Evaluation of Warm Mix Asphalt Versus Conventional Hot Mix Asphalt for Field and Laboratory-Compacted Specimens

by

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ABSTRACT

A recent joint study by Arizona State University and the Arizona Department of Transportation (ADOT) was conducted to evaluate certain Warm Mix Asphalt (WMA) properties in the laboratory. WMA material was taken from an actual ADOT project that involved two WMA sections. The first section used a foamed-based WMA admixture, and the second section used a chemical-based WMA admixture. The rest of the project included control hot mix asphalt (HMA) mixture. The evaluation included testing of field-core specimens and laboratory compacted specimens. The laboratory specimens were compacted at two different temperatures; 270 °F (132 °C) and 310 °F (154 °C). The experimental plan included four laboratory tests: the dynamic modulus (E*), indirect tensile strength (IDT), moisture damage evaluation using AASHTO T-283 test, and the Hamburg Wheel-track Test.

The dynamic modulus E* results of the field cores at 70 °F showed similar E* values for control HMA and foaming-based WMA mixtures; the E* values of the chemical-based WMA mixture were relatively higher. IDT test results of the field cores had comparable finding as the E* results. For the laboratory compacted specimens, both E* and IDT results indicated that decreasing the compaction temperatures from 310 °F to 270 °F did not have any negative effect on the material strength for both WMA mixtures; while the control HMA strength was affected to some extent. It was noticed that E* and IDT results of the chemical-based WMA field cores were high; however, the laboratory compacted specimens results didn’t show the same tendency. The moisture sensitivity

findings from TSR test disagreed with those of Hamburg test; while TSR results indicated relatively low values of about 60% for all three mixtures, Hamburg test results were quite excellent.

In general, the results of this study indicated that both WMA mixes can be best evaluated through field compacted mixes/cores; the results of the laboratory compacted specimens were helpful to a certain extent. The dynamic moduli for the field-core specimens were higher than for those compacted in the laboratory. The moisture damage findings indicated that more investigations are needed to evaluate moisture damage susceptibility in field.

DEDICATION

I dedicate this work to my family and in particular my parents for their love and support throughout my entire life.

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First, I would like to express my sincere thanks to my adviser Dr. Kamil E. Kaloush for his unconditional encouragement and support throughout my academic study at ASU. I am grateful to all of his guidance and proud of being one of his graduate students.

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CHAPTER 1. INTRODUCTION

1.1 Background

Warm Mix Asphalt (WMA) is a term refers to the production of asphalt mixtures at temperatures lower than the classic Hot Mix Asphalt (HMA) production temperatures. The magnitude of temperature reduction can be as much as 50 ºF [28 ºC] or higher *(1)*. The idea of producing asphalt material at reduced mixing temperatures was carried out in 1956 by Professor Ladis Csanyi at Iowa State University when he attempted to foam the asphalt binder using steam *(2)*. Warm mix asphalt was first introduced to the world on the mid 1990's in Europe. Since the early years of exploring WMA, many trial sections were placed in Germany, Norway, France and other European countries. In the late 1990's, the first WMA pavement was constructed in Europe (*3*). Later, after WMA technology was first brought to the U.S. in the early 2000's, many research studies were intended to explore and enhance the viability of using different WMA additives and come up with new methods to produce WMA. The production of an asphalt mix at reduced temperature can be mainly achieved through either the foaming-based approach or the chemical-based approach. Both approaches result in a reduction of the binder viscosity in such that full coating of the aggregate can be achieved; however, different mechanisms are applicable to each approach *(4)*. Compaction temperature can be reduced as low as 190 ºF (88 °C) *(5)*. Also, production of the WMA can extend the paving window especially in cold weather *(6)*.

Foaming-based approach is the process of adding water into the asphalt binder during production. When water gets heated, it evaporates and turns into

steam. Steam has the ability to expand dramatically, which allows for reduction in the viscosity of the binder *(7)*. This process can be achieved using one of two scenarios; either by injecting the water directly through a foaming nozzle, or by using a hygroscopic agent material such as Zeolite.

Chemical approach is the process of adding chemical components during production of asphalt mixtures in order to reduce the stiffness of the binder. Chemicals can be added either directly to the asphalt binder or to the mixture during production. Chemicals include waxes, and components that lubricate and enhance the coating of aggregate particles *(8)*. Hurley and Prowell have reported that the usage of chemical-based approach can lead to a reduction of 30% in the production temperature *(9)*.

Producing WMA at low temperatures has raised concerns about the mixture properties in terms of rutting and moisture damage *(9)*. Since WMA is exposed to a lesser amount of aging compared to HMA, the chance of being susceptible to rutting and moisture damage is high. However, most WMA additives have shown no evidence of increasing the rutting potential *(9)*. The National Center for Asphalt Technology (NCAT) has reported that the usage of chemical additives has no significant effect on the complex modulus of the asphalt pavement *(5)*. The usage of anti-stripping agent has a major role on decreasing the risk of moisture damage *(9)*. Some studies on foaming-based WMA indicated a slight decrease in the TSR values.

1.2 Objective

The objective of this study was to evaluate the laboratory performance of two different WMA mixtures using foamed-based and chemical-based modification processes. Two WMA sections and a control HMA section were built on State Route (SR 85), Gila Bend-Buckeye Highway just outside Phoenix, Arizona. The study included laboratory testing of field cored specimens as well as laboratory-compacted specimens using field mixes at two different temperatures (270 °F and 310 °F).

1.3 Scope of Work

This thesis is divided into six chapters. Chapter 1 presents a general introduction to warm mix asphalt concept along with the objectives and scope of work of the study. Chapter 2 summarizes a literature review on the available WMA technologies, concepts, and benefits. In addition, background of the laboratory testing protocols for the tests conducted in the study is included in this chapter. Chapter 3 presents a description of the paving project and the experimental plan for the laboratory testing, terminology and classification of the specimen groups. Chapter 4 presents the results of all laboratory testing that were conducted along with the statistical analysis. Finally, conclusions and recommendation for future research are included in Chapter 5.

CHAPTER 2. LITERATURE REVIEW

2.1 Types of Asphalt Mixtures

Asphalt mixtures as shown in FIGURE 1 can be categorized into four known applications according to the correspondent mixing temperature; cold mixes, half-warm mixes, warm mixes, and hot mixes. WMA can be distinguished from the other types of mixtures as being mixed on the range of 200 °F to 275 °F. As the mixing temperature increases, asphalt mixtures are classified as follows:

- Cold mix asphalt is mixed at temperature ranges from 68 °F to 120 °F.
- Half warm mix asphalt is produced on the range of 120 °F to 200 °F.
- Warm mix asphalt (WMA) is produced at temperature ranges from 200 °F to 275 °F.
- Hot mix asphalt (HMA) is produced at temperatures ranges from 285 °F to 340 °F *(10).*

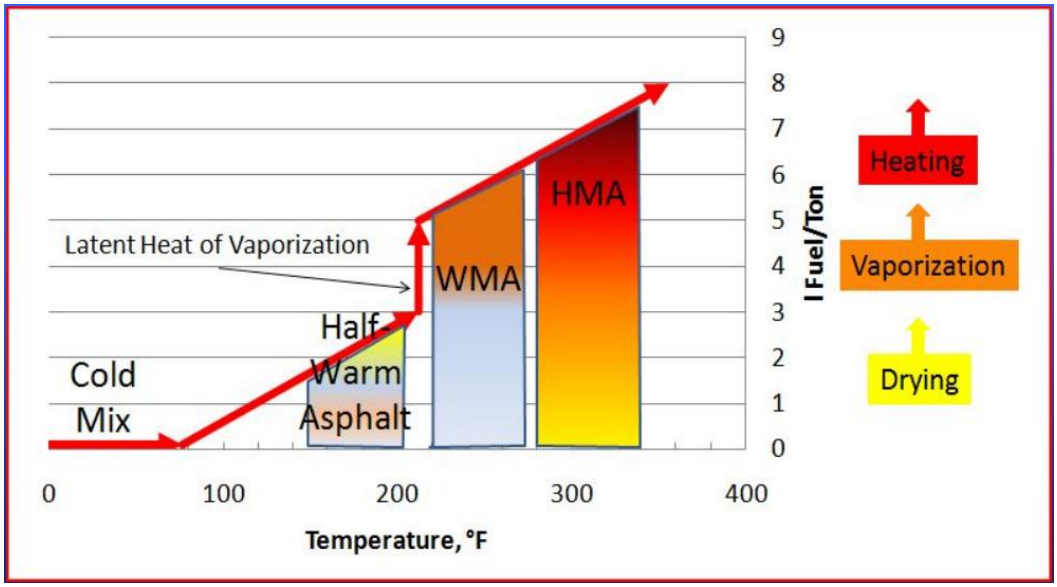

FIGURE 1 Types of asphalt mixtures. (*10*)

Hot mix asphalt (HMA) as being compacted at higher temperatures than the cold mixtures, it subsequently has higher stability and durability compared to the cold mixtures. Cold mixes are considered on the lower pavement layers for low traffic-volume roads *(11).*

2.2 WMA Technologies

WMA technology has been growing significantly in the past decade. The idea of WMA production is based on the possibility of reducing the binder's viscosity; in fact, most of today's versions of WMA are based on the 1997 German Bitumen Forum *(12)*. Producing an asphalt mix at lower temperature can be achieved mainly by following one of two main approaches; foaming approach, and chemical modifiers approach. Both technologies result in a reduction of the binder's viscosity in order to allow for coating the aggregate propely, however, different mechanisms are applicable on each approach. The reduction of the binder's viscosity can be achieved according to one of two procedures, either by foaming the binder or by adding an additive to the asphalt binder or mix *(4)*.

