fatigue Test Results for Control HMA and WMA made with Cecabase RT®

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 [77, 78]. Figure 54 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 54, the test results show that the F_N for WMA made with Cecabase® 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.

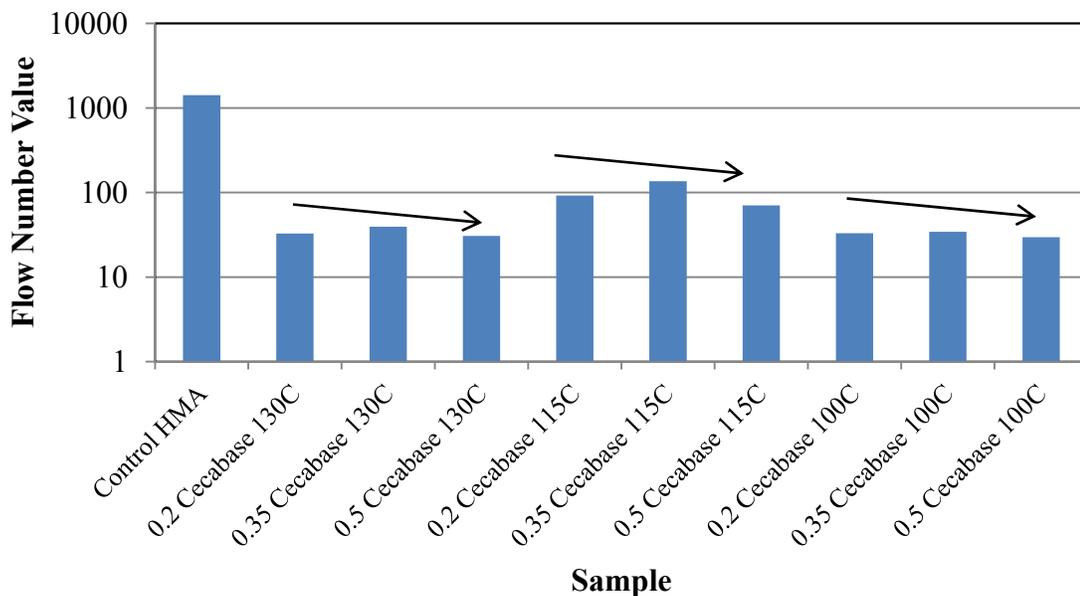


Figure 54 Flow Number of Control HMA and WMA made with Cecabase RT®

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 54. Based on the results conducted, it was found most of the WMA has higher rutting depth compared to the control mixture. Figure 54 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 54,

it is also found that WMA made with 0.2% Cecabase RT® 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 RT® is added and lower mix/ compact temperatures were used.

