# 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 $CO_2$ 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.

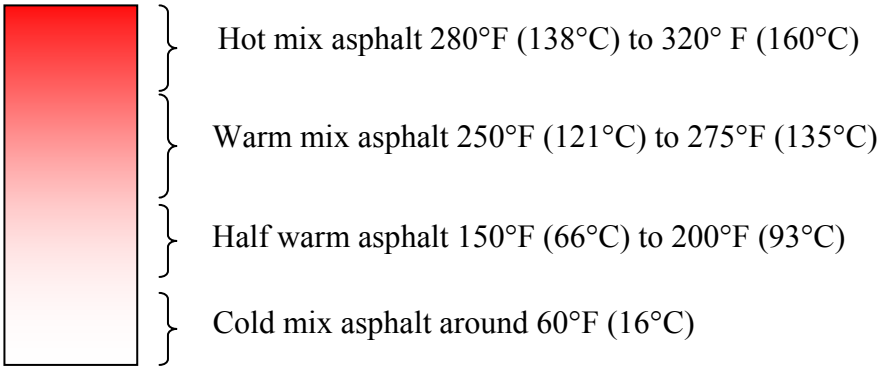



**Figure 1 Typical Mixing Temperature Range for Asphalt Mixtures**

## 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 1Examples 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].

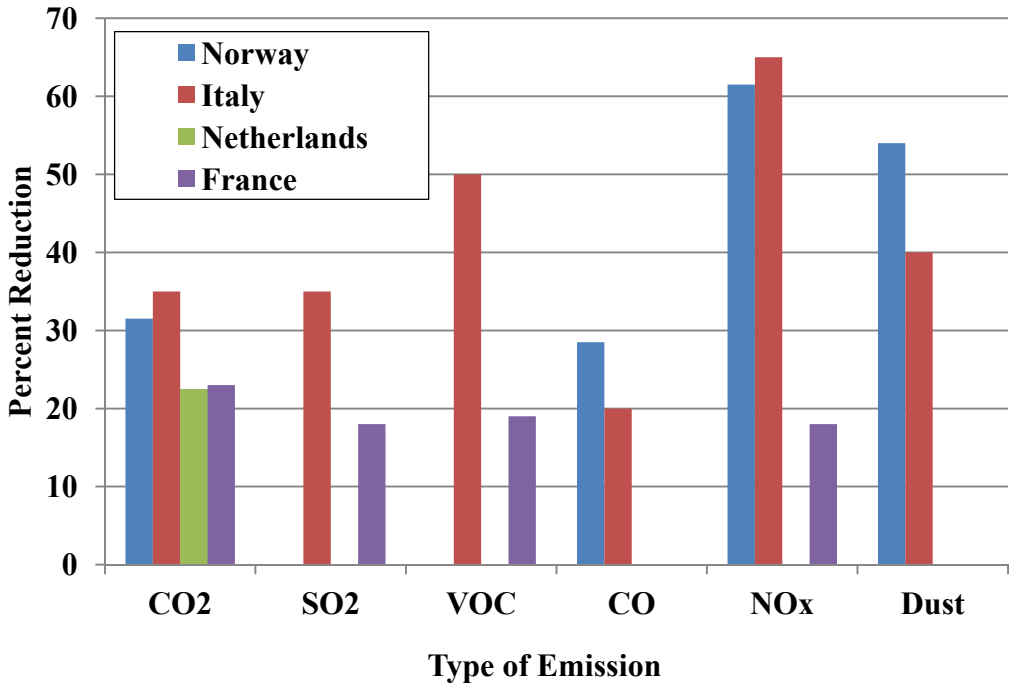



**Figure 2 Reported Reduction in Plant Emission with the use of WMA for Selected EU Nations(data by WMA Technical Working Group[3])**

**<u>Better Health to Contractors, Engineers, and Public</u>**

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 7.7ºC (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.

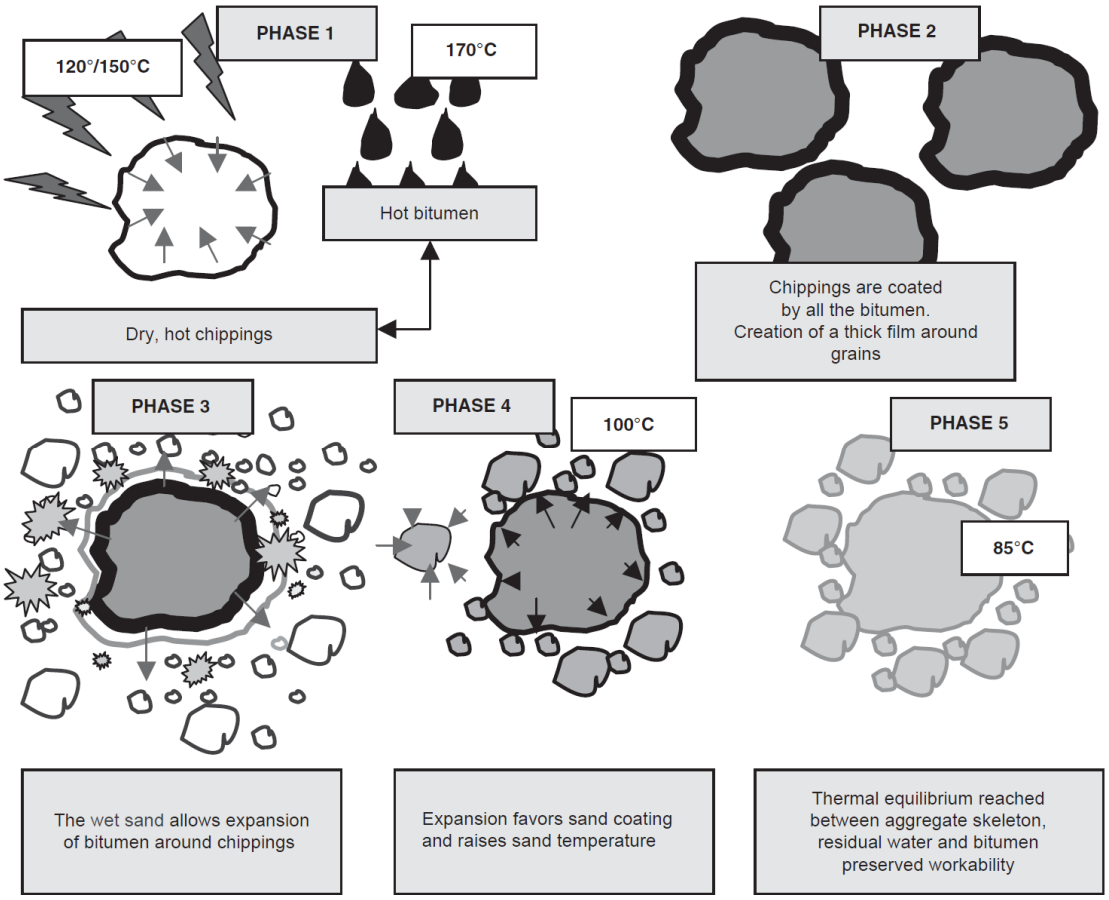



**Figure 3 LEA Technique (from LEA-Co[21])**

## 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].

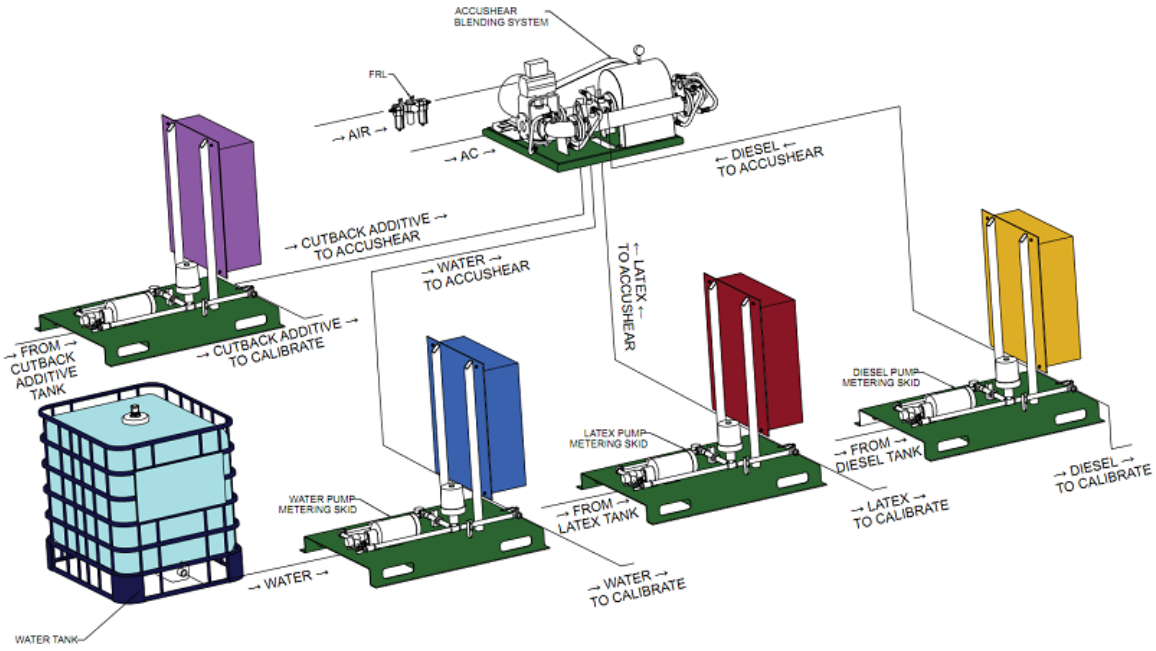



**Figure 4 Accu-Shear Dual Warm-Mix Additive system (from Standsteel)**

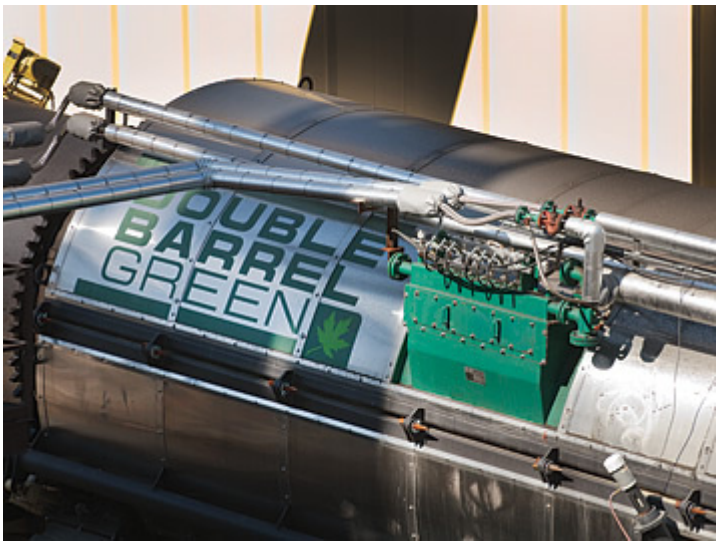



**Figure 5 Double Barrel Green System (from Astec Industries)**

**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 $CO_2$ emissions by 15%. Aspha-min® (a.ka. zeolite) is a product of Eurovia Services GmbH, Germany. Aspha-min® has been used in Europe for several years and U.S. has been using it in paving projects as well as a paving demonstration at the 2004 World of Asphalt [5, 15, 44].

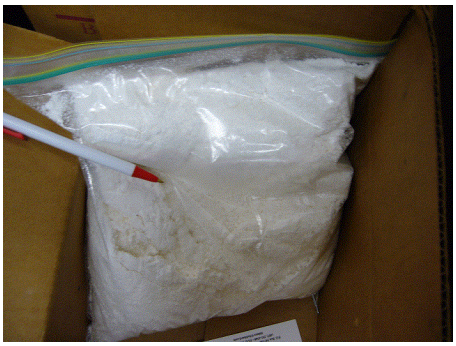


**Figure 7 Granular form of Asphalt-min®**

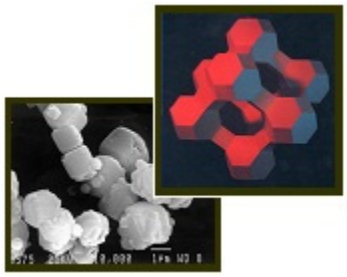


**Figure 8 Electron Microscope Image of Zeolite from McKeon[45]**

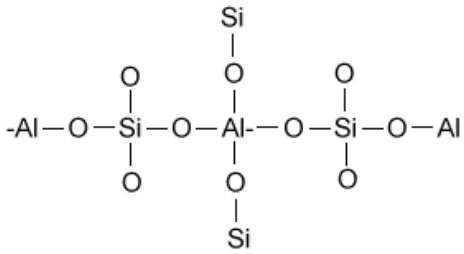



**Figure 9 Basic Zeolite Structurefrom Marcus and Cormier[46]**

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

**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 usinga 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 deformationusing the Mechanistic-Empirical Pavement Design Guide (MEPDG) analysis.