2.2.1 Foaming-based Methods

Foaming approach is basically the procedure of adding certain amount of water to the asphalt binder during mixing. Due to heating, the water evaporates and turns into steam. It expands by factor of 1,673 *(10)*. The amount of water added to the binder can control the amount of steam expansion which consequently can achieve the desired degree of cooling to the binder. The process of introducing the water into the binder can be done using one of the following two scenarios:

- Inject water directly through a foaming nozzle.
- Using a hygroscopic agent material such as zeolite.

These materials are normally blended with the hot aggregates in such that they release water at higher temperatures and create foaming environment allows the binder to effectively coat the aggregates at low temperatures. This foaming system lasts until the temperature drops below 212 ºF *(13).*

There are many WMA products use the foaming technology; following is a brief summary of the available foaming agents in the industry.

i. *Advera-PQ* Corp.

Advera is a foaming-based additive used to produce WMA. It is manufactured by PQ Corporation, Malven, PA. It comes in a form of white fine powder that has 18-21% of its weight as water. Advera is a synthetic Zeolite component (Sodium Aluminum Silicate) that releases water at temperatures above 210 °F, and consequently reduces the viscosity of the binder by creating water-based foam that increases the binder's workability. This allows for reduction in mixing temperatures from 50-70 ºF. The manufacturer recommends adding Advera on dosages of 0.25% of the weight of the asphalt mix (typically 5 lbs/ton of mix) *(14), (15).*

ii. *Double Barrel Green-Astec*

Double barrel technology relies on creating foaming ambient by injecting a small amount of water via a multi-nozzle device. Water turns into steam once it contacts the binder and then evaporates resulting in a reduction in the viscosity of the binder coating the aggregates. This technology allows the binder to effectively

coat the aggregates at temperatures that normally range from 230-270 °F. The process requires injecting amount of water of 1% of the weight of the asphalt mix (typically 1 lb. water per ton of mix) *(16), (17).*

iii. Green Machine-Gencor

Green Machine-Gencor is a foaming process that introduces the water into the mixing process causing the binder to foam. Gencor system injects water into the foaming process, using only the energy of the pump that provides the binder. This process recommends injecting amount of water of 1.25% to 2% by weight of mix *(18).*

iv. Aquablack-Maxam

Aquablack is a foaming process uses the micro-bubble foaming technology. Micro-bubbles stay in the mix until it's compacted. This process retains only ¼ cup of water per ton of warm mix asphalt *(19).*

v. WMA System-Terex

Terex is a foaming technology reduces the mixing temperatures by up to 90 ºF. The production of the foamed asphalt occurs just outside of the drum and immediately injects into the drum's mixing chamber to coat the aggregates *(20).*

vi. Low emission Asphalt-Suite-Kote

The mechanism of low emission technology involves adding chemical admixture to the hot coarse aggregate, then followed by adding wet sand (fine aggregates) that creates the foaming ambient to enhance the coating of aggregates once it gets heated. The amount of wet sand could be as high as 40% of the weight of the mix and can also contains Reclaimed Asphalt Pavement (RAP) *(21).*

2.2.2 Chemical-based Methods

Chemical approach relies upon adding chemical components during production in order to reduce the binder's stiffness during mixing and compaction. Two main ways to add the chemicals are available; either by adding it directly to the binder, or to be added to the admixture during production. Additives include waxes and chemicals that lubricate and enhance the coating of aggregate particles *(22)*.

i. Evotherm-MeadWestvaco

Evotherm is a product of MeadWestvaco Asphalt Innovations, Charleston, South Carolina. Evotherm utilizes chemical package that comes in a form of emulsion blended with binder and then mixed with hot aggregates. MeadWestvaco reports that Evotherm allows for mixing temperatures between 185 Fº to 240 ºF, in addition to the tremendous reduction in emissions *(13), (14)*. Two products of Evotherm are available; DAT that (Dispersed Asphalt Technology), and 3G (REVIX). 3G technology is based on reducing the internal friction between aggregates particles and the thin films of binder by the act of the emulsion *(14)*.

ii. Redsit-Akzo-Nobel

Redsit is a chemical product of Akzo-Nobel that comes in pellet form, and mostly added to the binder prior to mixing. Akzo-Nobel reports that Rediset is able to reduce the mixing and paving temperatures by at least 30 ºC. Also, the product has a high resistance to moisture in such that the producer claims that Redsit can replace the use of anti-stripping agent on the mix *(23)*.

iii. Revis-Mathy-Ergon

Revis is a product of Ergon Asphalt and Emulsions Inc. and Mathy construction Co. The manufacturer reports that Revix is able to reduce the mixing temperatures by up to 75 ºF. Rvix will be internationally marketed by WMV Specialty Chemical Division's Asphalt Innovations team as MWV Evotherm 3G (*24*). There is too little information about this product in the literature.

iv. Sasobit-Sasol

Sasobit is a product of Sasol Wax Co. Sasobit is a fine crystalline that comes in bags in a form of powder. Sasobit has the ability to dissolve easily into the binder at temperatures above 248 ºF. Sasol describes Sasobit as an asphalt flow improver during mixing and compaction, where it can reduce the mixing temperatures from 300 Fº to 250 ºF which can lead to tremendous savings in fuel consumption. For ultimate results, Sasol recommends adding Sasobit at 3% by weight of the mix, and also to be added to and blended with the hot binder *(25), (14)*.

2.3 Benefits of Warm Mix Asphalt Technology

1. Reduced emissions

Emissions and fumes generated from HMA production and compaction have been a major concern on the safety of the paving crew members; in fact, the National Institute for Occupational Safety and Health (NIOSH) in the U.S. published a hazard review manual in 2000 to address the health effects and consequences of occupational exposure to asphalt. Based on studies made on humans and experimental animals, NIOSH indicated that exposure to asphalt for long time can

cause local skin carcinomas. The manual summarized the following precautions and practices for safety *(26)*.

- "Prevent dermal exposure.
- Keep the application temperature of heated asphalt as low as possible.
- Use engineering controls and good work practices at all work site to minimize worker exposure to asphalt fumes and asphalt-based aerosols.
- Use appropriate respiratory protection." *(27)*

WMA technology could significantly minimize the risk of chemical fumes emitted from the asphalt plants. TABLE 1 summarizes the percentages of reduced emission when using different WMA additives.

TABLE 1 Emission Reduction for WMA Compared to HMA Mixes

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

[1)] Data from Charlotte, North Carolina in September 2004
[2)] Data from M-95 Iron Mountain, Michigan in September 2006
[3)] Data from Road#46 in Raman, Canada in 2005
[4)] Data from FV Frogn in Nesodden, Norway in April 2001 *(28)*

2. Fuel and energy savings

Energy savings and emission reduction can be defined as the most important WMA benefits. As WMA mixtures are mixed at lower temperatures, a tremendous amount of fuel will be cut compared to the conventional HMA. Many

researches indicated that up to 30% of the energy cost can be reduced when using WMA technology *(26)*. Saving on energy could be even escalated to 50% or more when using the Low Energy Asphalt (LEA); where the aggregates or portion of it are not heated beyond the boiling point (*10)*. Another possible benefit of mixing at low temperatures is the reduction on the wear of the asphalt plant as it being operated at lower temperatures.

3. *Viable tool to compact stiff mixtures*

WMA technology allows easier compaction for stiff mixes such as that have (RAP) *(2)*. Also, the low aged binder for WMA will compensate the high stiffness RAP binder, so the workability will be enhanced greatly when using WMA, in fact, In Germany, trials have been conducted with RAP percentage as high as 90% to 100% when Aspha-min Zeolite and Sasobit were used in trial sections *(2)*.

4. *Enhance the thermal cracking resistance*

Most of the binder aging that an asphalt mixture undergoes occurs during mixing at the asphalt plant and due to the exposure to high temperatures. As the WMA mixtures are mixed at lower temperatures compared to the HMA mixtures, thus the binder will subsequently have lesser oxidization due to the lower heat. Therefore, the hardening of WMA mixes would be minimized and thus the endurance to thermal cracking will increase significantly *(25)*. However, the low amount of aging that WMA undergoes may raise the concern of rutting; many studies stated that rutting has not been an issue with WMA *(9)*.

5. *Widen the compaction window*

WMA technologies allow for reduction on the binder viscosity. This can lead to achieving the same density as HMA with much lower compaction temperatures. As the WMA is mixed at lower temperatures compared to HMA, the difference on temperature between the mix and the ambient is consequently less. Thus, the rate of temperature loss will decrease significantly and WMA would cool slower and the allowed time for compaction would be longer.