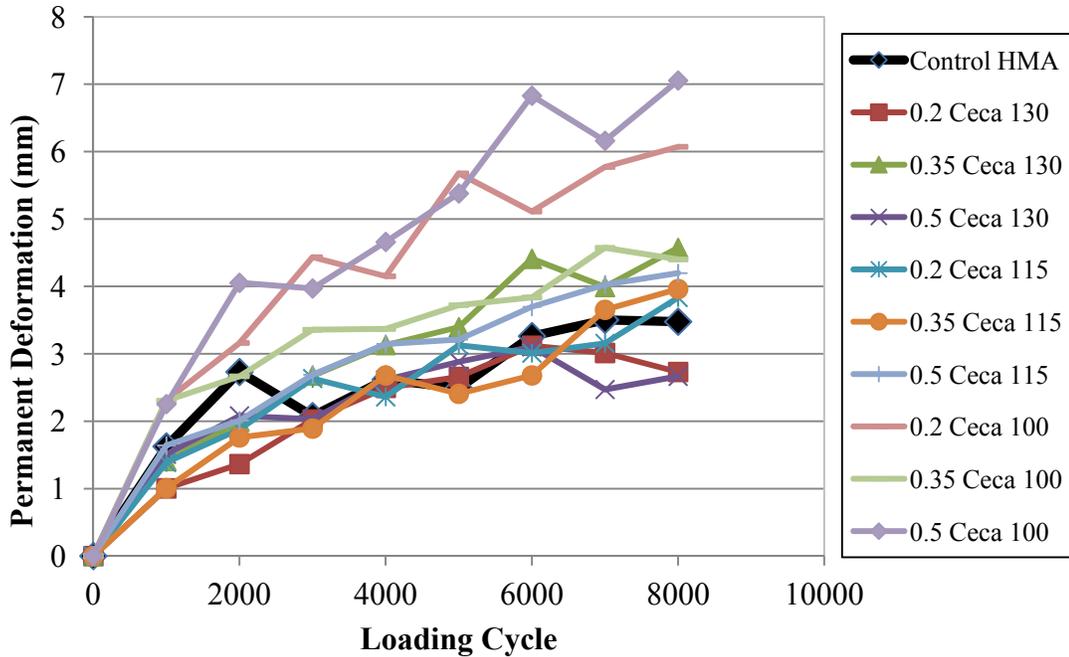


Figure 55 APA Rutting Results for Control HMA and WMA made with Cecabase RT®

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.

WMA Design Framework

To date, contractors and state agencies have introduced the WMA technologies into existing mix designs, including Ohio [29], Iowa [100], Minneapolis [101], Virginia [102], etc. In addition, numerous laboratory studies were also conducted throughout the United States to assess the rutting, fatigue and moisture susceptibility of WMA [5, 103-105]. For instance, National Center for Asphalt Technology (NCAT) has conducted an extensive study on WMA using several kinds of technologies [10, 15, 24]. Although various studies have been conducted on WMA, there are still many uncertainties when using WMA in an existing mixture design. In this report, 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 assess 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 11. From Table 11, 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.

Table 11 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	<u>Similar or Higher E* </u> Comparable or better rutting resistant	-	<u>Lower Rutting</u> Rutting decrease when mix/ compact temp. increase	-	-
	Advera® WMA	No Change	Lower	<u>Lower E* </u> 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	<u>Lower E* </u> Increase rutting potential	Lower F _N	Higher Rutting	Higher Fatigue Life	<u>Higher TSR</u> TSR increase when mix/ compact temp. increase
Organic Additive	Sasobit®	Increase	<u>Lower</u> 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	<u>No Significant Different</u> Lower tensile Strength was found
Chemical Package	Cecabase RT®	No Change	Lower	<u>Lower E* </u> Increase rutting potential	<u>Lower F_N</u> 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 = $[G^*/\sin(\delta)_{aged}]/[G^*/\sin(\delta)_{unaged}]$

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

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 12[106]. 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 12 Recommended Production Temperature below Which High Temperature Grade Should be Increase by One Grade [106]

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, °F												
52	<215	<215	<215	<215	<215	220	220	225	225	230	230	
58			220	225	230	265	235	240	240	245	245	
64		220	230	235	235	240	245	245	250	250	250	
67		220	230	235	240	245	250	255	255	255	260	260
70		220	230	240	245	245	250	255	255	260	260	260
76		225	235	245	255	255	260	260	265	265	265	270

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[107].

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.

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 [108] 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

$Gmb_{theoretical}$: 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

$Gmb_{theoretical-i}$: 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:

$$N_D = \text{minimum}(|AV_i - AV_{desired}|)$$

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

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.

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 [89]. Additionally, F_N was used in the past study to develop the specification of SuperpaveTM Simple Performance Test, currently referred to as Asphalt Mixture Performance Test (AMPT), in the state of Michigan [109]. 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 13 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 13 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

WMA Construction and Maintenance

Construction and maintenance of WMA could be critical because a different setting was used to produce WMA compared to traditional Hot Mix Asphalt (HMA) production. Newcomb [110] indicated that new guidelines are needed for proper Quality Control/Quality Assurance (QC/QA) of WMA especially for an asphalt plant with high production rates. Several concerns of WMA production and placement arose recently due to the low production temperature. These concerns are [25, 111] as discussed in the following paragraphs:

1. Moisture content in Aggregate and RAP stockpile
2. Complete fuel combustion of burner
3. Balance between aggregate drying and maintaining adequate bag house temperature
4. Mixture placement

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 [3]. 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 [112]; 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 [25]. 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 [25]. 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.

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 [113]. 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 [113]. Prowell and Hurley [25] 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 [25].

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 [114]. 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 [25]

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 [25].