**RotationalViscosity 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.

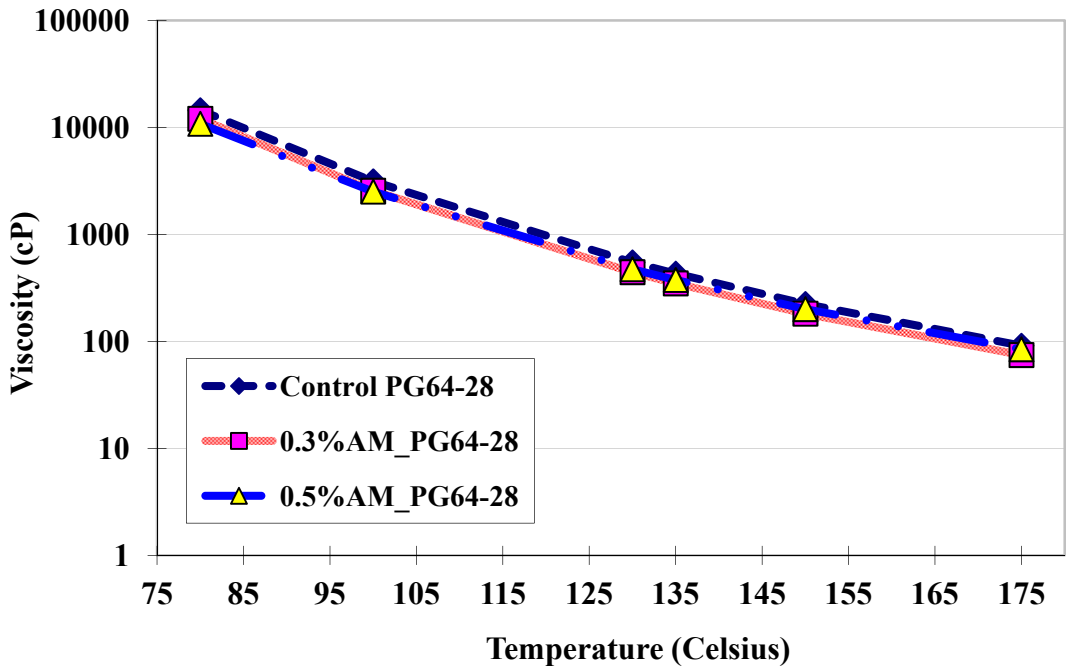



**Figure 10 Comparing Viscosity Test Results for PG64-28 Control and WMA binders**

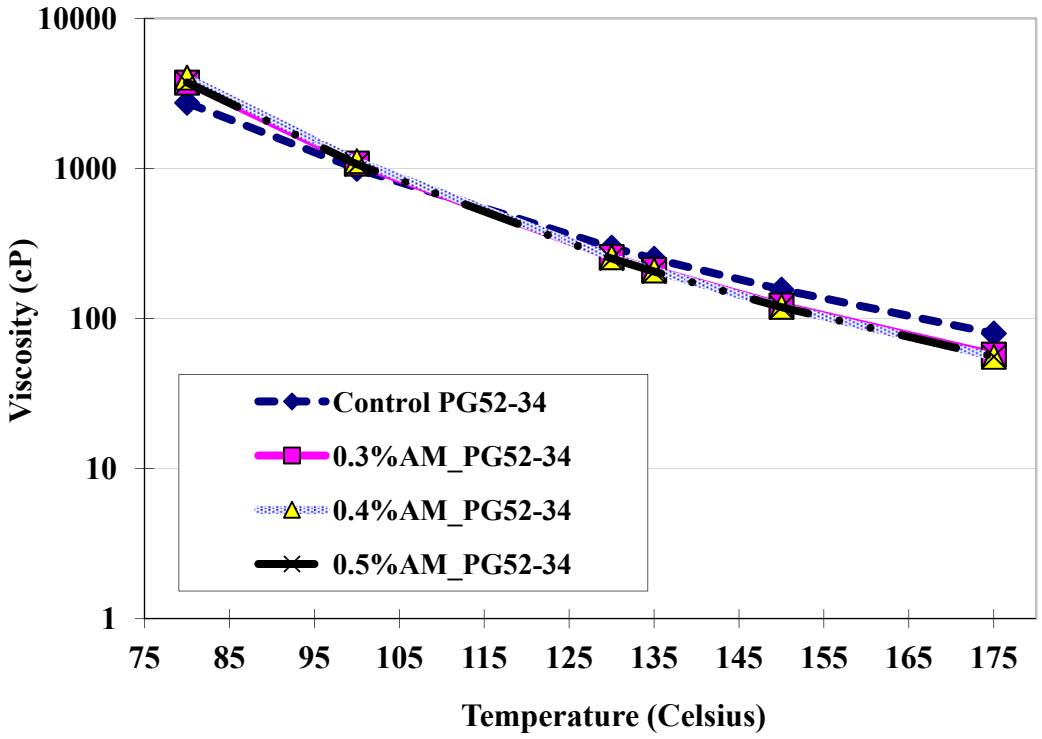



**Figure 11 Comparing Viscosity Test Results for PG52-34 Control and WMA Binders**

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+/-0.03Pa·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 andpaired t-test with 95% confidence level was performed. For the PG64-22 binder, the 95% confidence interval for the mean difference between the control binder and the binder with 0.3% Aspha-min® is found in a small range (-0.090, 0.693) and the range for control binder and the binder with 0.5% Aspha-min® is found within (-2.80, 9.10). For the PG52-34 binder, the 95% confident interval for the mean difference between Control PG52-34 and 0.3%AM_PG52-31, Control PG52-34 and 0.4%AM_PG52-34, and Control PG52-34 and 0.3%AM_PG52-34 are located in the

range of (-0.0057, 0.0752), (-0.0008, 0.0683), and (-0.0139, 0.0939), respectively. Therefore, even though the Aspha-min® slightly reduced the viscosity of the binder, the statistical test results indicate that the additional 0.3% to 0.5% Aspha-min® did not significantly affect the viscosity.

Typically, mixing and compacting temperatures are evaluated from a viscosity-temperature graph. However, it is not feasible to follow the traditional rule in this case. Eurovia[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 andis 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(δ) for both PG52-34 and PG64-28 binders. In addition, PG64-28 binder with the addition of 0.3% and 0.5% Aspha-min® failed to meet Superpave$^{TM}$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**

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

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

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

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

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

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

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(δ) of un-aged and short termaging[11]. Due to the limited availability of current test results, only the aging factor of PG64-28 was evaluated. Table 3shows 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(δ) RTFO to G*/sin(δ) original) between original and short-term aged binder for the control mix and warm mix asphalt**

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

**BinderCreep 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% Asphamin® 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 differenceat a 95% confidence level in the $M_R$ between the two compaction temperatures.

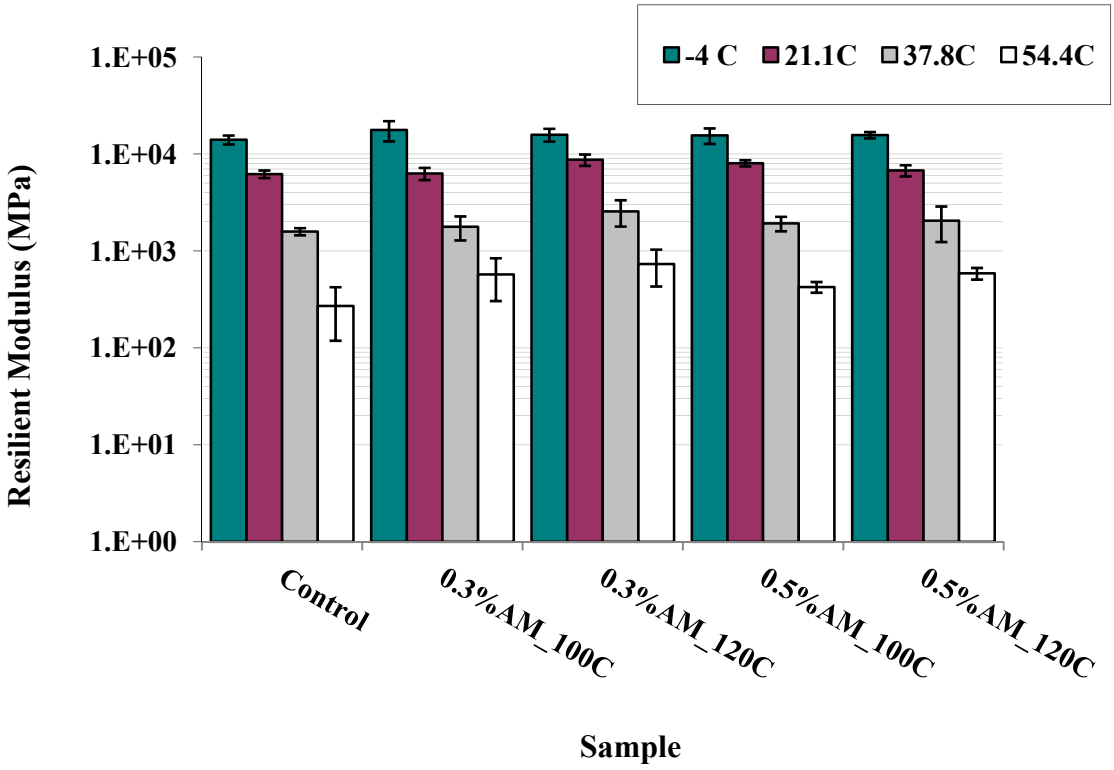



**Figure 12 Resilient Modulus tested at 4°C, 21.1°C, 37.8°C and 54.4°C for control mixture compacted at 140°C and WMA mixture compacted at 100°C and 120°C**

**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 wasperformedusing 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.

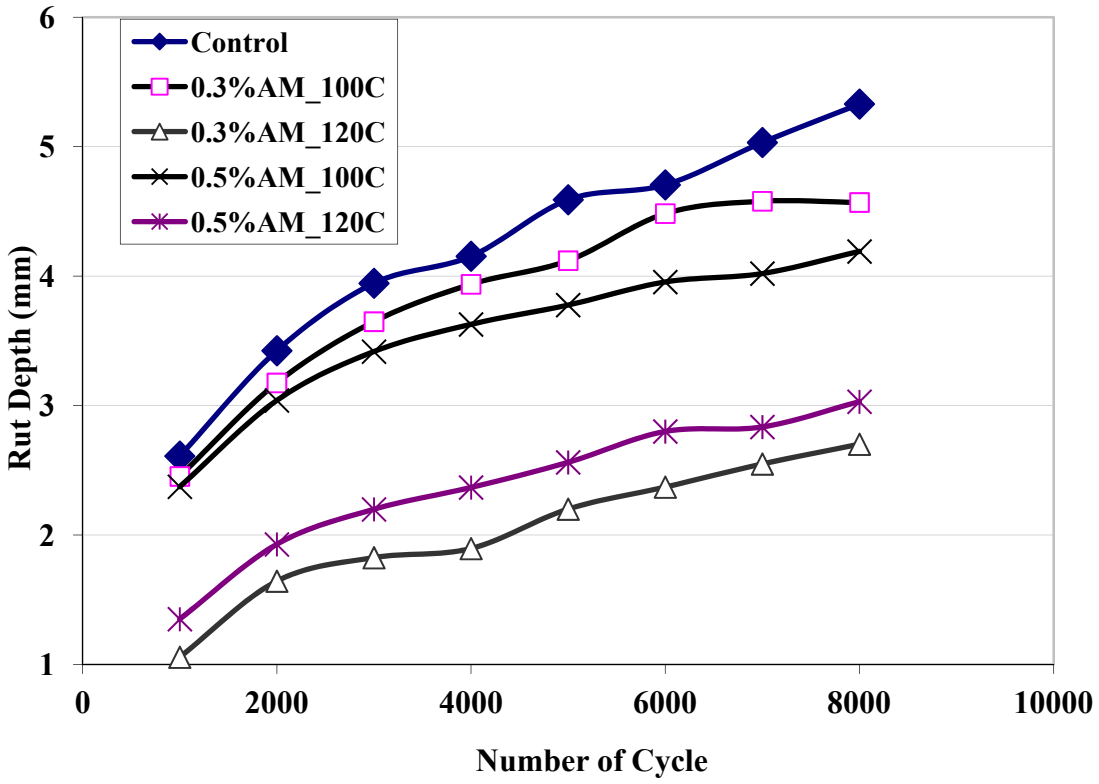



**Figure 13 APA rutting test results for the control mixture and the WMAat 64°C**

**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 ($\sigma$) and amplitude of the sinusoidal strain ($\varepsilon$) 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-strainin 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**

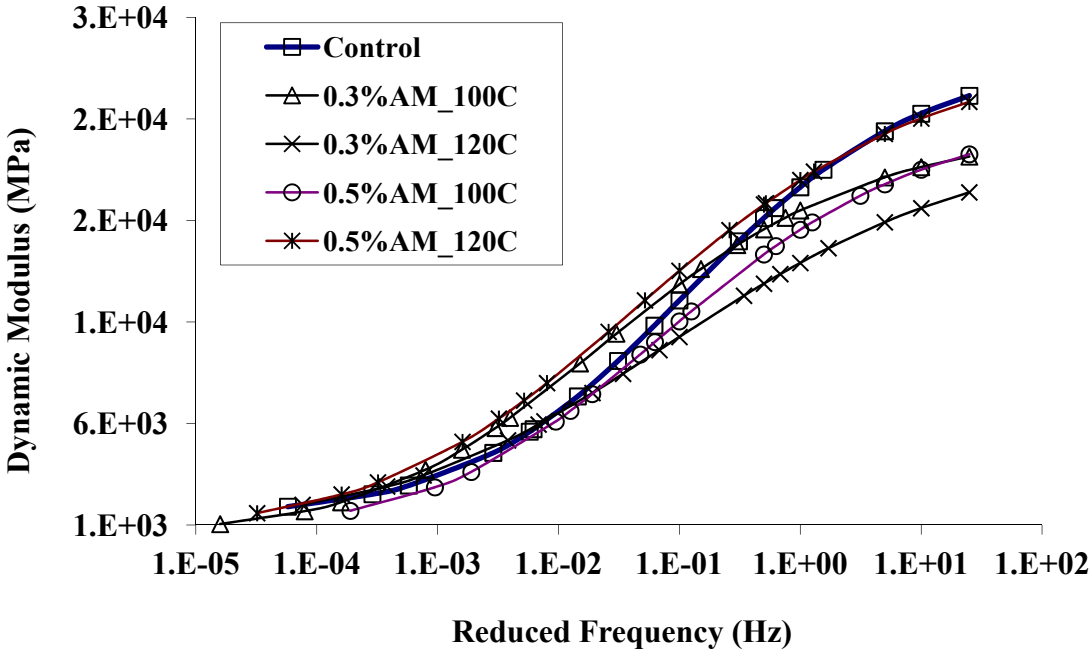



**Figure 15 Sigmoidal Master Curve of Dynamic Modulus Test Results for Control and WMA Mixtures**

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.

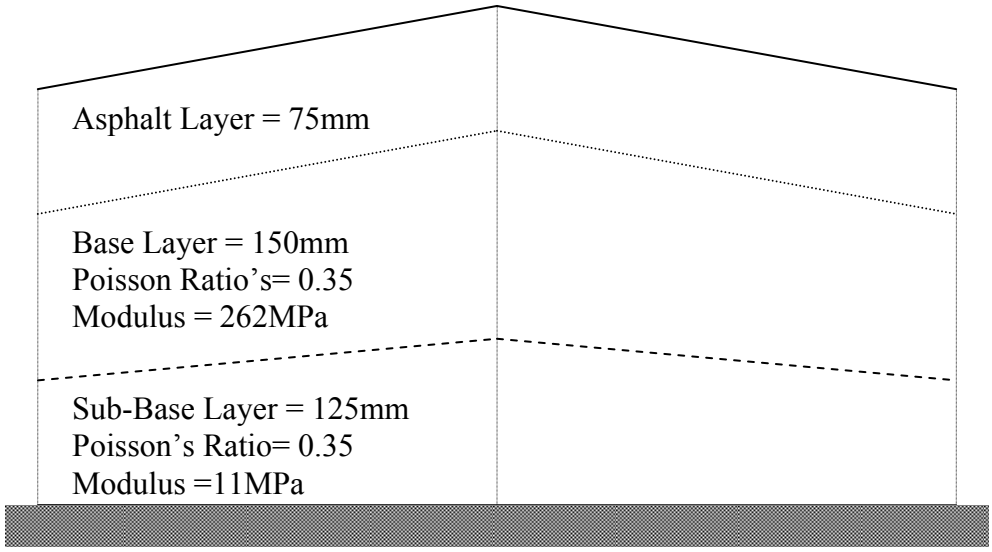



**Figure 16 Pavement Structure for the Control and WMA in MEPDG Study**

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.