2.4 Testing Protocols

2.4.1 Dynamic Modulus Test

2.4.1.1 Background of the Dynamic Modulus Test

The term modulus, in general, can be easily described as the ratio between stress and strain. It is known as the modulus of elasticity (E) as long as the material behaves in the elastic range, in such that the relation between stress and strain falls into a linear elastic relationship. In materials such as asphalt mixtures, the behavior is found to be in a visco-elastic manner. The modulus of the visco-elastic materials is defined by the term complex dynamic modulus (E*), which represents the response developed under sinusoidal loading conditions *(29)*.

The dynamic modulus protocol was first introduced by Coffman and Pegan in the 1960's at Ohio State University. Then the test was undertaken as the "Modulus Test of Choice" by the Asphalt Institute in the late 1960's by Kallas, Shock and Witczak *(29)*. Further, it was named as an ASTM procedure in 1979 under the name "Standard Test Method for Dynamic Modulus of Asphalt Concrete Mixtures" *(30)*. In 2002, NCHRP released the refined version for the

protocol included in the new Design Guide for New and Rehabilitated Pavements under NCHRP Project 1-37 that was led by Witczak and others at Arizona State University. Currently it is an AASHTO TP 62-07.

The dynamic modulus testing procedure can be generally addressed by applying a uniaxial load in either case of compression or tension. The modulus has been defined as (E*) for the case of applying compression loading, and (G*) for the case of applying tension loading. However, most of the testing was done using compression loading.

2.4.1.2 Theoretical Background of the dynamic modulus test

The dynamic modulus test for asphalt concrete mixtures, as described earlier, consists of applying an uniaxial sinusoidal (i.e., haversine) compressive loading to a cylindrical HMA specimen in either case of confined or unconfined ambient, as shown in FIGURE 2 *(30).* As the asphalt mixtures behavior falls under the linear visco-elastic materials, the relation between stress to strain under the sinusoidal loading was found to be a complex number called the complex modulus (E*) that is consist of a real and imaginary portions. The absolute value of the complex modulus |E*| is defined as the dynamic modulus which mathematically represents the ratio of the maximum dynamic stress (δ_0) to the maximum recoverable axial strain (ε_0) *(30).*

$$|E^*| = \frac{\delta 0}{\varepsilon 0}$$

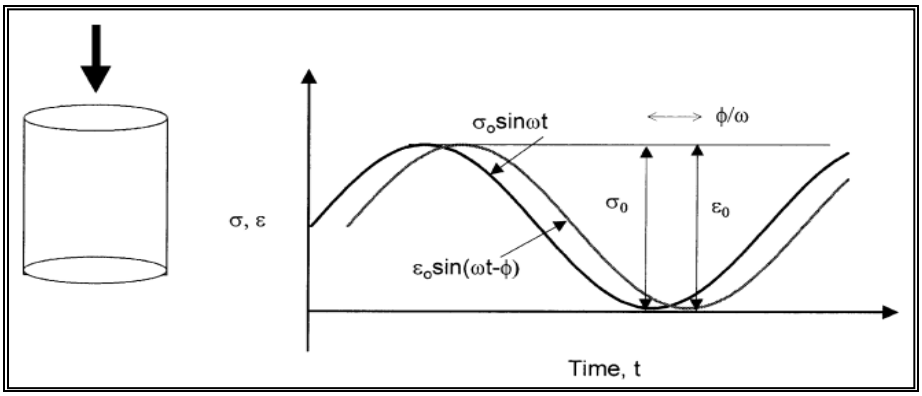

FIGURE 2 Haversine loading pattern. ***(30)***

The theoretical term of the sinusoidal stress (δ) at any given time (t) and angular load frequency (ω) is defined as:

$$\delta = \delta_0 \sin(\omega t)$$

Also, the theoretical term of the sinusoidal strain (ε) at the same time and frequency is defined as:

$$\varepsilon = \varepsilon_0 \sin(\omega t - \Phi)$$

By dividing the peak sinusoidal stress by the peak sinusoidal strain, E* can be defines as:

$$E^* = \frac{\delta o \sin(\omega t)}{\varepsilon o \sin(\omega t - ø)}$$

By simplifying the equation, E* can be denoted as:

$$E^* = \frac{\delta o e^{i(\omega t)}}{\varepsilon o e^{i(\omega t - ø)}}$$

Where, δ_o = peak (maximum) stress

ε_o = peak (maximum) strain

ø = phase angle, degrees

ω = angular velocity

t = time, seconds

i = imaginary component of the complex modulus *(29).*

The phase angle, ø, represents the viscous behavior of the asphaltic material. It can be simply defined as the angle by which ε_o lags behind δ_o as shown in FIGURE 2 The value of ø indicates the viscous properties of the materials as follows:

- If ø = 0º, the material is considered as pure elastic material and the complex modulus (E*) is equal to the absolute value, or dynamic modulus.
- If ø = 90º, the material is considered as pure viscous material.

As E* indicates the dynamics modulus for the compression case of loading and (G*) indicates the complex shear modulus for the tension case of loading, both moduli are mathematically related by the following formula:

$$E^* = 2(1 + \mu).G^*$$

Where: μ is the Poisson's Ratio *(29)*.

2.4.2 Indirect Diametral Tensile Strength (IDT) Test

The standard indirect diametral test is a part of the AASHTO TP 94 *(31)*: *Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device*. The test has been recommended for mixture characterization in the Long-Term Pavement Performance (LTTP) Program *(30)*. The test has been also in use to support the structural design in the 1986 and 1993 *AASHTO Guide for Design of Pavement Structures*. The test gained popularity due to its simplicity and applicability to conduct on thin lifts of field cores. The main purpose of the test is to determine the tensile strength of the

tested specimens using the procedure described in Attachment A to the SHRP Protocol P07. The test is conducted by applying compressive loading through two diametrically opposed plates on a cylindrical specimen as shown in FIGURE 3. Tensile stress will develop upon failure along the diameter of the specimen.

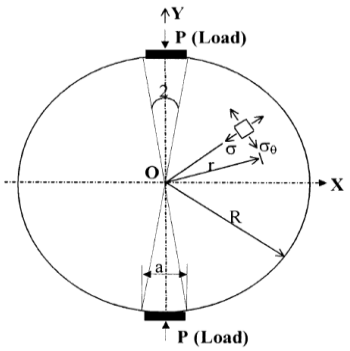

FIGURE 3 Indirect tensile strength testing.

The loading of the specimen is based on maintaining a constant strain rate until the failure of the specimen, which is defined by splitting the specimen apart along its diametral axis. The peak horizontal tensile stress on the center of the specimen can be calculated using the following equation:

$$\delta_{xy} = \frac{2\,P}{\pi t d}$$

Where:

δ_{xy} = Horizontal peak tensile stress

P = the applied load

t = thickness of the specimen or the field core

d = diameter of the specimen

2.4.3 Moisture Sensitivity Test AASHTO T283

The AASHTO T 283-89 is based on research performed by Lottman *(32)* and subsequently by Tunnicliff and Root *(33)*. The ASTM D4867 is a comparable method, with some differences. In either test, Marshall-size specimens with and without moisture saturation are tested for indirect tensile strength. The specimens without moisture saturation are the ones that are unconditioned, and those with moisture saturation are the ones that are conditioned for the purpose. The TSR (ratio between the tensile strengths of conditioned and unconditioned specimens) are determined as an indication of moisture damage potential.

The Lottman Test used in this study can be briefly described as follows:

1. The specimens were divided into dry and wet subsets as per the protocol. The dry subset was stored at room temperature and then tested.
2. The specimens of the wet subset were placed in a vacuum container filled of water under a vacuum of 10-26 inch Hg partial pressure (13-67 kPa absolute pressure) for approximately 8 minutes.
3. The vacuum is then removed and the specimen left submerged in water for approximately 7 minutes then the weight of the saturated, surface-dry specimen after partial vacuum saturation was determined by Method a of AASHTO T 166 (*34*) to get the degree of saturation of the specimen.
4. The samples are each wrapped with a Saran Wrap plastic film and placed in a plastic bag containing 10 ± 0.5 mL of water and sealed.
5. The plastic bags were placed in a freezer at a temperature of 0 ± 5°F (-18 ± 3°C) for a minimum of 16 hours.

6. After this, the plastic bags are placed in a water bath at a temperature of 140 ± 1.8°F (60 ± 1°C) for 24 ± 1 hour.
7. The specimen is removed from the bath and unwrapped, then conditioned for two hours at 70°F (25 °C).
8. The tensile strength of the wet subset was then obtained at 70 °F (25 °C). The specimens were placed on its side between the bearing plates of the testing machine and loaded till failure.
9. The Tensile Strength Ratio (TSR) is defined as the ratio of the average tensile strength of the wet specimens to that of the dry specimens. FIGURE 4 shows an illustration of the freezing and thawing cycles of the tested specimens.

FIGURE 4 Freezing and thawing cycle.