Mixture Placement

Since the compaction temperature for WMA is lower, the placement of WMA to the pavement could be different compare to HMA. However, experiences from United States and European countries show that the placement of WMA is business as usual [3, 16, 25, 35, 115]. For compaction, several field demonstrations show that WMA is similar or even better than HMA mixtures [22, 24, 35, 102]. Prowell and Hurley indicated that the WMA required a greater compaction effort if the production temperature was pushed to its lower extreme [25]. In this case, the compaction should be monitored using nondestructive device or calibrated cores for QC/QA.

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 [27, 28]. The main objectives of this study are:

- 1) Review and synthesize information on the available WMA technologies
- 2) Measure the complex/dynamic modulus of WMA and the control mixtures (HMA) for comparison purpose and for use in mechanistic-empirical (ME) design comparison
- 3) Assess the rutting and fatigue potential of WMA mixtures
- 4) Provide recommendation for the proper WMA for use in Michigan considering the aggregate, binder, and climatic factors.

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 assess 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 11.

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 around the state of Michigan. 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. Besides, the construction and maintenance of WMA were also discussed in this study to provide further information and/ or guideline for contractors and state agencies to be used in quality control and maintenance of WMA.

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Appendices

Appendix 1: HMA and WMA Mixture Gradation Design

Table 14 Gradation of HMA and WMA used in this Project

Sieve Size (No.)	Sieve Size (mm)	Percent Passing	Retained
1/2 inch	12.500	100.00%	0.00%
3/8 inch	9.500	99.10%	0.90%
No. 4	4.750	75.00%	24.10%
No. 8	2.360	55.90%	19.10%
No. 16	1.180	41.30%	14.60%
No. 30	0.600	27.50%	13.80%
No. 50	0.300	14.50%	13.00%
No. 100	0.150	7.50%	7.00%
No. 200	0.075	5.50%	2.00%
Pan	0.000	0.00%	5.50%

Appendix 2: Volumetric Properties

Table 15 Volumetric Properties of HMA and WMA used in this Project

Mixture Type	Average G_{mm}	Average G_{mb}	Average Air Void	VMA	Compaction Energy
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
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
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