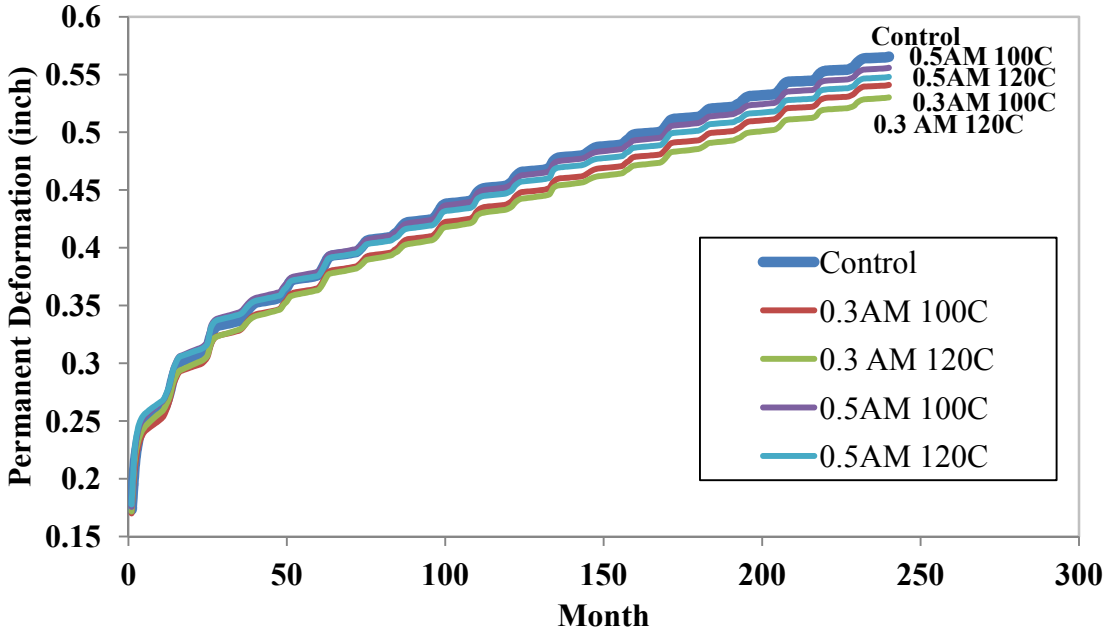



**Figure 17 Predicted rutting depth over 20 years using MEPDG analysis**

## 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

ADAVERA® 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**

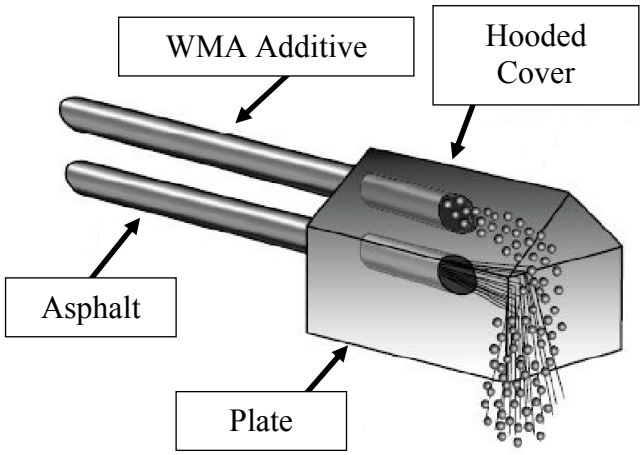



**Figure 19 ADVERA® WMA Mixing Box (from PQ Corp)**

**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$^{TM}$ 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-strainin 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).

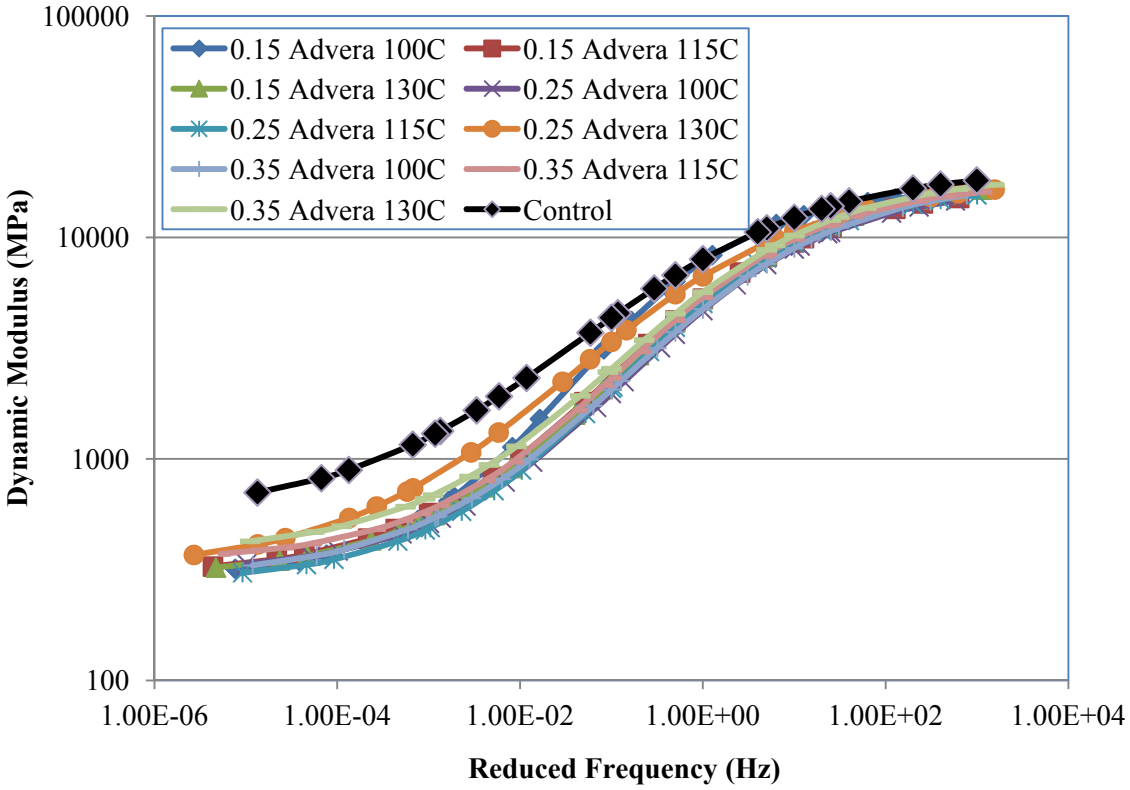



**Figure 20 Sigmoidal Master Curve of Dynamic Modulus Test Results for Control HMA and WMA Mixtures**

**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 25ºC and 0.085mm/s. Figure 21shows the tensile strength testing setup, and Figure 22 shows a typical result from the indirect tensile strength test.

Figure 23shows 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**

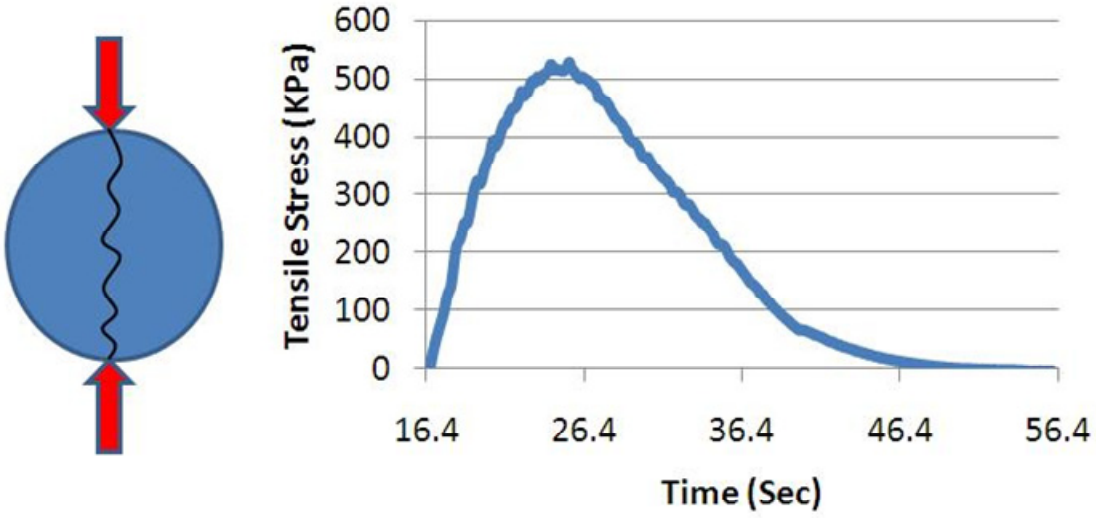



**Figure 22 Typical Result for Indirect Tensile Strength**

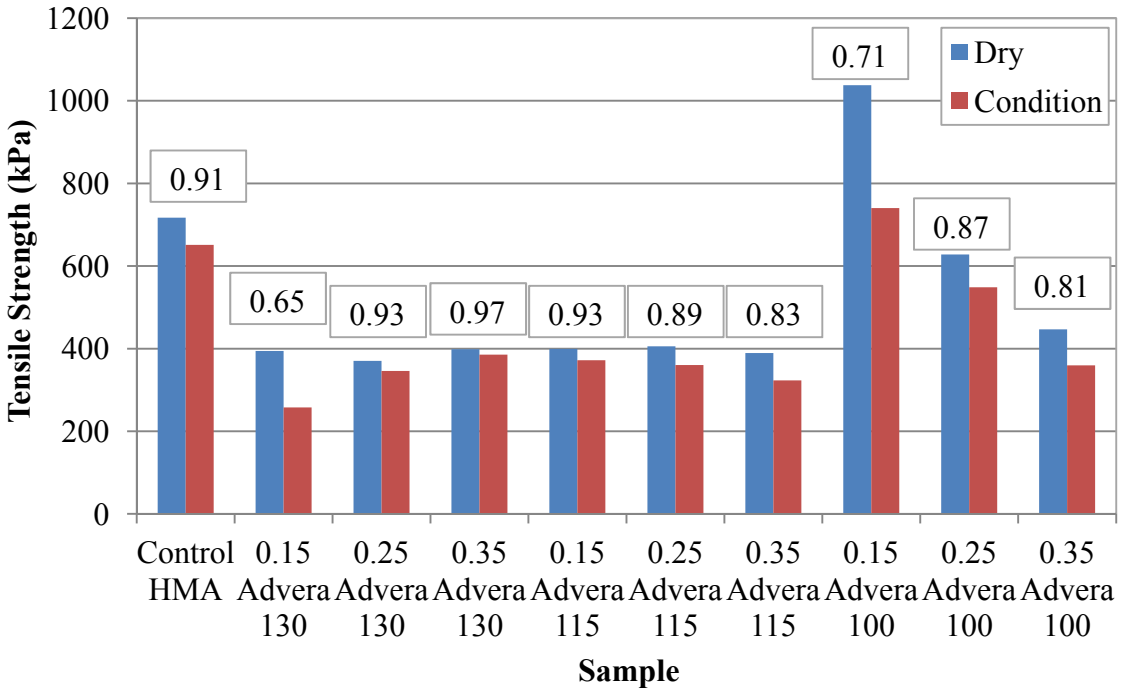



**Figure 23 Tensile Strength Testing Results for Control HMA and WMA made with ADVERA® WMA**

**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.

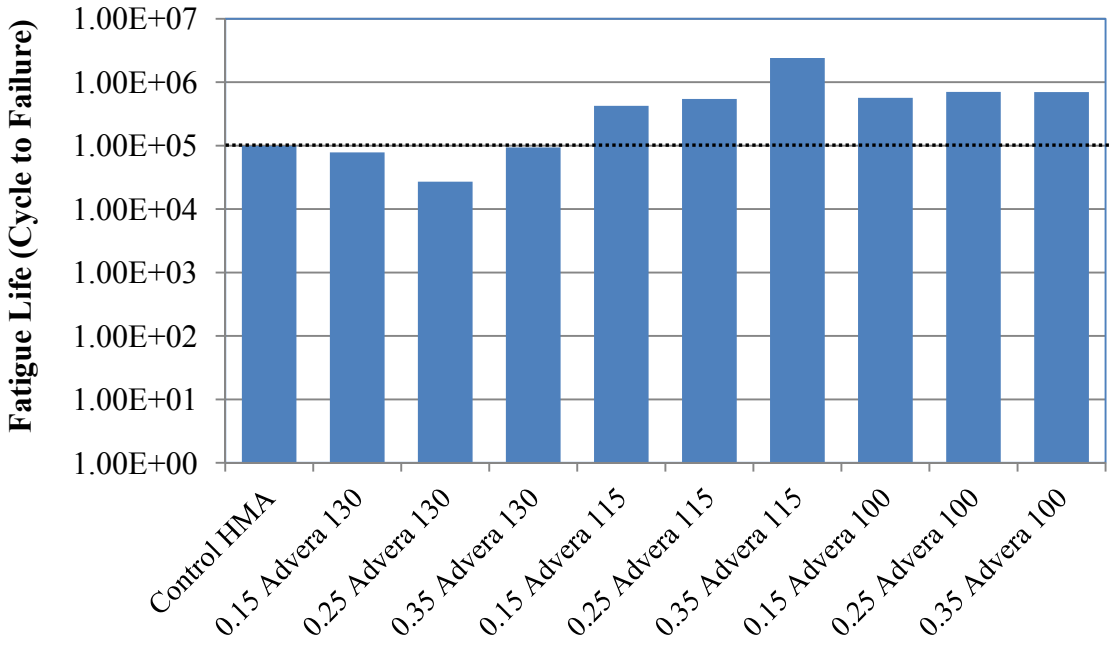



**Figure 24 Results of Four Point Beam Fatigue Testing for Control HMA and WMA made with ADVERA® WMA**

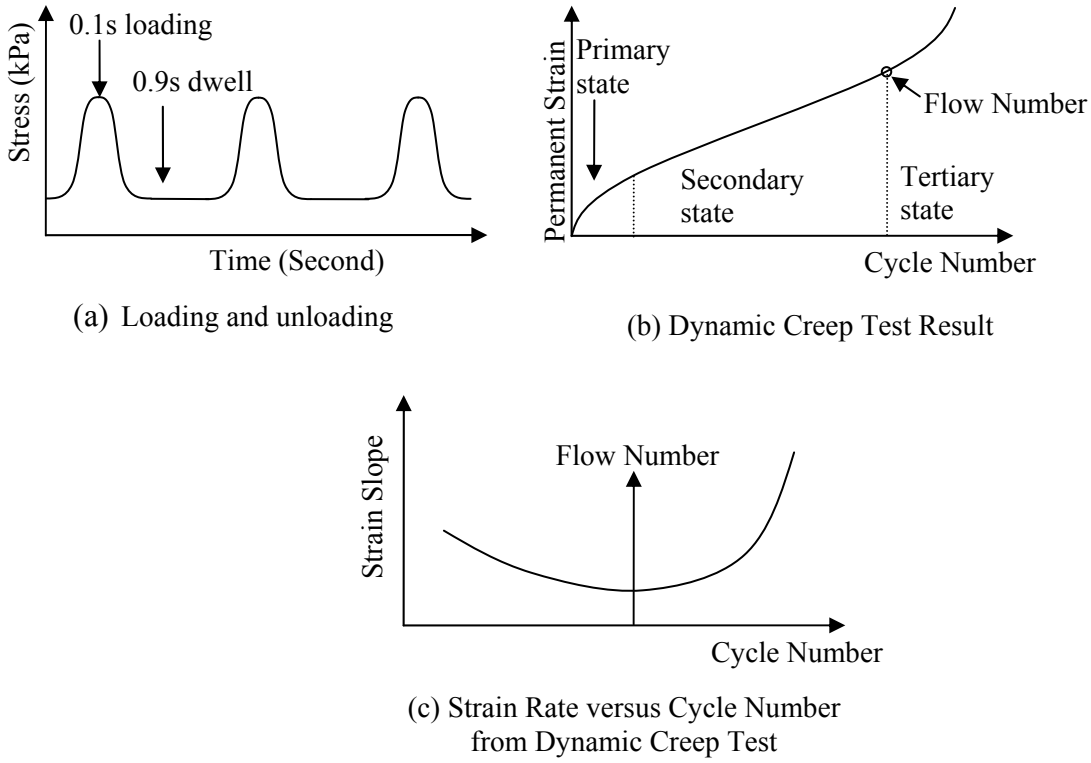
## Flow Number Testing

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 resistanceas 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 Witczak [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].