2.4.4 Hamburg Wheel-Track Test AASHTO T324-04

Hamburg test is known as the Hamburg Wheel-Track testing and was developed and first introduced in Hamburg, Germany. The test has been widely in use to evaluate and assess the effects of moisture damage on HMA. Many agencies and DOT's over the U.S have put extensive efforts to implement and adopt the testing for use in the U.S. Federal Highway Administration (FHWA) and Colorado Department of Transportation (CDOT) have done an extensive study to assess the potential of moisture damage in the state of Colorado since 1990. CDOT has put together Colorado Procedure CP-L 5112, which indicates the testing temperature according to site location and grade of the binder used (35), (36).

The basic concept of the test is to measure the combined effect of rutting and stripping on the asphalt pavement. The testing device as shown in FIGURE 5 uses two reciprocating steel wheels moves, at the same time, over two replicates of rectangular slabs or gyratory compacted cylinders. The steel wheel is 203.2 mm (8 in) in diameter and 47 mm (1.85 in) in width, and it's designed to apply a load of 705 ± 4.5 N (158 lb ± 1.0 lb). The device also provided with two Linear Variable Differential Transducers (LVDT's), one for each replicate in order to measure the rutting at the center of the specimen. The LVDT's are made to measure up to 0.01 mm and designed to be self-adjusted at the beginning of each test.

FIGURE 5 Hamburg wheel-tracking testing device.

The test protocol indicates passing the loaded steel wheel repeatedly over the test specimen until the specimen fails or reaches the maximum number of passes of 20,000 passes. The failing criterion is defined as 20 mm (4. inches), which represents the maximum allowed rut depth). The testing involves the conditioning of specimens for 30 minutes in a water bath that is capable to maintain the temperature within ±1.0 ºC of the designated test temperature. The water bath should have a circulation system in order to maintain a steady conditioning temperature. The testing temperature varies according to the grade of binder used in the mix.

CHAPTER 3. PROJECT DESCRIPTION, EXPERIMENTAL PLAN AND SPECIMENS PREPARATION

3.1 Description of the Project

In June 2009, the Arizona Department of Transportation (ADOT) constructed a new southbound (SB) roadway connecting the previously completed road that parallels the existing SR 85 mainline from approximate MP 130.71 to another completed section of the same roadway at approximate MP 137.00. The project included two WMA sections with two different additives as well as a control HMA mixture section. The first WMA mixture included a chemical additive and will be referred as chemical-based WMA; while the second WMA mixture was a foaming process and will be referred to as foaming-based WMA. The chemical-based WMA mixture was placed on the right travel lane of SR 85 with a length of 9700 feet (3166 feet south of and 6534 feet north of MP 136); while the foaming-based WMA mixture was placed also on the right travel lane with a length of 7232 feet (4739 feet south of and 2493 feet north of MP 133). The rest of the project length was completed with a control HMA mixture. The targeted compaction temperature for the foaming-based field WMA mixture was 230 °F to 245 °F (110 °C to 118 °C); it was 250 °F (121 °C) for the chemical-based compared to a 311 °F (155 °C) for the control HMA mixture. FIGURE 6 shows the milepost and location of the project different sections.

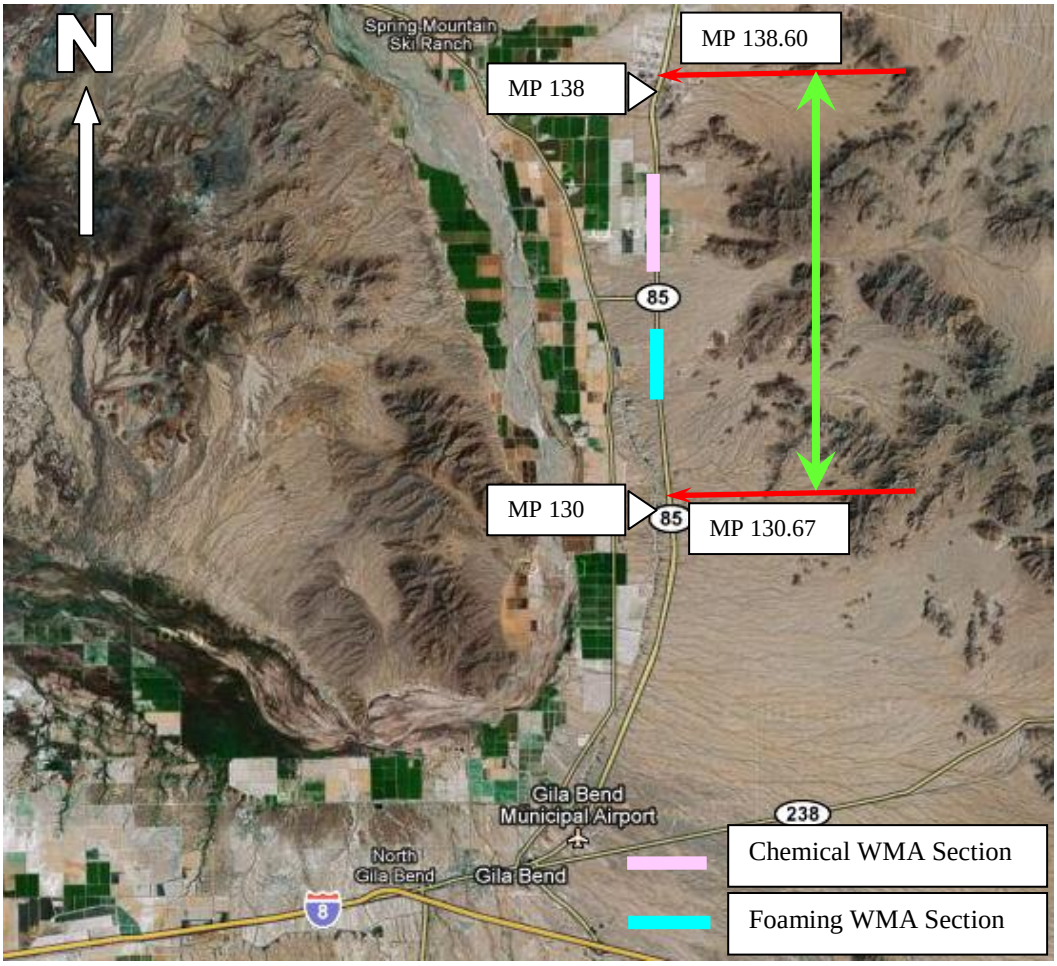

FIGURE 6 Milepost and location for the test sections. (Google Maps).

3.2 Mixture Design

The mix design for this project was a 3/4" ADOT 416 special item in accordance with the ADOT Standard Specifications for Road and Bridge Construction. The binder grade used was PG 76-16 with a design asphalt content of 4.8% and the target air void was 5.5+0.2 %. Hydrated lime was used as an anti-stripping agent mixed with aggregate in percentage of 1% of weight of aggregate. The estimated lab mixing temperature of the control HMA was 331 °F (166 °C) and lab compaction temperature was 311 °F (155 °C). TABLE 2 shows the typical aggregate gradation of the mix.

TABLE 2 Composite Aggregate Gradation

Sieve Size	Composite w/ Admixture	Specification
2”	100	
1.25”	100	
1”	100	(100)
¾”	100	(90-100)
½”	86	
3/8”	76	(62-77)
¼”	65	
#4	57	
#8	41	(38-47)
#10	38	
#16	30	
#30	21	
#40	17	(11-19)
#50	13	
#100	8	
#200	5	(2.5-6.0)

3.3 Experimental Design

The experimental program for this study included two WMA mixtures and one conventional HMA mixture. WMA mix from the first section involved using Advera WMA additive and will be denoted as the Foaming-based mix. WMA from the second section involved using Evotherm WMA additive and will be denoted as the Chemical-based mix. Conventional HMA mix will be denoted as the Control mix. Specimens from each of the three mixes were divided into two categories; field-core specimens and laboratory-compacted specimens.

A. Field-core specimens: include cores that were taken from the actual pavement. Cores were typically 4” (100mm) in diameter, and 2” (50mm) in thickness. A total of 27 cores were taken from the pavement site; 9 from each section. Cores were sealed in plastic bags until they were utilized for

testing (E* and IDT). FIGURE 7 shows example of the field core specimens.

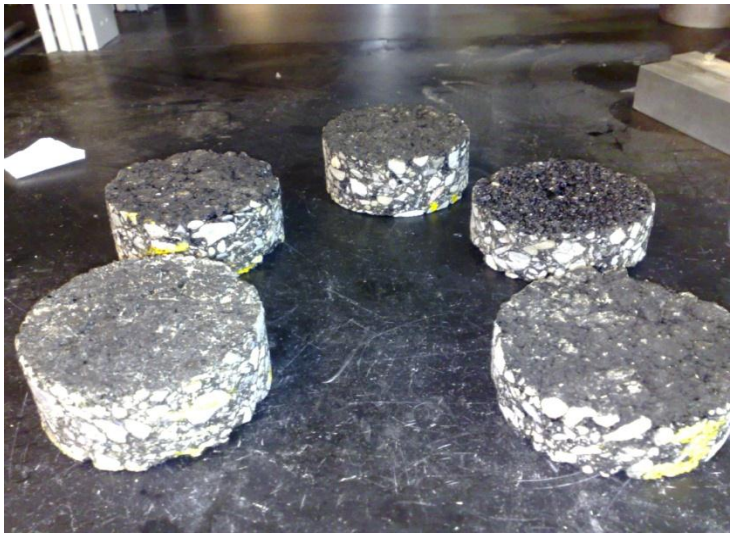

FIGURE 7 Field core specimens.