Appendix 3: Dynamic Modulus Testing Results

Table 16 Average Dynamic Modulus for HMA and WMA

	Temp.:	-10						4						21.3						39.2						
		Freq.:	25	10	5	1	0.5	0.1	25	10	5	1	0.5	0.1	25	10	5	1	0.5	0.1	25	10	5	1	0.5	0.1
	Control 165C	20601	19177	18054	15397	14208	11811	12258	10751	9586	7144	5988	4192	5726	4705	3985	2659	2143	1405	1769	1385	1148	770	698	555	
Advera	0.15	Advera 100C	16570	15011	13796	11099	9803	7350	16178	14052	12210	8461	6675	4214	5131	3880	2990	1447	1080	603	785	599	466	314	323	293
		Advera 115C	17464	15750	14353	11148	9788	6946	10076	8589	7454	5142	4046	2551	3367	2428	1860	1044	830	568	634	497	400	301	312	296
		Advera 130C	18664	16792	15349	11946	10324	7387	11561	9784	8380	5591	4234	2586	2751	1999	1529	882	717	512	660	521	413	312	318	294
	0.25	Advera 100C	17126	15346	13978	10824	9327	6596	9303	7754	6589	4314	3265	1971	3392	2419	1819	1023	834	592	638	504	406	305	320	311
		Advera 115C	17459	15651	14291	11232	9804	7136	10596	9251	7977	5429	3966	2426	2883	2074	1575	873	682	461	688	524	404	294	295	276
		Advera 130C	18450	16883	15640	12772	11448	8817	12693	11008	9687	6990	5703	3735	3414	2648	2127	1328	1069	756	877	674	531	372	366	312
	0.35	Advera 100C	18562	16660	15187	11837	10275	7372	9342	7746	6578	4250	3213	1940	3375	2447	1878	1098	899	658	694	535	426	311	316	288
		Advera 115C	17921	16151	14799	11694	10261	7505	11606	9787	8427	5674	4400	2734	2884	2091	1614	929	741	538	742	577	467	358	364	344
		Advera 130C	19439	17726	16378	13326	11900	9129	10916	9352	8172	5703	4534	2874	3345	2537	1993	1166	920	620	953	727	577	412	409	374
Sasobit	0.5	Sasobit 100C	16182	14672	13456	10764	9470	7072	11163	9564	8398	5991	5013	3260	3482	2656	2104	1265	1016	713	808	624	493	350	347	316
		Sasobit 115C	17591	15995	14721	11831	10511	8000	12788	11062	9762	6987	5298	3424	3528	2709	2162	1298	1014	675	950	743	608	446	438	411
		Sasobit 130C	23215	21459	19711	16337	14692	11716	12956	11386	10170	7561	6351	4439	4959	3946	3250	2063	1662	1121	1525	1174	970	692	640	544
	1.5	Sasobit 100C	19120	17417	15864	12795	11447	8804	11956	10312	9051	6446	5208	3408	4331	3061	2423	1453	1159	789	1025	785	636	460	440	387
		Sasobit 115C	18901	17249	16011	13405	12004	9525	12996	11268	9952	7251	5940	4050	3912	3070	2491	1549	1254	860	1153	897	736	529	503	424
		Sasobit 130C	20807	18988	17592	14502	13079	10339	11358	9826	8682	6251	5124	3437	3962	3076	2485	1519	1208	833	1255	966	803	562	551	504
	3	Sasobit 100C	17542	16092	14956	12491	11364	9101	12930	11427	10159	7550	6152	4272	4086	3213	2605	1596	1247	850	1227	950	788	553	582	481
		Sasobit 115C	20134	18553	17316	14541	13304	10931	14474	12762	11393	8578	6911	4934	4710	3744	3092	1966	1577	1085	1631	1272	1087	763	733	606
		Sasobit 130C	19718	18243	16944	14060	12760	10207	16192	14490	13127	10101	8296	5919	4938	3973	3297	2105	1693	1177	1602	1278	1096	764	764	647
Cecabase	0.2	Cecabase 100C	13005	11626	10631	8321	7679	5586	5983	4918	4113	2613	2178	1278	1733	1295	1022	597	535	366	481	433	410	388	329	294
		Cecabase 115C	15531	13856	12667	9923	9258	6891	7702	6617	5579	3574	3041	1790	2355	1774	1459	806	687	460	720	576	535	525	464	349
		Cecabase 130C	17459	15651	14291	11232	9804	7136	10596	9251	7977	5429	3966	2426	2883	2074	1575	873	682	461	688	524	404	294	295	276
	0.35	Cecabase 100C	14319	12261	11541	8934	8346	6185	6062	5010	4225	2745	2310	1358	1539	1180	928	568	500	358	442	368	343	351	263	204
		Cecabase 115C	16857	14843	13582	10558	9813	7110	7704	6360	5386	3479	2949	1730	1878	1422	1148	723	663	489	545	465	411	361	292	228
		Cecabase 130C	13377	11898	10870	8490	7904	5816	6619	5492	4691	3094	2661	1614	1527	1156	900	564	495	365	435	365	329	270	222	169
	0.5	Cecabase 100C	13149	11661	10488	8260	7599	5506	6274	5187	4386	2864	2402	1419	1767	1337	1070	623	556	351	510	442	509	520	446	365
		Cecabase 115C	14969	13155	11893	9173	8446	6003	8612	7173	6070	3985	3421	2047	2111	1606	1272	771	701	470	649	595	532	465	410	340
		Cecabase 130C	12727	11245	10245	8000	7335	5315	6447	5392	4614	3100	2649	1653	1623	1235	977	598	531	393	428	361	336	307	249	173
Water	1	Water 100C	14530	12883	11665	8950	8172	5696	7332	5978	4983	3147	2646	1532	1836	1378	1074	656	561	411	541	478	436	379	290	102
		Water 115C	14925	13277	12165	9513	8936	6668	7650	6306	5396	3572	3101	1883	2126	1561	1264	739	660	419	446	383	334	283	227	88
		Water 130C	13581	12170	11160	8770	8158	6012	6998	5860	5040	3402	2922	1822	1833	1405	1124	682	618	412	479	402	363	310	234	77
	1.5	Water 100C	13066	11833	10912	8719	8164	6148	7327	6053	5187	3533	3071	1900	1969	1497	1209	727	648	437	541	478	436	379	290	102
		Water 115C	13117	11800	10792	8488	7878	5745	6871	5771	4949	3327	2870	1764	1691	1283	1016	630	565	411	446	383	334	283	227	88
		Water 130C	13393	11938	10905	8549	7911	5798	6997	5852	5010	3386	2919	1817	1756	1342	1082	651	592	393	479	402	363	310	234	77
	2	Water 100C	14836	13182	11953	9202	8434	5911	8158	6756	5739	3731	2863	1761	2245	1675	1351	831	784	528	625	557	533	478	369	302
		Water 115C	15554	13868	12668	9960	9209	6698	8015	6615	5601	3699	3149	1895	2009	1532	1233	774	691	511	680	586	533	490	383	143
		Water 130C	13484	11949	10947	8607	7953	5809	7002	5839	4989	3354	2883	1775	1787	1368	1080	650	582	390	621	540	494	454	343	104