(a) Loading and unloading

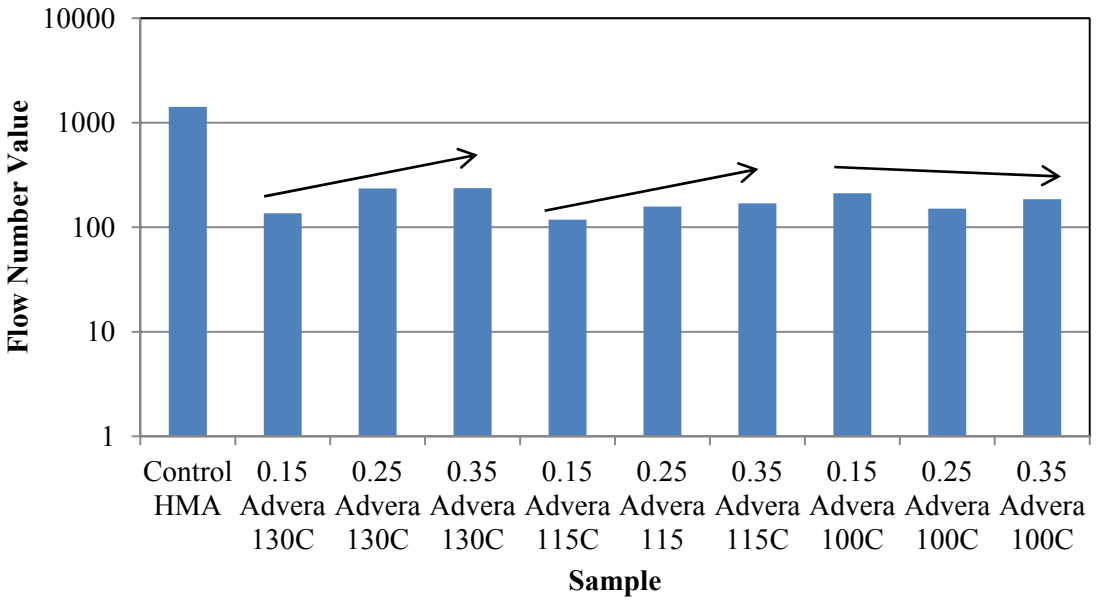
(b) Dynamic Creep Test Result

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

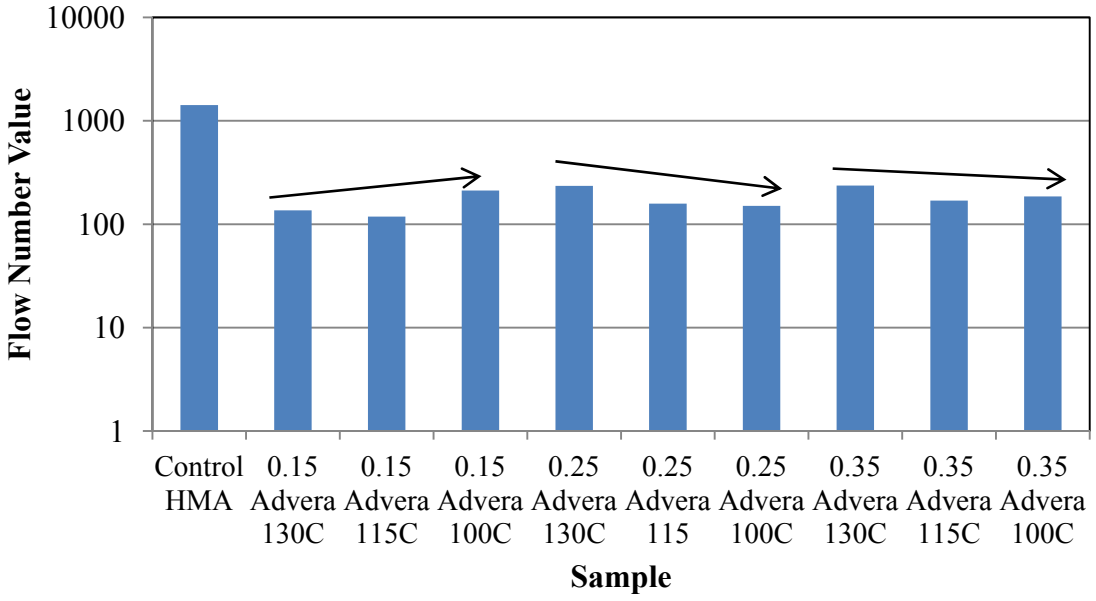
**Figure 25Flow Number Testing and the Flow Number Value**

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.

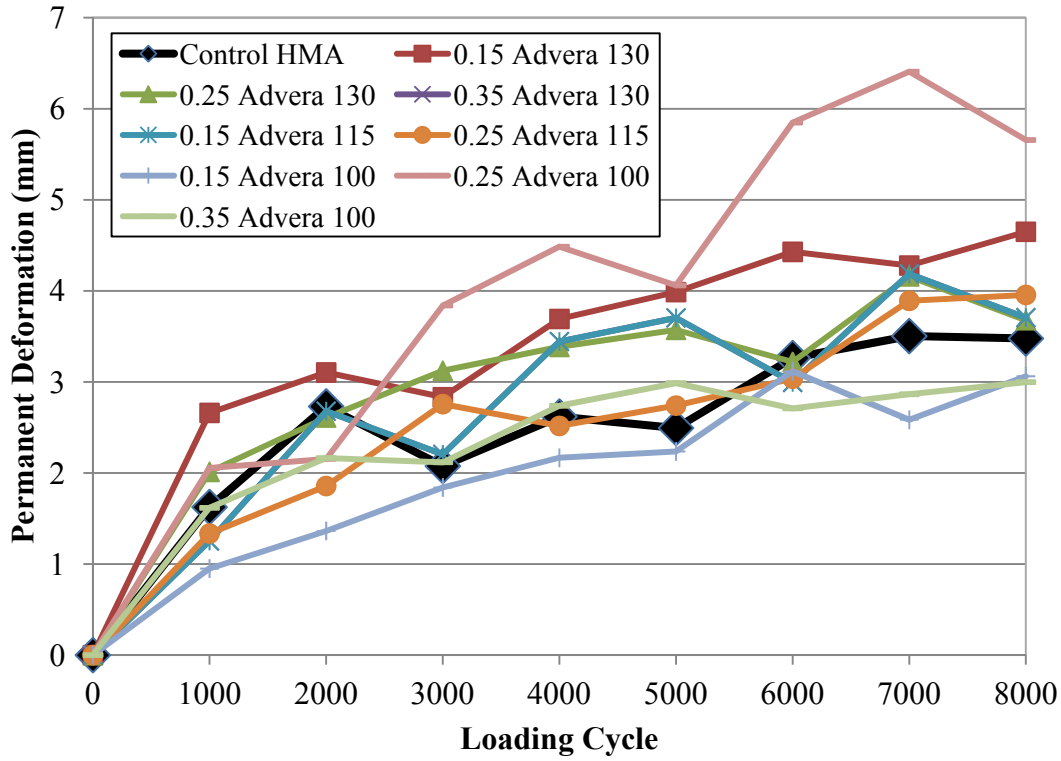



**Figure 27 APA Rutting Test Results for Control HMA and WMA made with ADVERA® WMA**

**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).

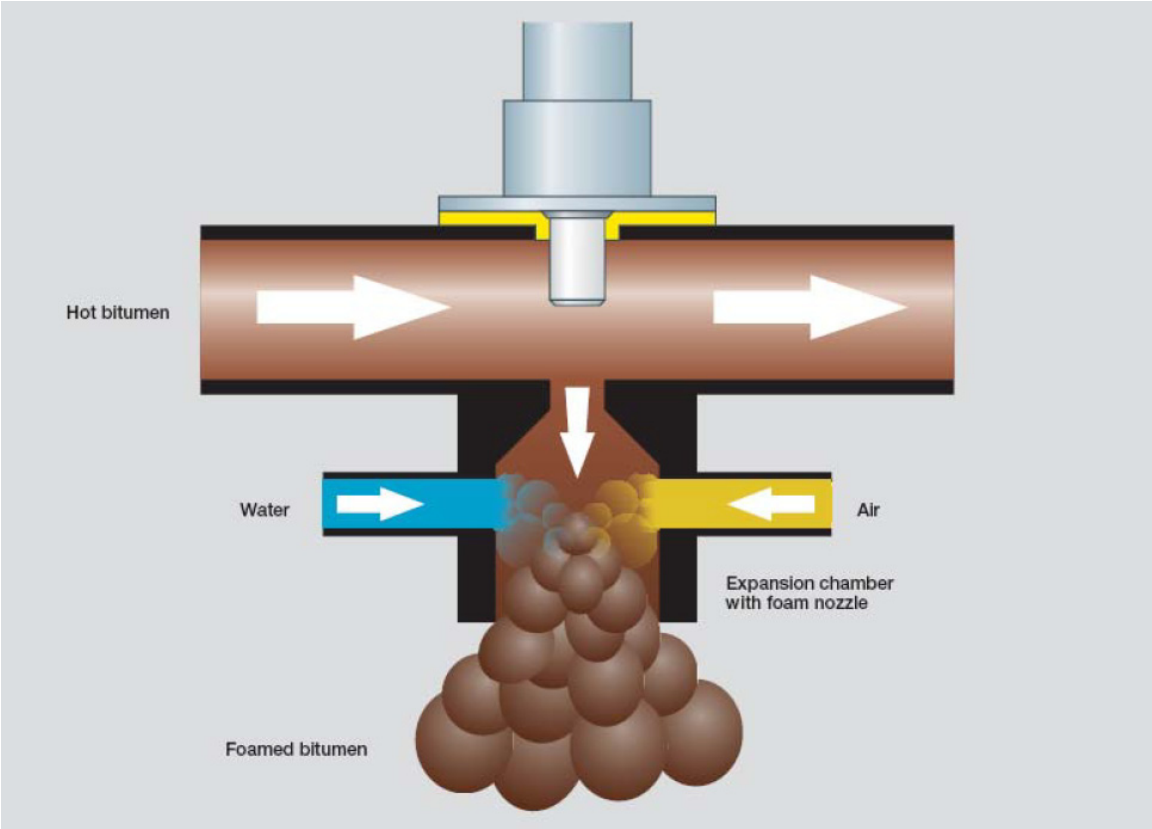



**Figure 28 Wirtgen WLB 10 Foaming Nozzle**


**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 ($\lambda$). The $E_r$ is defined as the ratio of maximum volume of foamed asphalt and the original volume of asphalt; and $\lambda$ 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 $\lambda$ 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 $\lambda$ 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 $\lambda$ 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 $\lambda$ [85].

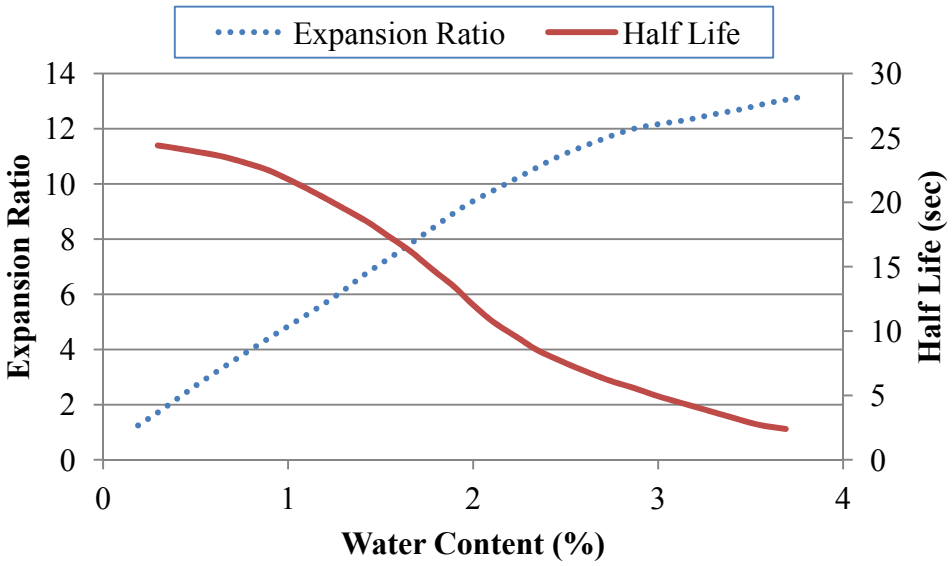



**Figure 30 Example of Foaming Properties of Asphalt Binder**

**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 Superpave$^{TM}$ asphalt mixture design procedure. A performance grade of PG 58-34 asphalt binder was used in this study. Tap water at the rate of 1%, 1.5% and 2% (based on binder weight) was injected into the asphalt binder using a syringe. It should be noted that a certain pressure should be applied to the syringe to allow water injected into the asphalt a short period of time (less than a second). Additionally, it was noteworthy that the asphalt binder was heated up to mixing and compacting temperature, which were 100°C, 115°C and 130°C, before the water was introduced. When the water came into contact with the asphalt, the molecules of the water became very volatile due to the high temperature of asphalt which was close to or above its boiling point. The water then vaporized and turned into steam. Immediately after water was injected to the bottom part of the asphalt binder, a spatula was used to rapidly mix the asphalt and the water in order to allow the steam to disperse completely in the asphalt binder. Figure 31 shows the procedure for producing the foamed asphalt binder.

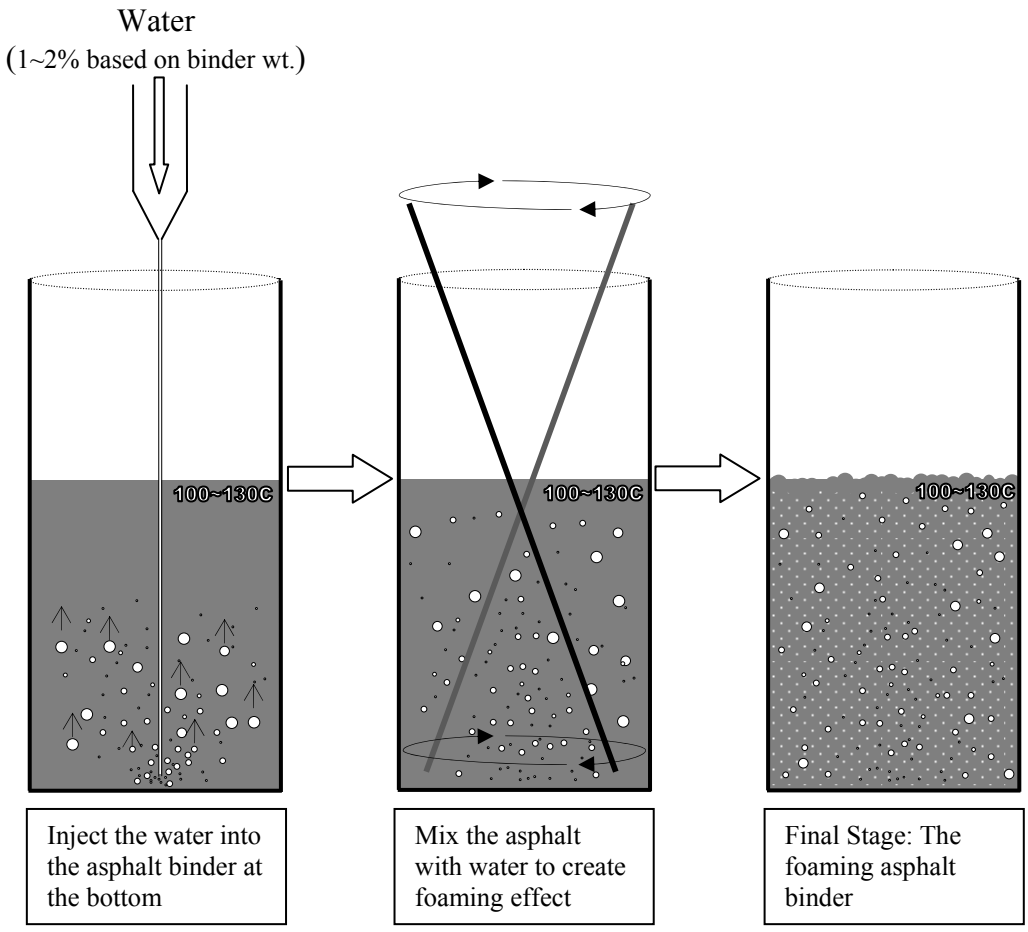



**Figure 31 Procedure to Produce Foamed Asphalt Binder**

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 Superpave™ 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 Superpave™ 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%.