B. Laboratory-compacted specimens: loose mix materials were taken from the paving site and brought to the lab in small buckets until they were reheated and compacted. In general, all of the three mixes; Control, Foaming-based and Chemical-based was reheated in the lab and compacted at two different compaction temperatures 270 °F (132 °C) and 310 °F (154°C). Both WMA mixes had the WMA additive already on it prior to reheating.

- Foaming-based mix that had the additive (Advera) been added on the plant will be denoted as Advera Added at Plant (AAP) mix.
- Chemical-based mix that had the additive (Evotherm) been added on the plant will be denoted as Evotherm Added at Plant (EAP) mix.

C. Foaming-based mix was also intended to conduct a small study to investigate the effect of reheating on WMA, so Advera powder was added to a loose control mix on the lab (on dosage of 0.25% of the mix weight). This mix was also compacted at 270 °F and 310 °F and will be denoted as Advera Added at Lab (AAL) mix. FIGURE 8 shows example of the E* laboratory specimens.

FIGURE 8 Laboratory E* specimens.

FIGURE 9 shows a summary of the sampling plan diagram and terminology for the three mixes.

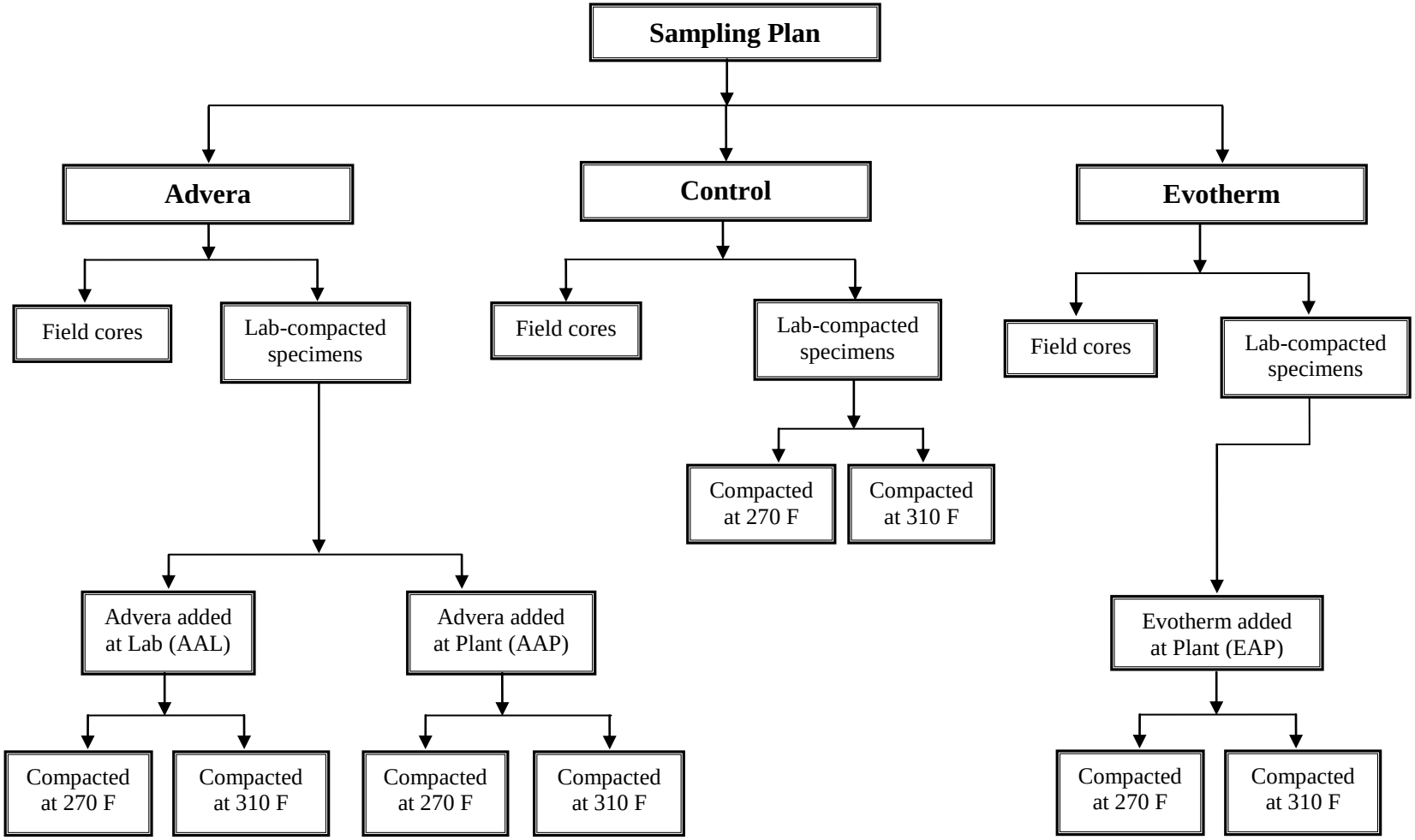

FIGURE 9 Sampling plan and terminology.

3.4 Testing Plan

Four laboratory testing were intended in general for this study in order to evaluate the WMA in comparison to the conventional HMA. The evaluation was divided into mixture strength evaluation and moisture damage evaluation. The mixture strength evaluation included; dynamic modulus as well as the indirect diametral tensile strength (IDT) tests. FIGURE 10 represents a summarized flowchart for both strength and moisture damage testing plan.

As illustrated in FIGURE 10, E* testing was conducted for the three mixes; Control, Foaming-based and Chemical-based. Each of the three mixes included the testing of field stacked cores as well as laboratory-compacted specimens. Laboratory prepared specimens were compacted at 270 °F and 310 °F. All field specimens were tested for E* using 3 replicates, except for the Chemical-based field cores which had only 2 replicates because of the limited number of cores. Also, laboratory specimens for the Foaming-based and the Chemical-based used 4 replicates while the Control mix used 3 replicates.

IDT testing was also conducted for all three mixes and each of the three mixes included the testing of field cores and laboratory prepared discs that were cut from the E* lab specimens. Field cores for both Foaming-based and Chemical-based used 2 IDT replicates while the Control mix used 8 replicates. Laboratory specimens for the Control mix used 4 replicates at each compaction temperature. For the Foaming-based mix, 4 replicates were used for all combinations except for AAL compacted at 310 °F which had 9 replicates. For

the Chemical-based mix, 3 replicates were used for both combinations compacted at 270 °F and 310 °F.

TSR test was done for only laboratory specimens compacted at 270 ºF. Specimens were divided into conditioned and unconditioned sets. Specimens that were used on the IDT test were considered as the unconditioned specimens. For conditioned specimens, 3 replicates were used for Control and Chemical-based mixes while 4 replicates were used for both Foaming-based mixes AAL and AAP.

Hamburg Wheel Tracking test were conducted for all combinations on slab specimens compacted at 270 °F. 2 slab replicates were used for each mixture. FIGURE 10 shows the testing plan for the study.