Appendix 4: Flow Number Testing Results

Table 17 Flow Number for HMA and WMA

Sample	Average Flow Number
Control 163/ 153 C	1418
0.15 Advera 130C	136
0.25 Advera 130C	235
0.35 Advera 130C	237
0.15 Advera 115C	118
0.25 Advera 115	158
0.35 Advera 115C	169
0.15 Advera 100C	212
0.25 Advera 100C	151
0.35 Advera 100C	185
0.5 Sasobit 130C	1196
1.5 Sasobit 130C	679
3.0 Sasobit 130C	580
0.5 Sasobit 115C	284
1.5 Sasobit 115C	463
3.0 Sasobit 115C	2346
0.5 Sasobit 100C	165
1.5 Sasobit 100C	874
3.0 Sasobit 100C	369
0.2 Cecabase 130C	33
0.35 Cecabase 130C	39
0.5 Cecabase 130C	31
0.2 Cecabase 115C	92
0.35 Cecabase 115C	136
0.5 Cecabase 115C	70
0.2 Cecabase 100C	33
0.35 Cecabase 100C	34
0.5 Cecabase 100C	30
1.0 Water 130C	34
1.5 Water 130C	40
2.00 Water 130C	37
1.0 Water 115C	36
1.5 Water 100C	38
2.00 Water 100C	89

Appendix 5: Tensile Strength Ratio Testing Results

Table 18 Tensile Strength Testing Results for HMA and WMA

Sample Name	Dry Tensile Strength	Moist. Tensile Strength	TSR
Control HMA	717	651	0.91
0.15 Advera 130	395	258	0.65
0.25 Advera 130	370	346	0.93
0.35 Advera 130	399	386	0.97
0.15 Advera 115	399	372	0.93
0.25 Advera 115	406	360	0.89
0.35 Advera 115	389	323	0.83
0.15 Advera 100	1038	740	0.71
0.25 Advera 100	628	549	0.87
0.35 Advera 100	447	360	0.81
0.5 Sasobit 130	430	449	1.04
1.5 Sasobit 130	436	432	0.99
3.0 Sasobit 130	447	422	0.94
0.5 Sasobit 115	421	386	0.92
1.5 Sasobit 115	429	397	0.92
3.0 Sasobit 15	452	419	0.93
0.5 Sasobit 100	592	538	0.91
1.5 Sasobit 100	421	378	0.9
3.0 Sasobit 100	393	337	0.86
0.2 Ceca 130	512	534	1.04
0.35 Ceca 130	503	521	1.04
0.5 Ceca 130	513	489	0.95
0.2 Ceca 115	414	408	0.99
0.35 Ceca 115	512	472	0.92
0.5 Ceca 115	522	463	0.89
0.2 Ceca 100	426	391	0.92
0.35 Ceca 100	609	570	0.94
0.5 Ceca 100	420	430	1.02
1.0 Water 130	360	410	1.14
1.5 Water 130	370	388	1.05
2.0 Water 130	386	399	1.03
1.0 Water 115	429	441	1.03
1.5 Water 115	448	429	0.96
2.0 Water 115	427	386	0.9
1.0 Water 100	378	360	0.95
1.5 Water 100	398	382	0.96
2.0 Water 100	406	387	0.95