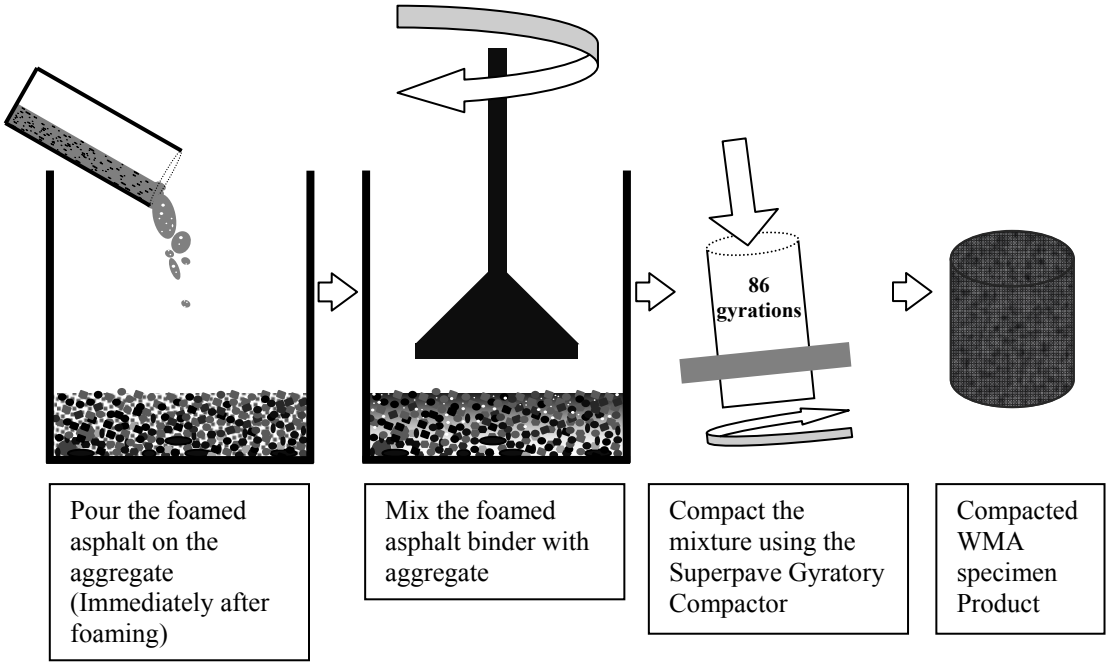



**Figure 32 Mixing and Compacting the Foamed Asphalt with Aggregate**

**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 curved obtained from different temperatures can be aligned to form a single master curve. In order to compare the control HMA and WMA, master curve technique was used in this study. In this study, a sigmoidal master curve was constructed for the

measured |E*| for control and WMA mixtures, and are shown in Figure 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).

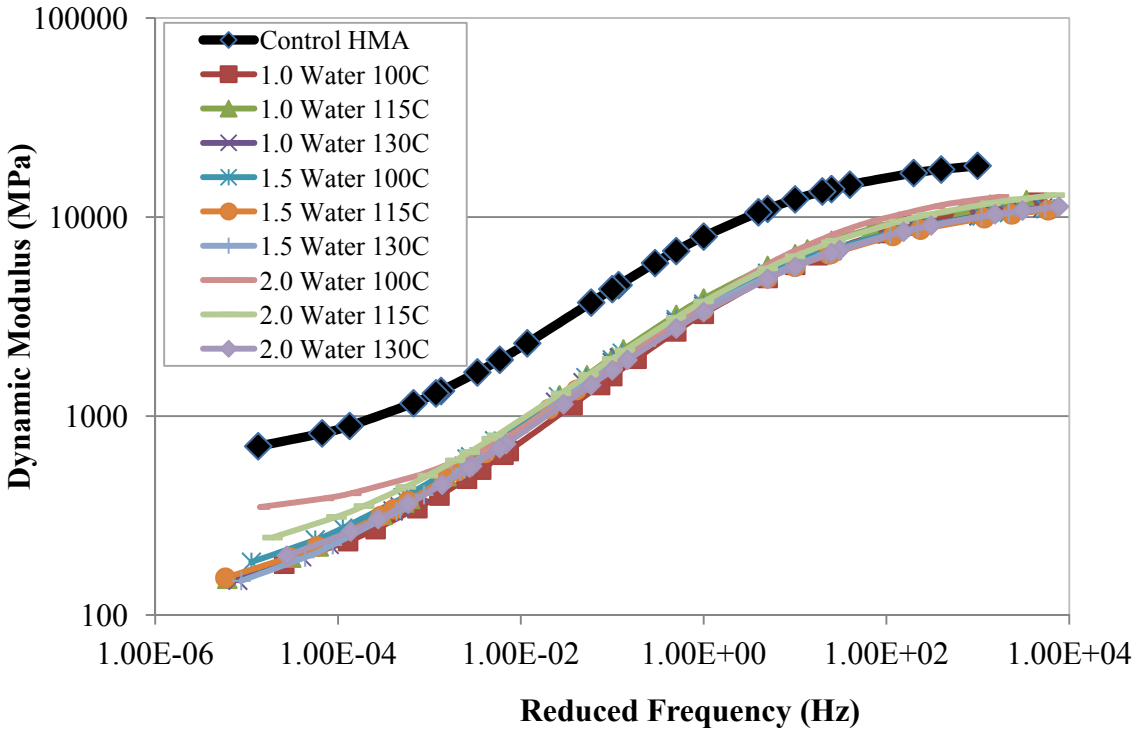



**Figure 34 Dynamic Modulus Test Results for Control HMA and WMA produced using Water Foaming**

**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.

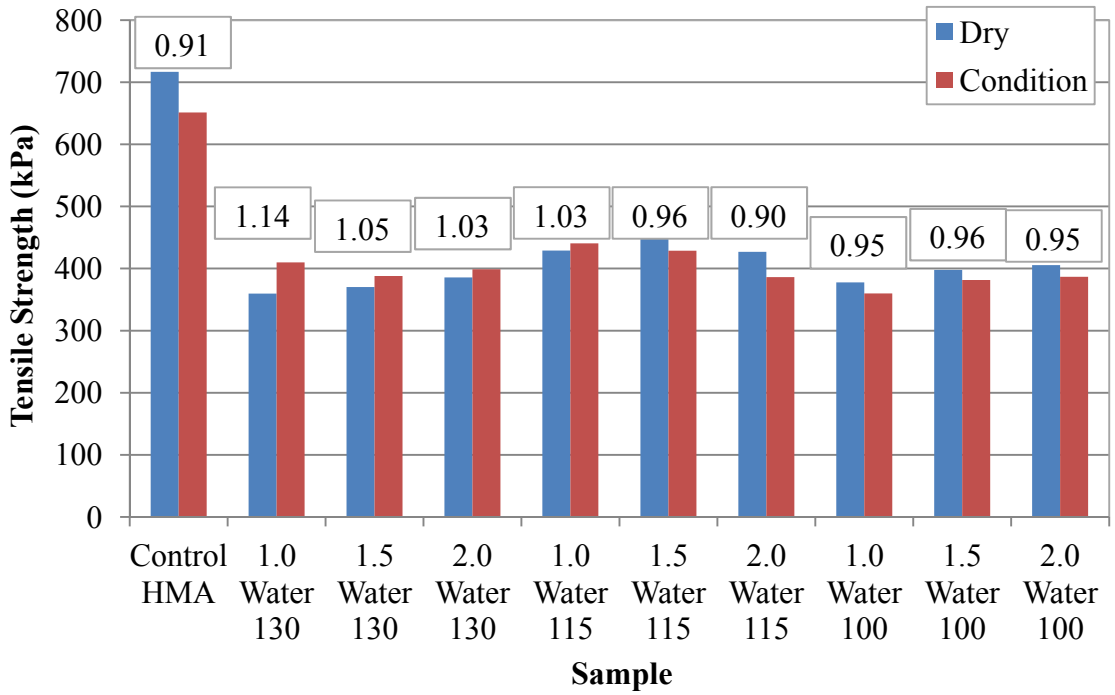



**Figure 35 Comparison of Indirect Tensile Strength and TSR for the Control Mixture, and WMA using 1%, 1.5% and 2% Water at 100°C, 115°C and 130°C**

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.