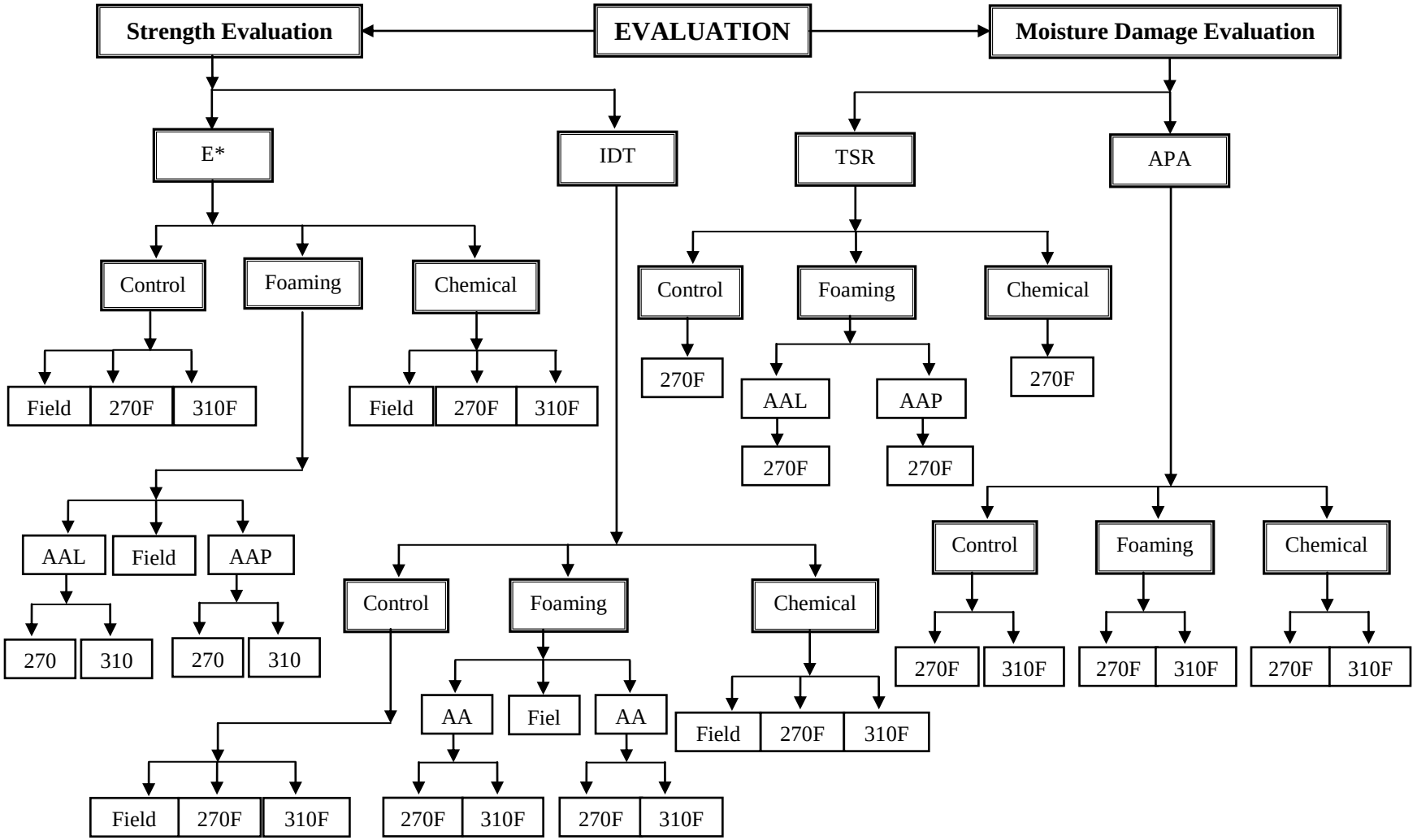

FIGURE 10 Evaluation testing Plan

3.5 Specimen Preparation

Samples from each section included field cores as well as loose asphalt concrete mixtures sampled from the field during construction. In the laboratory, the loose mixtures form the control section as well as the two WMA sections were reheated and compacted with a "Servopac Gyratory Compactor" at two different temperatures; 270 °F (132 °C), and 310 °F (154 °C). For both control and WMA mixtures, laboratory specimens were compacted into a 6-inch (150 mm) diameter gyratory mold. One 4-inch (100 mm) diameter sample was cored from each gyratory plug. The sample ends were sawn to arrive at typical test specimens of 4-inch (100 mm) in diameter and 6-inch (150 mm) in height.

3.5.1 Complex Modulus Sampling and Testing

The dynamic modulus (E*), per AASHTO TP 62-07 *(37)* was performed in the laboratory at only 70 °F (21.1 °C) and six load frequencies: 25, 10, 5, 1, 0.5 and 0.1 Hz. The stress levels were varied with the frequency to keep the specimen response within a linear viscoelastic limit (recoverable microstrain below 150 microstrain). A servo hydraulic testing machine was used to load the specimens. A dynamic haversine stress (continuous wave) was applied and measured through a load cell, whereas, the deformations were measured using two spring-loaded LVDTs (Linear Variable Differential Transducers). The LVDTs were secured in-place using brackets and studs glued onto the specimens. Guide rods were added to the instrumentation to ensure alignment.

As mentioned earlier, laboratory manufactured test specimens were cored and sawed to a typical dimension of 4-inch (100 mm) diameter and 6-inch (150 mm) height. For field cored specimens, the overlay thickness was only 2-inch (50 mm), so, three cores were stacked together using the same binder grade PG-76-16 as a light tack to hold the three cores together and to arrive at the required specimen height of approximately 6 inches (150 mm). In this case, the LVDTs were mounted to the middle core only with a smaller gage length of 1.5-inch (38 mm) instead of the 4-inch (100 mm) for a typical specimen, which satisfy the specification of the minimum gauge length to be greater than the maximum aggregate size which for this case is ¾ inch. FIGURE 11 illustrates the instrumented E* specimen compacted in lab as well as stacked cores from field.

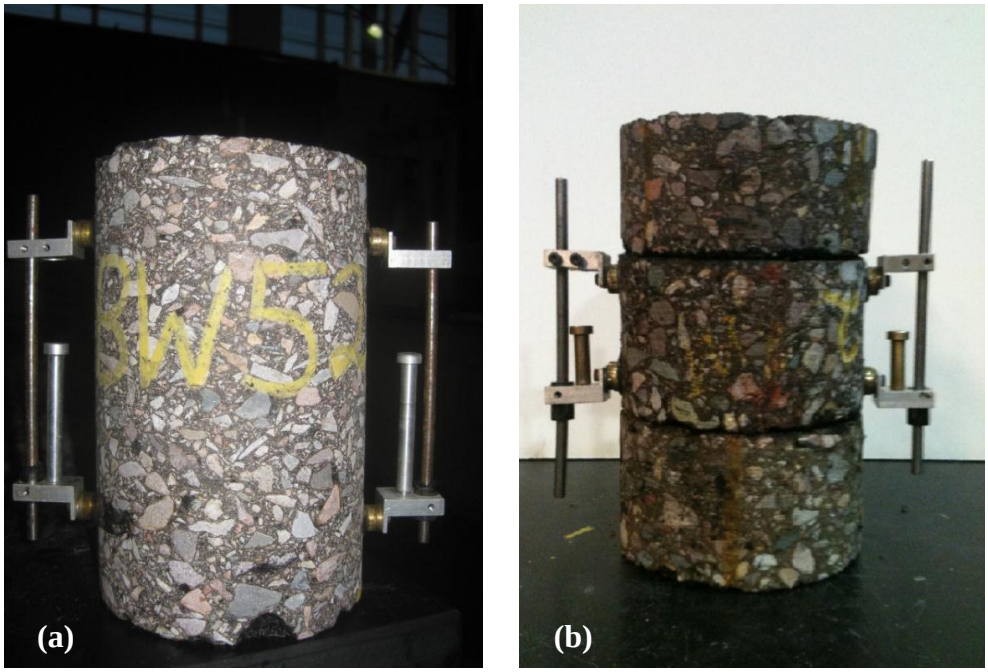

FIGURE 11 Instrumentation of E* specimens; (a) lab compacted specimen and (b) field stacked cores.

3.5.2 Indirect Diametral Test (IDT) specimen preparation and testing

In this test, a specimen of 4-inch (100 mm) diameter and about 2.5-inch (63 mm) thickness is loaded at a constant rate of 2.0 inch per minute (0.847 millimeter per second) until failure. The indirect tensile strength value is then determined as the peak stress value. The test can be performed on specimens compacted by the super pave gyratory compactor by cutting cored specimen into two or three parts. In this study, the cored specimens were cut into three parts each 4-inch (100 mm) diameter by 2-inch (50 mm) height. For field cores, the average height of the specimens was 2 to 2.5-inch in that they were ready to be directly tested. All the specimens were tested at a temperature of 70 °F (21.1 °C). FIGURE 12 shows the test setup and failure mechanism for one of the tested specimens.

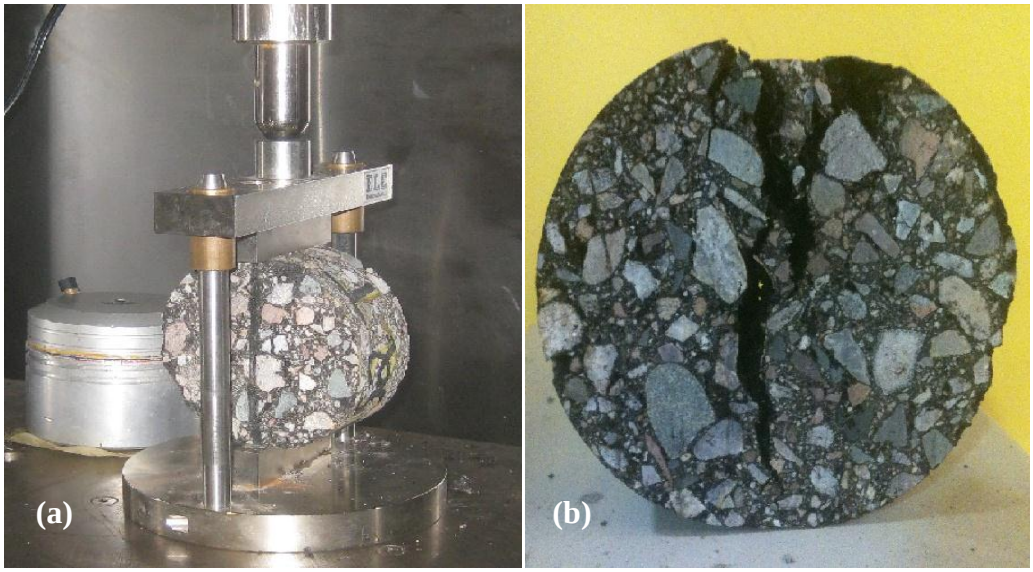

FIGURE 12 (a) Indirect tension test setup and (b) failed specimen.