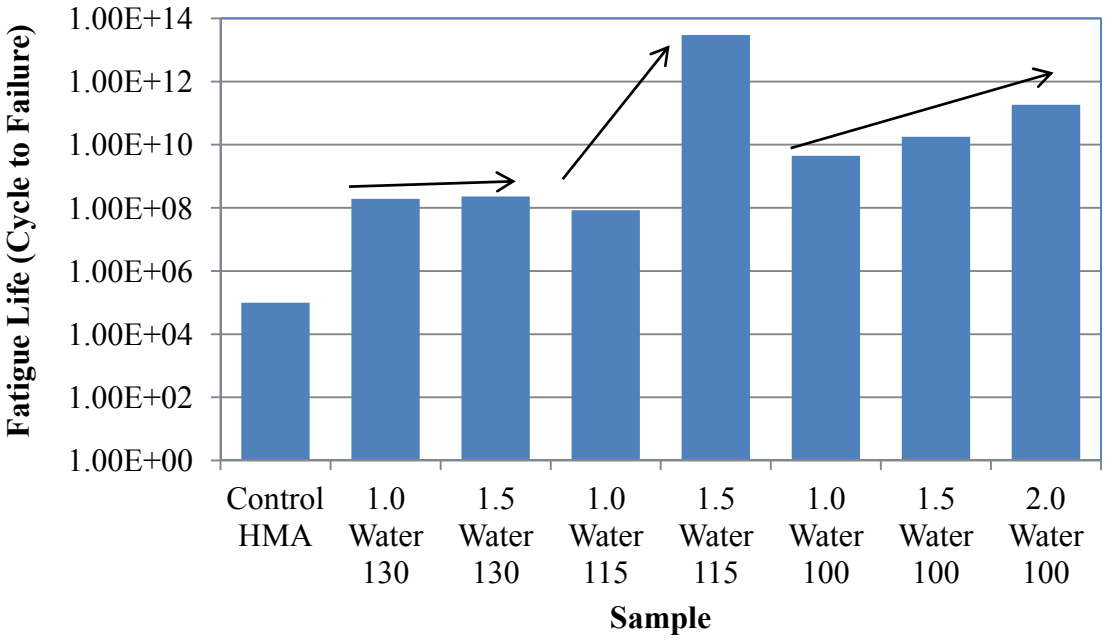



**Figure 36Comparing the Fatigue Life of Control HMA and Foamed WMA**

**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 37shows 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.

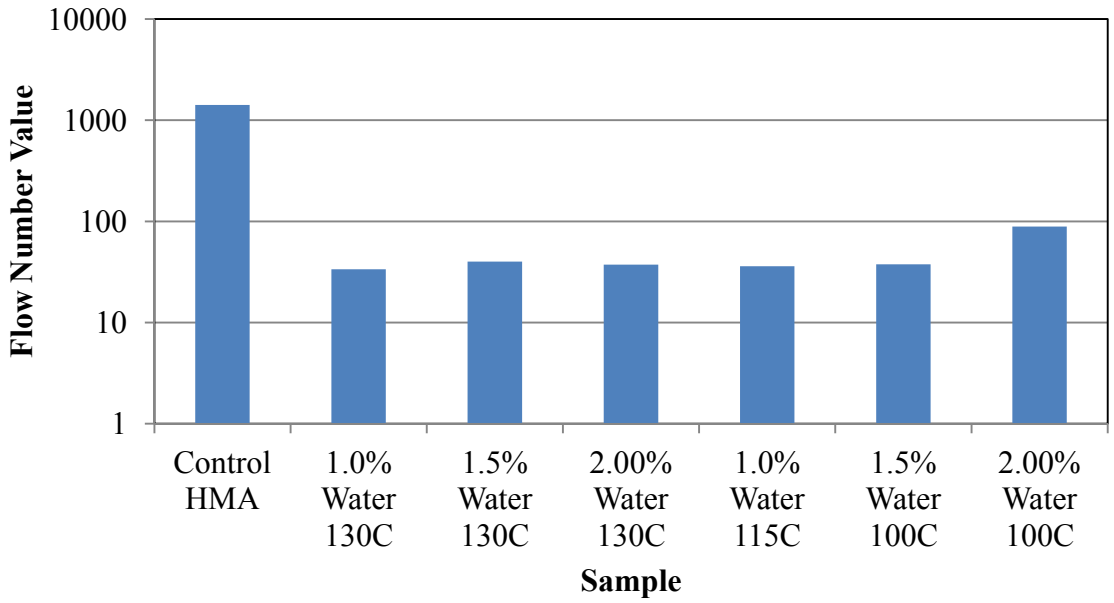



**Figure 37 Flow Number Test Results for HMA control and Foamed WMA with Water**

**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 38also 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.

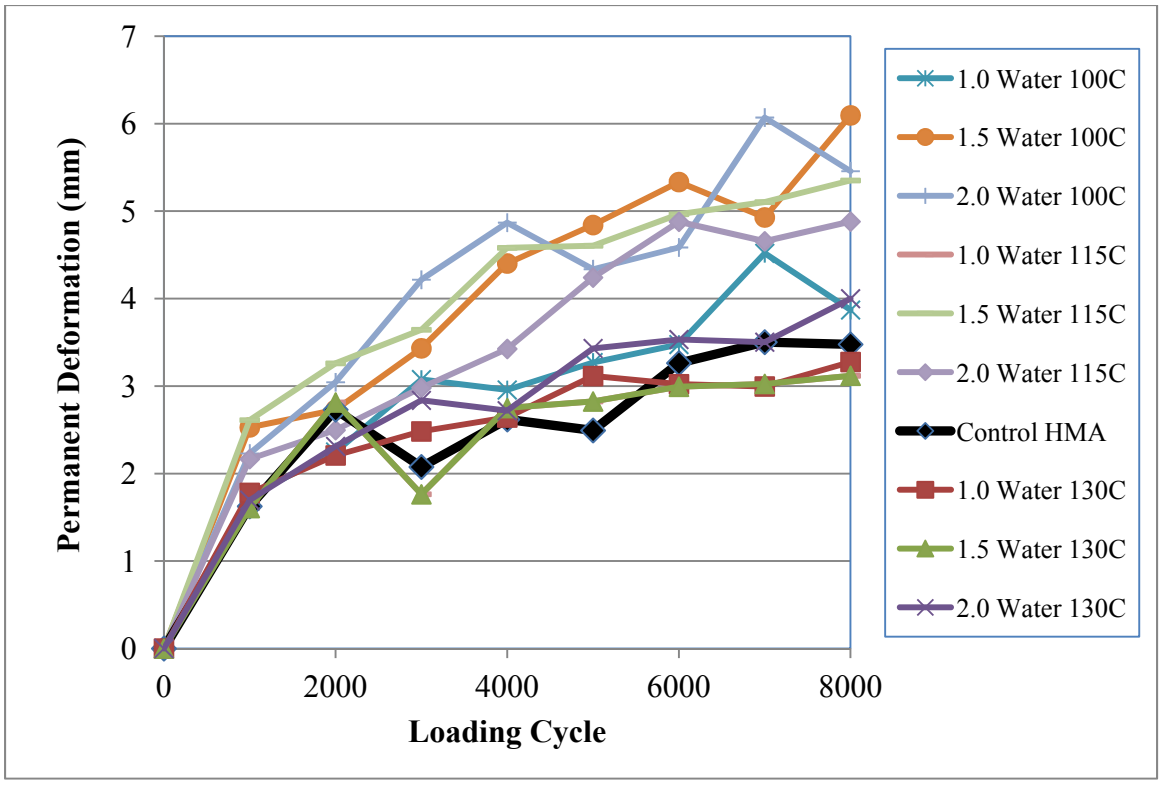



**Figure 38 APA Rutting Results for HMA Control and Foamed WMA with Water**

**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 ($H_2$) under catalytic conditions producing a mixture of hydrocarbons having molecular chain lengths of carbon ($C_5$) to $C_{100}$ plus carbon atoms. The process begins with the generation of synthesis gas then reacted with either an iron or cobalt catalyst to form products such as synthetic naphtha, kerosene, gasoil and waxes. The liquid products are separated and the FT waxes are recovered or hydrocracked into transportation fuels or chemical feed stocks. The Sasobit® recovered is in the carbon chain length range of $C_{45}$ to $C_{100}$ plus[92]. By comparison, macrocrystalline bituminous paraffin waxes have carbon chain lengths ranging from $C_{25}$ to $C_{50}$. The longer carbon chains in the FT wax lead to a higher melting point. The smaller crystalline structure of the FT wax reduces brittleness at low temperatures as compared to bitumen paraffin waxes.

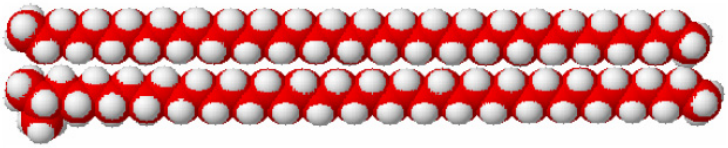


**Figure 39Chemical Structure Long Chain Aliphatic Polyethylene Hydrocarbon from Sasol Wax Americas[93]**

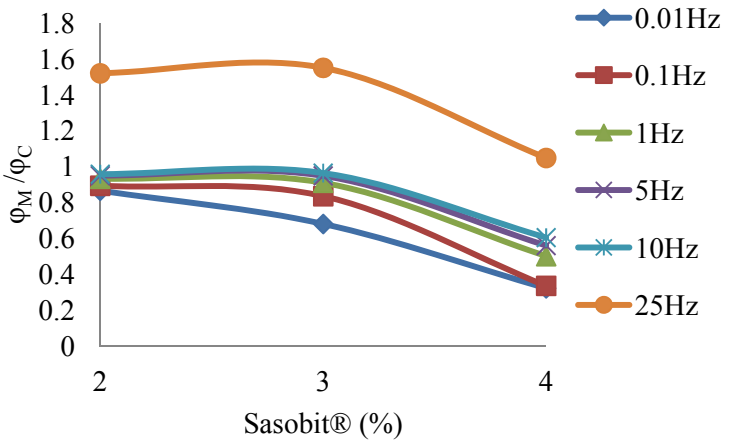
## Asphalt Rheological Properties

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.

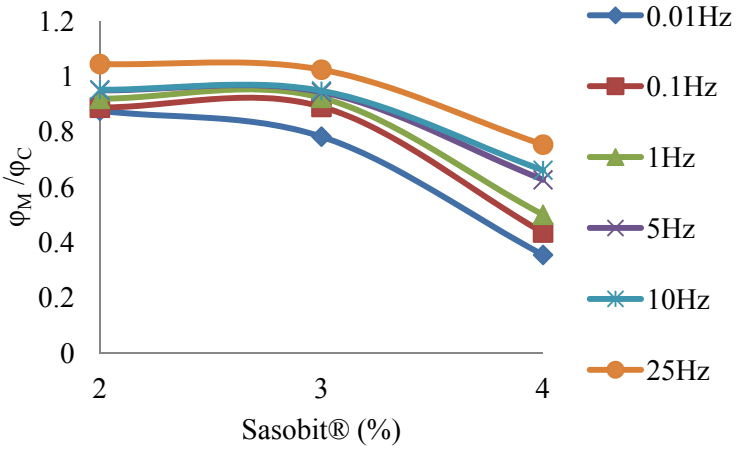
The results from the DSR for WMA and control binders were compared and shown in Figure 40 and Figure 41. Note $\phi_M$ and $\phi_C$are phase angles of WMA and control binders, respectively; $G_M$ and $G_C$are dynamic shear moduli forWMA and control binders, respectively. It was found that most of the ratios of phase angles between WMA and control binders were smaller than one, which indicates that the WMA binder has a smaller phase angle. It is observed that when the amount of Sasobit® increased from 2% to 4%, the average ratios of phase angles decreased from 0.961 to 0.323. Additionally, it was found that the ratio of phase angles at a testing frequency of 25hz was significantly higher compared to others in most cases.

In Figure 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.

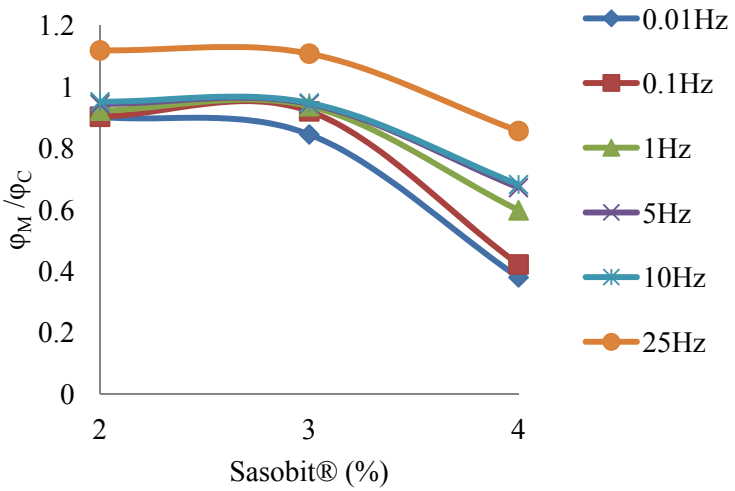
In general, the results indicated that when frequencies increase, dynamic shear modules increase while phase angles decrease. It was observed that temperature affects the value of both the phase angle and dynamic shear modulus ratios.




**(a) 46°C**

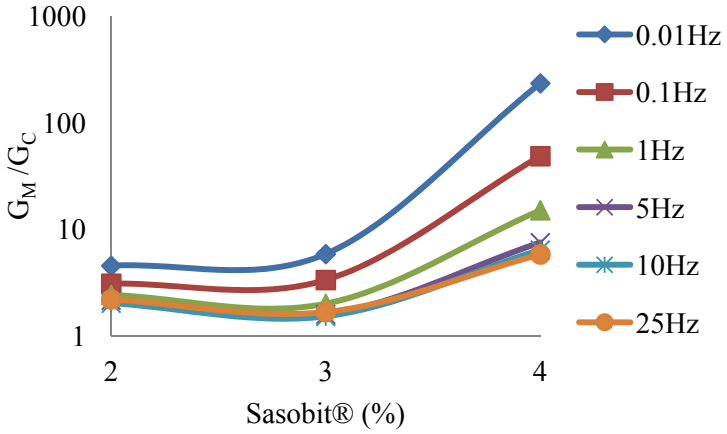



**(b) 55°C**

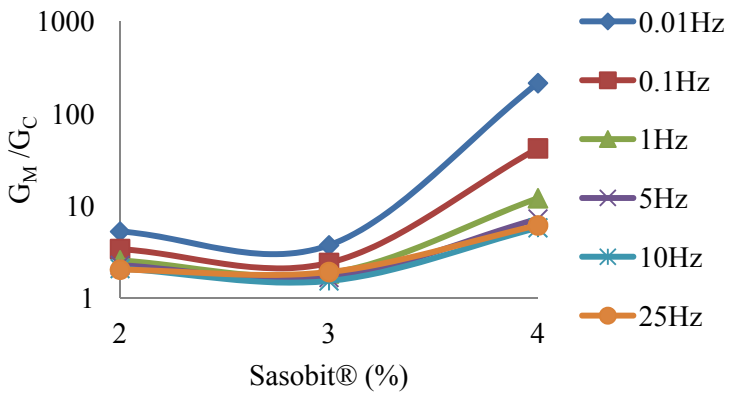



**(c) 58°C**

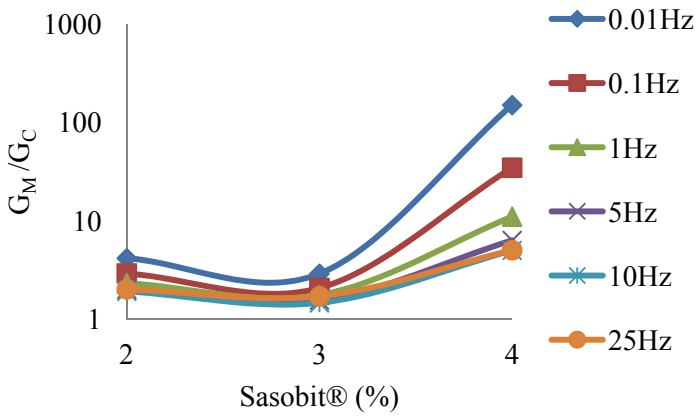
**Figure 40Ratios of Phase Angles for WMA and Control Binders overDifferent Percentages of Sasobit® Additive at (a)46°C, (b)55°C and (c) 58°C**




**(a) 46C**




**(b) 55C**




**(c) 58C**

**Figure 41Ratios of Dynamic Shear Modulus between modified and control binders overDifferent Percentages of Sasobit® Additiveat (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 (δ) before and after short-term aging. The short-term aging process is known as the asphalt binder condition after pavement construction and is simulated by heating in the oven for 12 hours. For WMA samples, four different temperatures were used for short-term aging in this case study: 100°C, 115°C and 130°C for WMA. For the control HMA, 163°C was used during aging process.

Table 7shows G*/sin (δ) 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 (δ) | | 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 NOx, 5% decrease in $CO_2$ and a slightly decrease in VOC when compared to HMA[94].

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

**Figure 42HMA 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 gyration number using Superpave$^{TM}$ 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 8Volumetric 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 18ºC higher than its compaction temperature (i.e. 171ºC) for cold weather paving. For WMA, it was assumed that the compacting temperature is similar to HMA, which is 171ºC in order to compare the hauling and compacting time with HMA.

**Table 9Weather Condition at Iron Mountain on September 2007**

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

Figure 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 ºC

in this case) if the time needed for the entire process (hauling and compacting) is lesser. Thus the use of WMA technology can significantly improve the cold weather paving by extending the hauling distance and paving time.

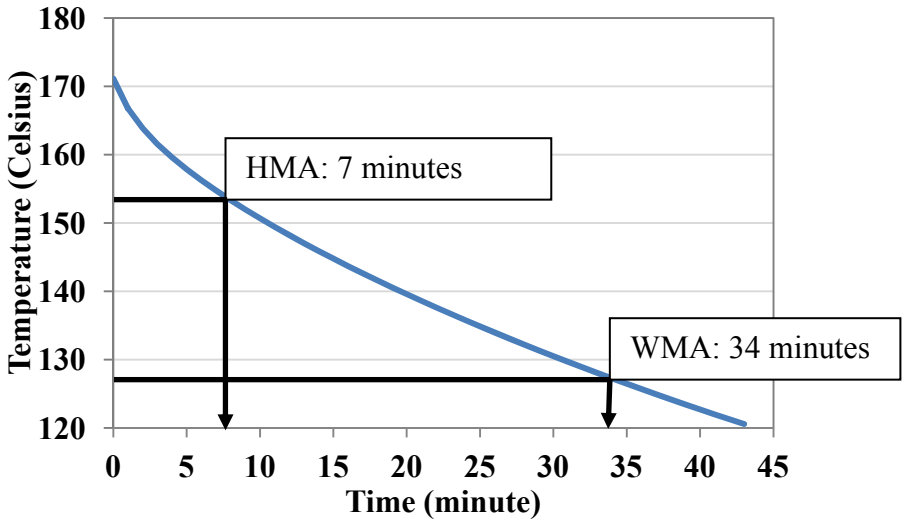



**Figure 43Mixture Cooling time calculated using MultiCool Program**

**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.

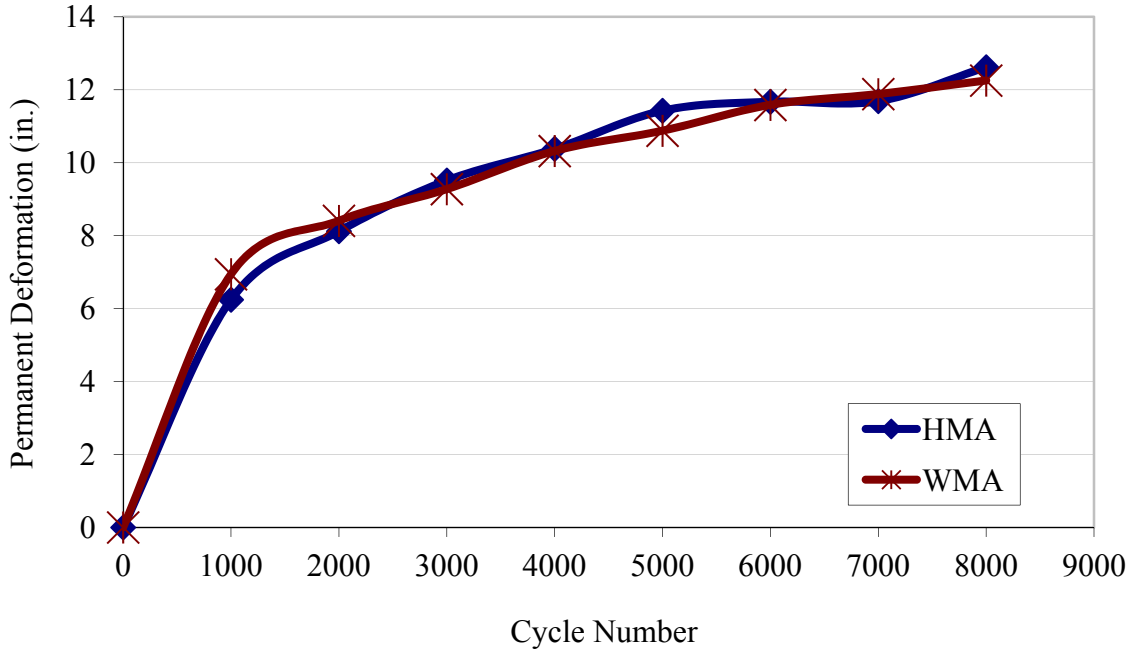



**Figure 44 Comparison of APA Rutting for HMA and WMA collected from Field Trial**

## 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.

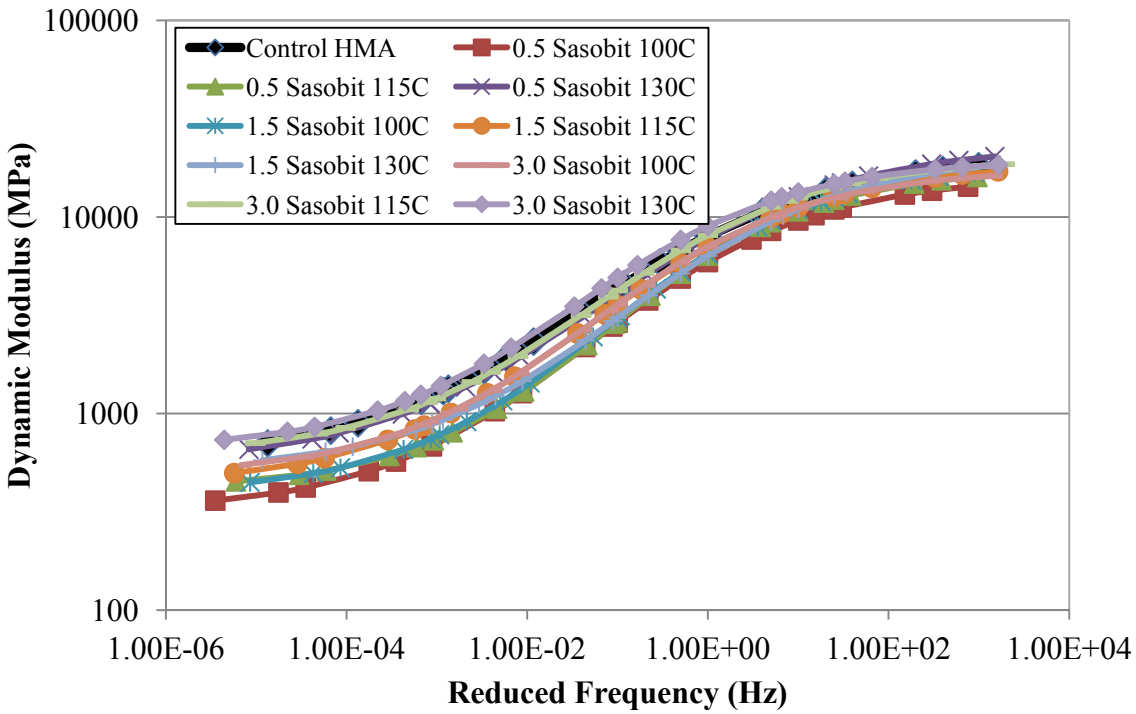



**Figure 45Dynamic Modulus Results for Control Mixture and WMA Mixture**

**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 25ºC 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.

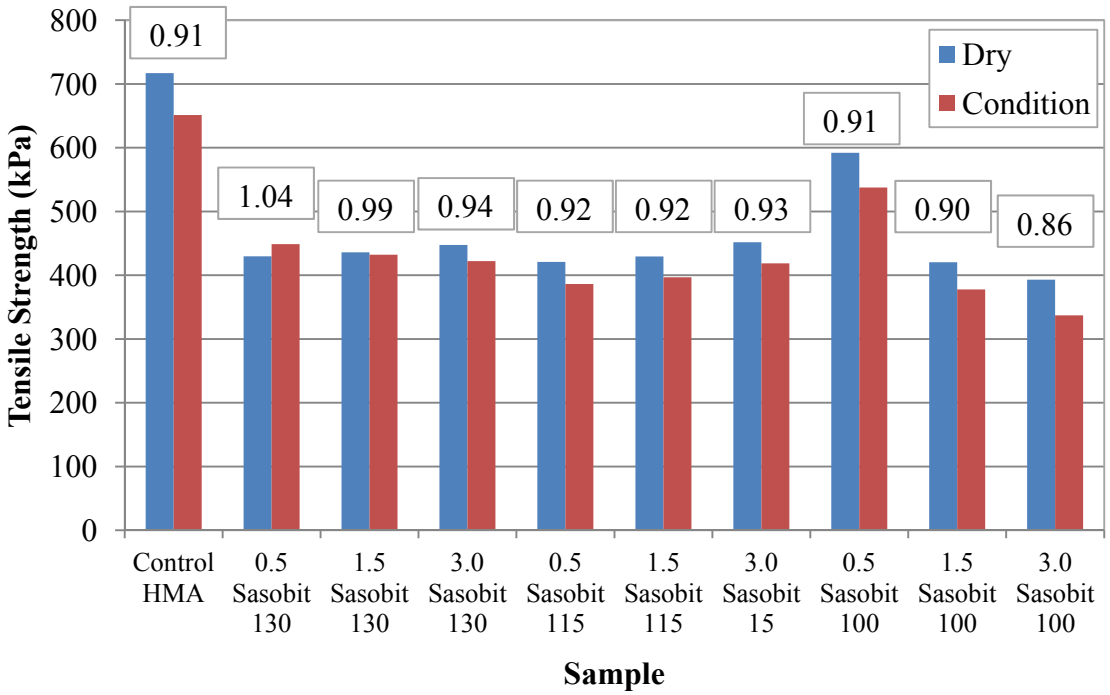



**Figure 46Tensile Strength Ratio Result for Control and WMA Mixtures**

**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.

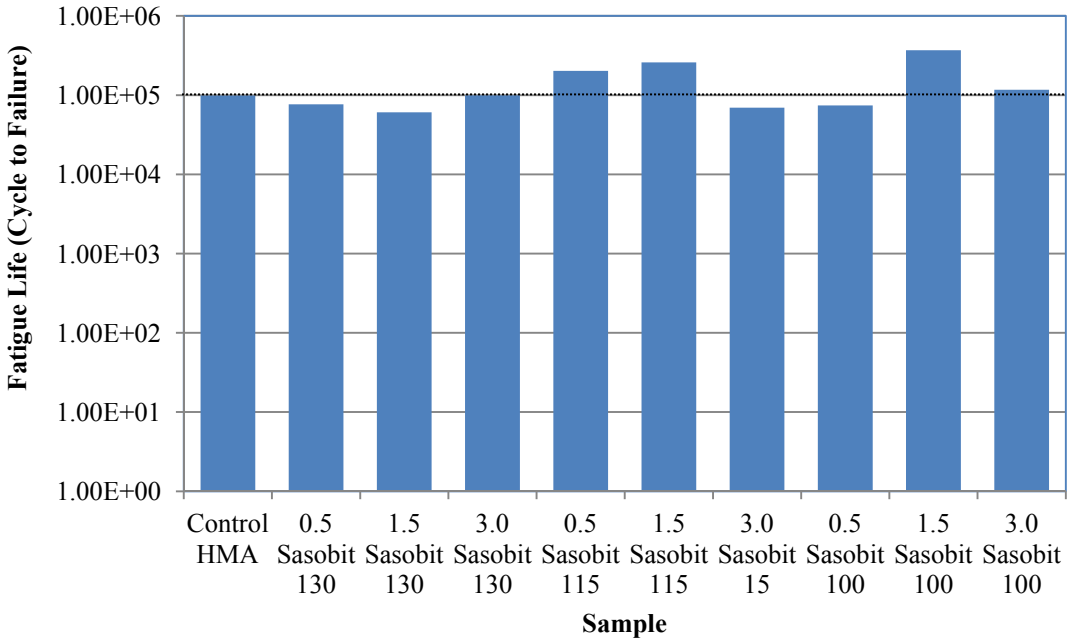
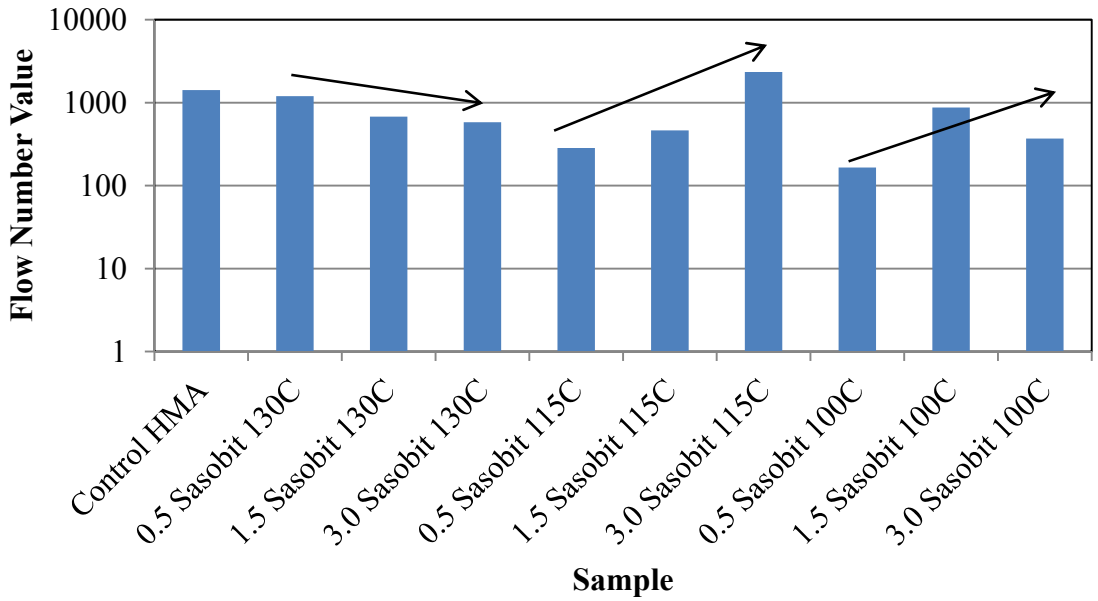


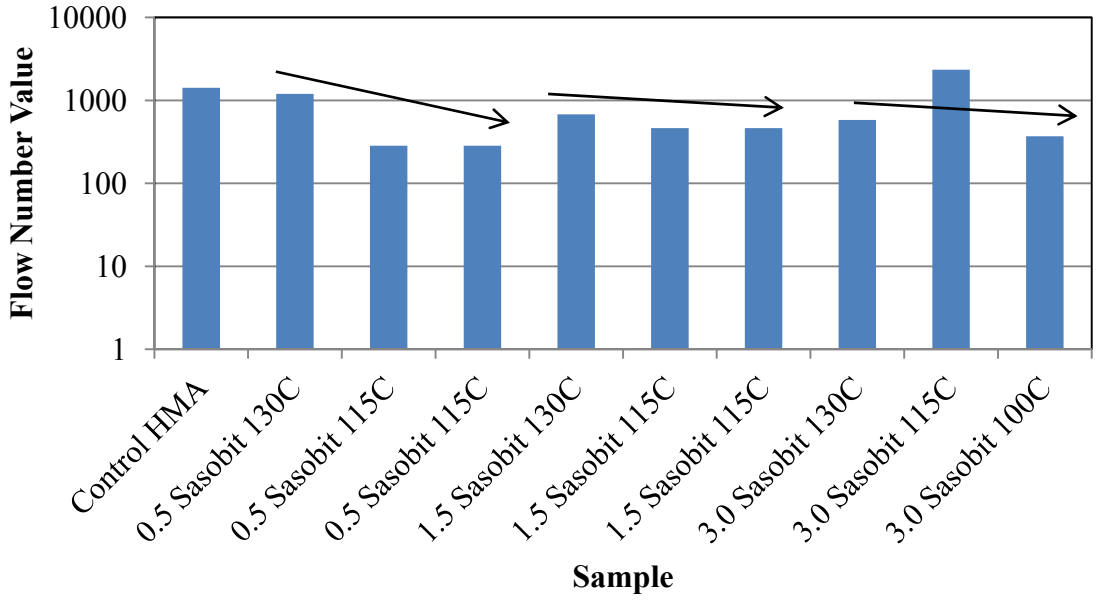

**Figure 47 Four Point Beam Fatigue Testing Results for Control HMA and WMA made with Sasobit®**

## 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 48shows 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.

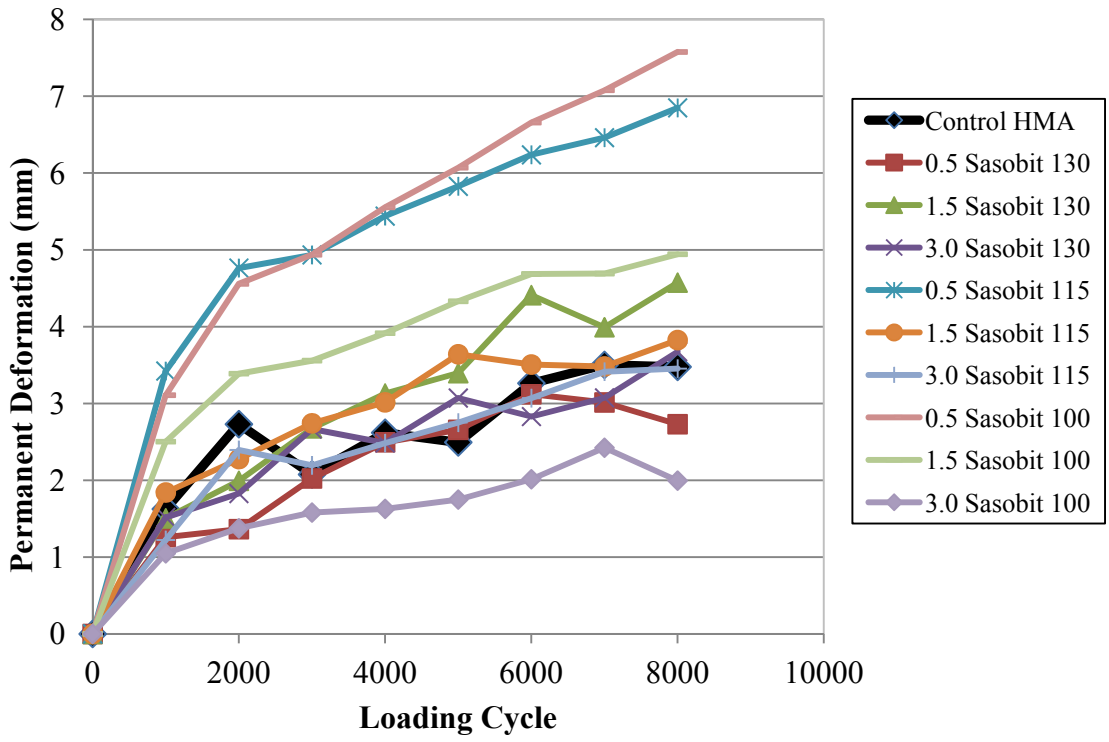



**Figure 49 APA Rutting Results for Control HMA and WMA made with Sasobit®**

**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 18ºC higher than the conventional temperature (171ºC in this case, for cold region paving). It was found that WMA extend the paving time by 27 minutes which will allow a longer hauling distance during the construction. The performance was compared based on the |E*|, $F_N$, TSR, four point beam fatigue and APA rutting tests. The summary of findings in this case study is presented below:

1. The 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-striping 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$^{TM}$ 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.