3.5.3 Hamburg Wheel Tracking Specimens Preparation

This part of the study was conducted at the Arizona Department of Transportation laboratories. The Hamburg testing device is designed to accommodate two replicates at the time. The replicates could be either slab specimens or cylinders, in such that:

- Slab specimens are 320 mm (12.5 in) long, 260 mm (10.25 in) wide, and 38 mm (1.5 in) to 100 mm (4. in) thickness. Thickness of the slab should be at least twice the size of the nominal maximum aggregate of the mixture.
- Gyratory-compacted cylinders are arranged in 2 adjacent cylinders on each side of the machine. The cylinder is 150 mm (6. in) diameter and 38 mm (1.5 in) to 100 mm (4. in) thickness. Thickness of the cylinder should be at least twice the nominal maximum aggregate size of the mixture.

Mixing temperature of the specimens in accordance to the mix design must be with respect to achieve a viscosity of 170 ± 20 cSt. Also, the compaction temperature of specimens should meet the requirement to achieve a viscosity of 280 ± 30 cSt. Compaction of the slab specimens must be done by using a linear kneading compactor as shown in FIGURE 13.

FIGURE 13 Compaction of beams using kneading compactor.

After compaction to the designated air voids, slabs must be cooled at room temperature until it is cool to touch. Air voids then must be calculated to the beam in accordance with T 269 procedures as shown in Appendix B. Then, slabs should be mounted on trays using plaster material such as Plaster-of-Paris. The plaster is used to fill the voids between the tray and the beam and also with a thin layer underneath the slab as shown in FIGURE 14.

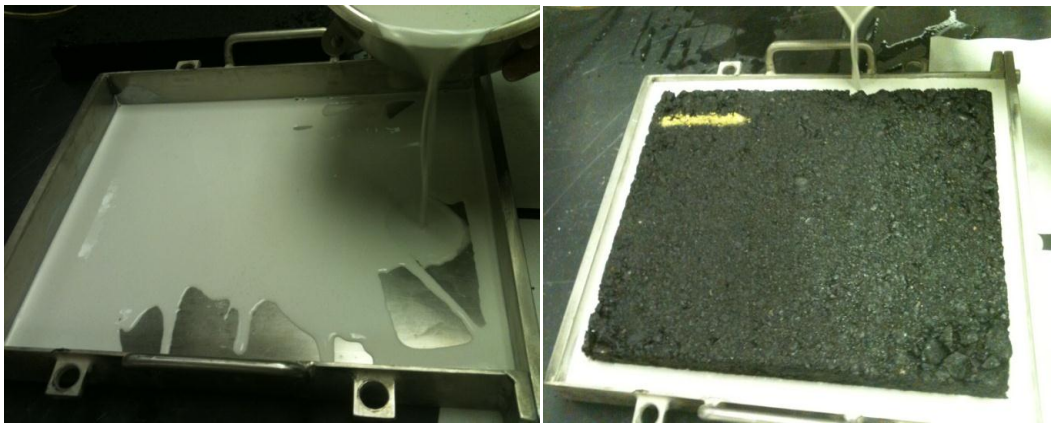

FIGURE 14 Mounting the Hamburg slab specimen.

CHAPTER 4. RESULTS AND ANALYSIS

4.1 Volumetric Properties

4.1.1 Theoretical Maximum Specific Gravity

Theoretical maximum specific gravity (Gmm) was determined for all three mixes as per AASHTO T 209 procedure. TABLE 3 summarizes the Gmm calculation for the three mixes.

TABLE 3 Calculation for Control, Advera and Evotherm Trial Mixtures

Specimen ID	Mass in Air (g)	Bowl+lid+water in air (g)	Bowl+lid+mix in air (g)	Gmm (g/cm3)	Average Gmm (gm/cm3)
	A	B	C	D = A/(A+B-C)	
Control	1500.4	7752.8	8642.5	2.457	**2.456**
	1500.2	7752.8	8642.3	2.457	
	1500.9	7752.8	8642.3	2.455	
Advera	1500.2	7752.8	8641.3	2.453	**2.455**
	1500.4	7752.8	8642.7	2.458	
	1500.2	7752.8	8641.7	2.454	
Evotherm	1500.0	7742.5	8639.0	2.486	**2.454**
	1500.0	7743.1	8624.1	2.423	

4.1.2 Air Voids Trials

Three gyratory specimen trials were compacted for each mix at three different approximate air void level; 4%, 8% and 12%. The reason for that is to draw the air voids versus mass in mold plot which determine the corresponding mass in mold weight to the targeted air voids. TABLE 4 summarizes the calculations for the trials of the three mixes.

TABLE 4 Compaction Trials for Control, Advera and Evotherm Mixtures

Mix Type	Specimen ID	Mass in Mold (g)	Mass in air (g)	Mass in water (g)	SSD Mass (g)	Volume (cm^3)	Gmb	% Va
Control	GBHT1	6100	2610.5	1416.3	2629.8	1213.5	2.151	12.41
	GBHT2	6400	2736.0	1523.4	2756.2	1232.8	2.219	9.64
	GBHT3	6800	2905.2	1668.4	2909.0	1240.6	2.342	4.65
Advera	GBWT1	6100	2616.5	1429.5	2642.0	1212.5	2.158	12.10
	GBWT2	6400	2734.0	1523.3	2744.9	1221.6	2.238	8.84
	GBWT3	6800	2953.8	1705.6	2959.4	1253.8	2.356	4.04
Evotherm	ZE_T1	6100	2472.7	1388.4	2534.6	1146.2	2.157	12.16
	ZE_T2	6400	2583.5	1452.4	2600.3	1147.9	2.251	8.36
	ZE_T3	6800	2752.0	1590.5	2755.8	1165.3	2.362	3.84

Air voids for the laboratory compacted specimens for all three mixtures were determined to be 9% in order to match the air voids level of the field core specimens, so the comparison between field and laboratory specimens will be meaningful. From the mass of mold – air voids relationship shown in FIGURE 15, mass of mold were determined to be 6390g, 6350g and 6340g for the Control, Foaming-based and Chemical-based mixes respectively.

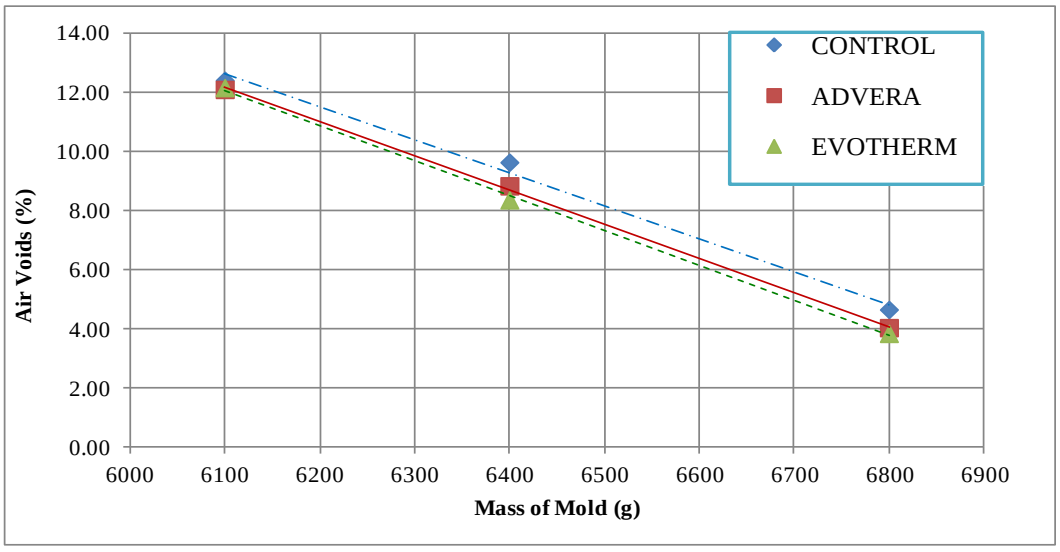

FIGURE 15 Compaction trials for control, Advera and Evotherm mixtures.

4.2 Dynamic Modulus Testing (E*)

The dynamic modulus, E* experiment was conducted in the laboratory using the IPC UTM 25 testing machine and included the testing of field cores as well as laboratory compacted specimens. As mentioned earlier, the test was conducted at only 70 °F (21.1 °C). A total of three replicates for each mixture type were prepared and instrumented for the dynamic modulus test. The average dynamic modulus values for the control as well as the two WMA mixtures were determined at different frequencies.

4.2.1 E Test Results for the Control Mix*

TABLE 5 summarizes the E* results for the control mixture including field stacked cores, lab-compacted specimens at 270 °F and lab-compacted specimens at 310 ºF.

TABLE 5 E* Testing Results for the Control Mixture, MPa

Specimen Type	Specimen ID	Air Voids (%)	Frequency (Hz)					
			25	10	5	1	0.5	0.1
Control Field stacked cores	HM1	9.96	11989	9762	7650	4568	3584	2045
	HM2	10.01	15486	11226	8881	7518	5842	3479
	HM3	8.38	21804	17182	12847	7233	5104	2616
Control Compacted @ 270 °F	2C8_01	8.21	13078	11195	9973	7332	6314	4295
	2C8_02	8.55	12521	10434	8918	6483	5511	3532
	2C9_02	9.22	12587	10599	9329	6616	5682	3779
Control Compacted @ 310 °F	3C8_01	8.87	13514	11886	10747	7729	6800	4669
	3C8_02	8.00	12918	11512	10132	7583	6622	4569
	3C9_01	9.98	12646	10348	9018	6704	5770	3845

4.2.2 E Test Results for the Foaming-based Mix*

TABLE 6 summarizes the E* results for the foaming-based mix including field stacked cores, lab-compacted specimens at 270 °F and lab-compacted specimens at 310 ºF. Laboratory specimens involve mix that has the WMA additive (Advera) been added on the lab (AAL) as well as mix that has the WMA additive (Advera) been added on the plant (AAP).