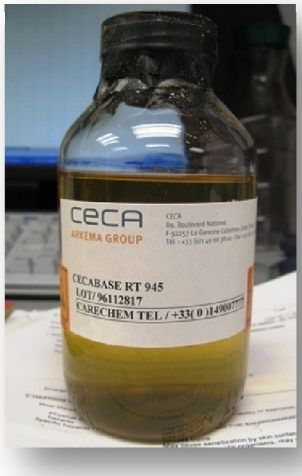



**Figure 50 Cecabase RT®**

**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$^{TM}$ 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$^{TM}$ 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 andis 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 affectthe aging temperature and also the amount of Cecabase RT®. Additionally,

Table 10 shows that all the binders meet the Superpave$^{TM}$ 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).

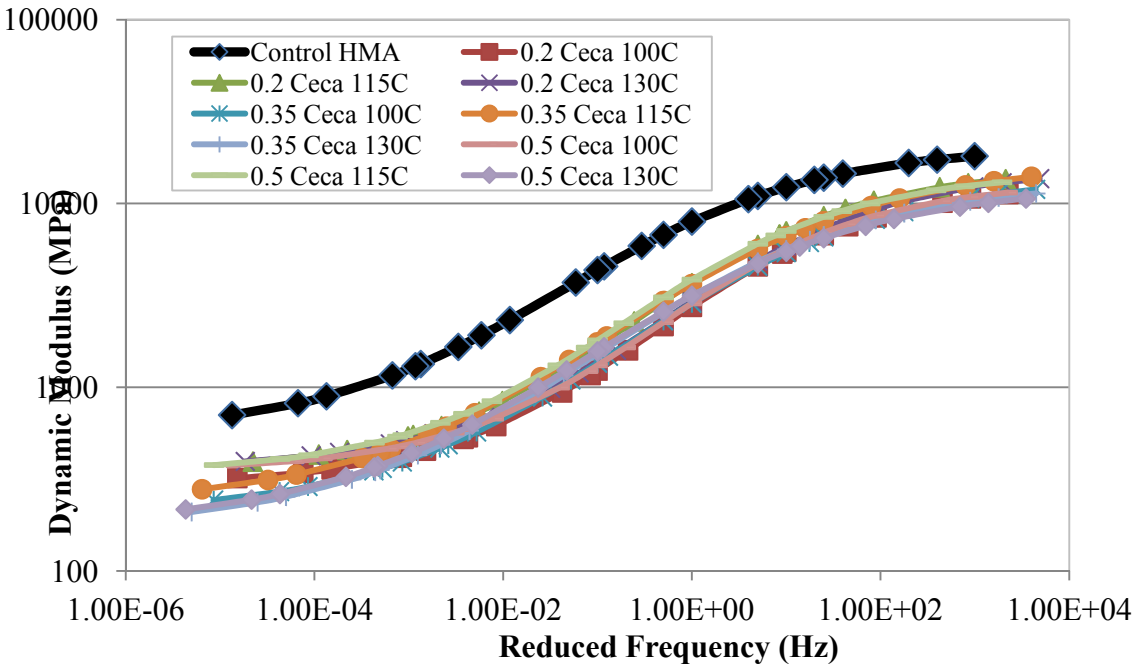



**Figure 51 Master Curve of Dynamic Modulus of Control HMA and WMA made with Cecabase RT®**

**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 25ºC and 0.085mm/s.

Figure 52shows 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.

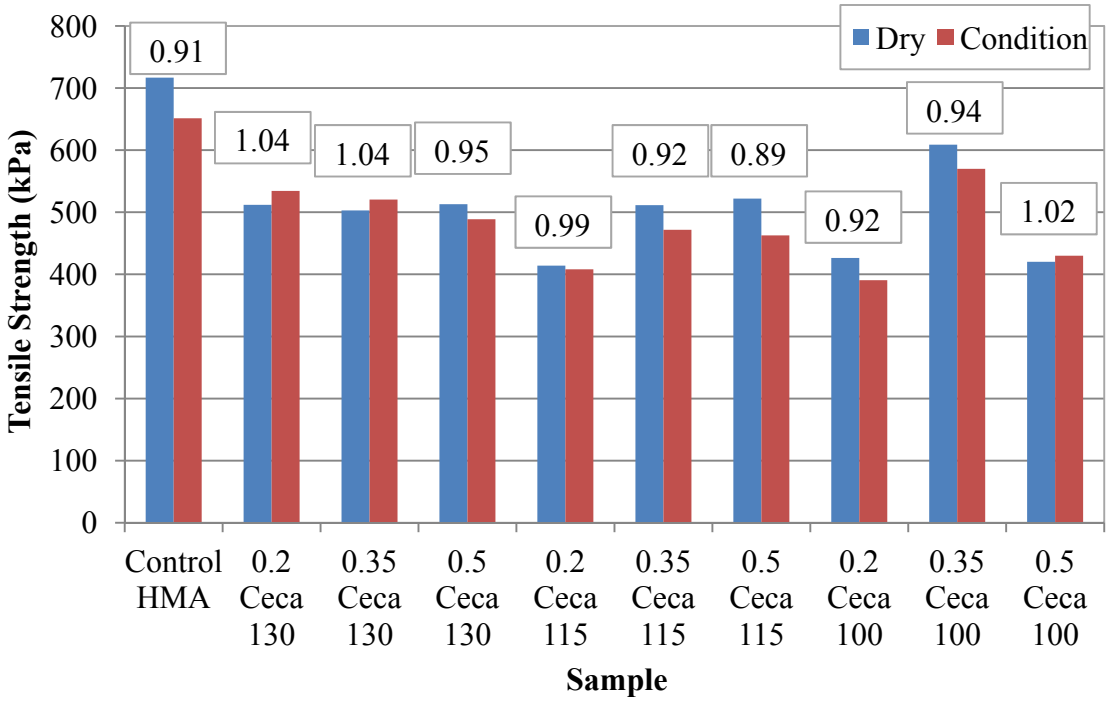



**Figure 52 TSR Results of Control HMA and WMA made with Cecabase RT®**

## 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.

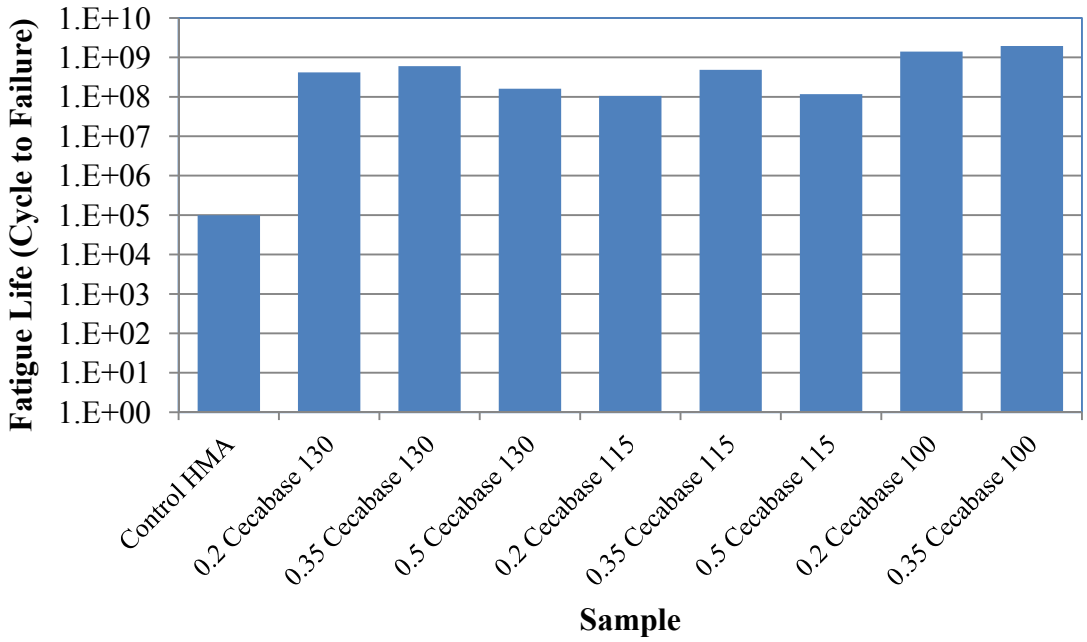



**Figure 53 Four Point Beam Fatigue Test Results for Control HMA and WMA made with Cecabase RT®**

## 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 54shows 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 Ceabase® RT are lower than the control HMA. These results are in line with the findings from |E*| which shows that WMA has a higher rutting potential. As mentioned previously, the reason was due to lesser aging of WMA during the production. The testing results also indicated that the $F_N$ slightly decreases when more Cecabase RT® is added.

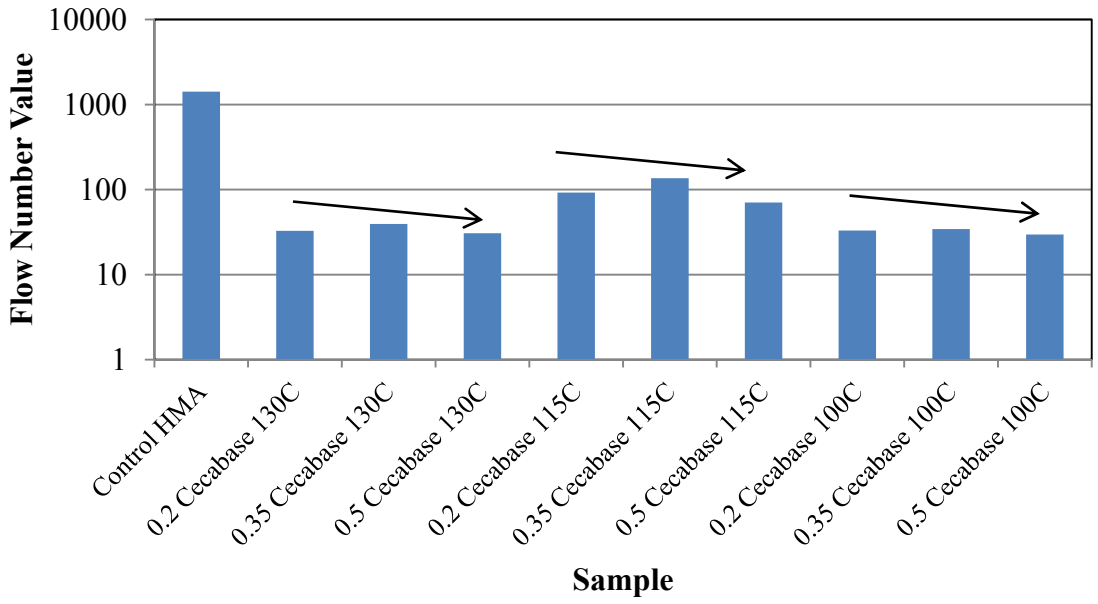



**Figure 54 Flow Number of Control HMA and WMA made with Cecabase RT®**

**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 54also 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.

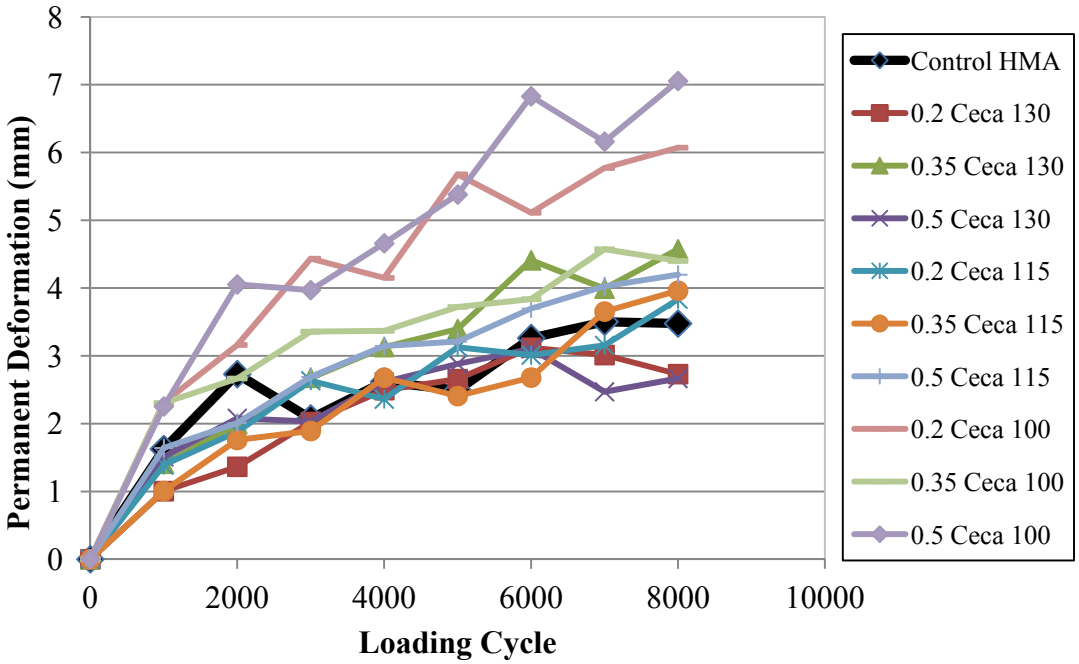



**Figure 55 APA Rutting Results for Control HMA and WMA made with Cecabase RT®**

## 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 access 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 access the rutting, fatigue and moisture susceptibility of WMA. The findings from laboratory evaluation will be discussed in this section to develop the WMA mix design framework.

The summary of the performance testing results for all WMA case studies arepresented 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 | Similar or Higher \|E*\| Comparable or better rutting resistant | - | Lower Rutting Rutting decrease when mix/ compact temp. increase | - | - |
| | **Advera® WMA** | No Change | Lower | Lower \|E*\| Increase rutting potential | Lower $F_N$ | Higher Rutting | Higher Fatigue Life | TSR value no change or higher; But, lower tensile strength was found |
| | **Water Foaming** | No Change | Lower | Lower \|E*\| Increase rutting potential | Lower $F_N$ | Higher Rutting | Higher Fatigue Life | Higher TSR TSR increase when mix/ compact temp. increase |
| **Organic Additive** | **Sasobit®** | Increase | Lower Samples at 130°C has higher aging factor. Aging factor increase when temp. increase | No Significant Different | No Significant Different | Samples with less Sasobit® have higher rutting. | No Significant Different | No Significant Different Lower tensile Strength was found |
| **Chemical Package** | **Cecabase RT®** | No Change | Lower | Lower \|E*\| Increase rutting potential | Lower $F_N$ $F_N$ decrease when more Cecabase RT® was added | Samples produced at 100°C have higher rutting. No significant for the rest of the samples. | Higher Fatigue Life | TSR value no change or higher; But, lower tensile strength was found |

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

## 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 | <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$^{TM}$ 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

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

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

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

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

C: correction factor

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

Gmm: Maximum specific gravity of the sample

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

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

$N_D$: 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 Superpave$^{TM}$ 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 13is 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 reducesthe 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 access WMA rutting, fatigue and moisture susceptibility. Based on the testing results, most of the WMA has higher fatigue life and TSR which indicated WMA has better fatigue cracking and moisture damage resistant; however, the rutting potential of most of the WMA tested were higher than the control HMA. A summary of the findings from all testing result was summarized in Table 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 16Average 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 |