TABLE 6 E* Testing Results for the Foaming-based Mixture, MPa

Specimen Type	Specimen ID	Air Voids (%)	Frequency (Hz)					
			25	10	5	1	0.5	0.1
Foaming Field stacked cores	WM1	9.96	13077	9134	7194	3998	2961	1549
	WM2	10.01	19559	16288	13921	8910	7136	4219
	WM3	8.38	16277	12008	8883	5060	3948	2938
AAP Compacted @ 270F	GBW52	9.17	13042	10441	8115	4844	3847	2115
	2A9_01	9.47	12914	11339	10005	7473	6505	4379
	2A9_03	9.19	12573	11029	9896.5	7237	6348	4404
	2A9_04	9.36	11989	10134	8692	6479	5646	3946
AAP Compacted @ 310F	GBW 02	10.24	15357	11990	9575	6107	4844	2846
	3A9_01	10.30	11117	10691	9852	7503	6574	4822
	3A9_02	9.94	12408	10551	9435	7524	6064	4209
	3A9_03	9.87	10705	9520	8522	6306	5474	3810
AAL Compacted @ 270F	GBH50	8.37	14257	11956	10183	7005	5898	3694
	GBH51	8.55	18798	15093	11908	7324	5904	3288
	GBH52	8.98	9303	7820	6418	4365	3640	2348
AAL Compacted @ 310F	GBH 01	9.23	14869	12974	11237	7175	6112	3577
	GBH 02	9.14	11137	10119	7997	5723	4882	3314
	GBH 03	9.35	15024	12645	10624	7180	5692	3098

4.2.3 E Test Results for the Chemical-based Mix*

TABLE 7 summarizes the E* results for the chemical-based mix including field stacked cores, lab-compacted specimens at 270 °F and lab-compacted specimens

at 310 ºF. Laboratory specimens involve mix that has the WMA additive (Evotherm) been added on the plant (EAP).

TABLE 7 E* Testing Results for the Chemical-based Mixture, MPa

Specimen Type	Specimen ID	Air Voids (%)	Frequency (Hz)					
			25	10	5	1	0.5	0.1
Chemical Field cores	WA-70U	8.05	25271	21468	19673	14231	12609	7555
	WB-70U	8.53	25456	25210	21995	16240	13956	9651
EAP Compacted @ 270 °F	2E8_01	9.97	8828	7792	6927	5232	4578	3089
	2E8_02	9.80	10848	9595	8500	6178	5160	3272
	2E8_03	9.32	19071	16126	14127	10141	8549	5537
	2E8_04	9.35	8588	7902	7267	5490	4811	3419
EAP Compacted @ 310 °F	3E8_01	9.71	14020	11910	10387	7345	6243	4121
	3E8_02	10.01	10786	9909.5	9071	6656	5784	3944
	3E8_03	9.16	14012	12220	10942	8332	7230	4989
	3E8_04	9.92	9709	8561	7764	5873	5261	3791

A comparison of the dynamic modulus values between the field cores for the three mixtures is shown in FIGURE 16. It can be noticed that the chemical-based WMA mixtures show higher moduli values at all test frequencies compared to the control HMA mixture and foaming-based WMA. In addition, both of the control and foaming WMA mixtures have almost the same dynamic modulus values. Chemical-based WMA mixture had much higher modulus compared to the other two mixes for reasons might be related to the sampling of the specimens, or the mat might be over-compacted for this particular spot were the cores were taken.

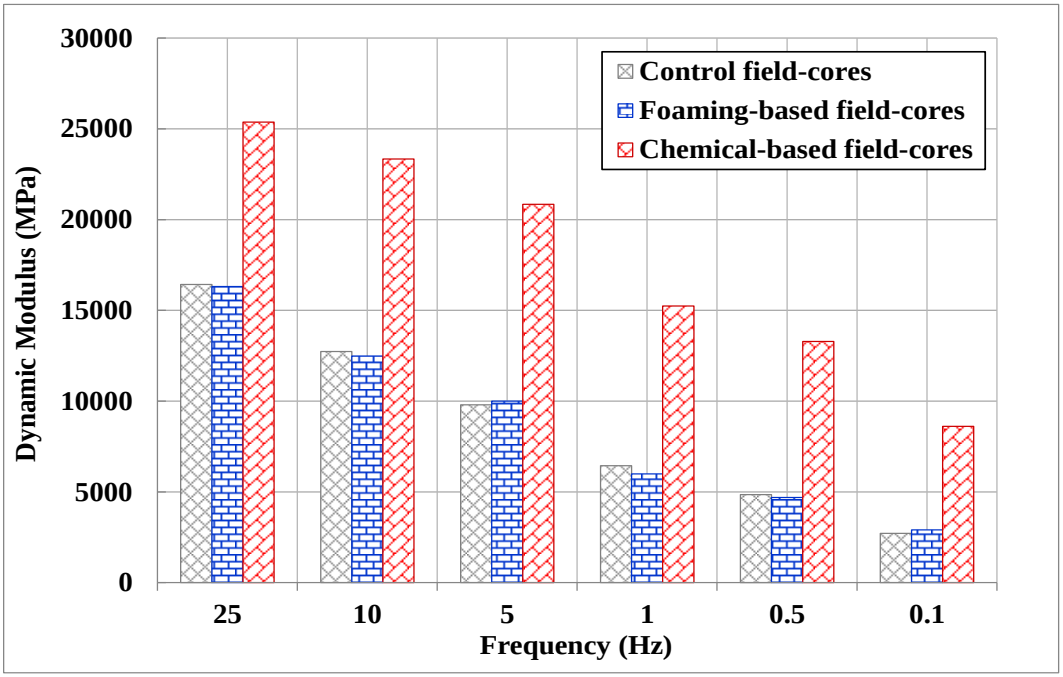

FIGURE 16 Field cores E* testing results for all mixtures.

To investigate the effect of the compaction temperature for both of the WMA and control mixtures, the lab specimens were compacted at two different temperatures. The first compaction temperature was selected to be around the normal compaction temperature of conventional HMA mixtures (310 °F); while the second one was lower at 270 °F. The laboratory specimens for the six combinations were manufactured at three replicates for each combination. The dynamic modulus for the Control, Foaming-based and Chemical-based mixes are shown in FIGURES 17, 18 and 19 respectively.

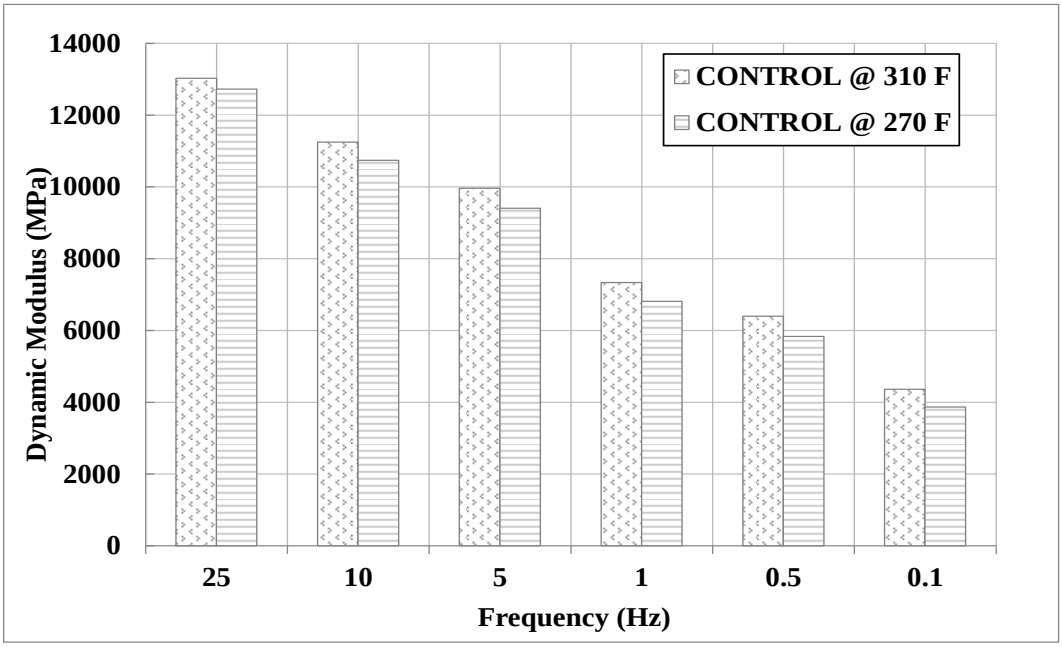

FIGURE 17 E*testing results for lab specimens of the control mix.

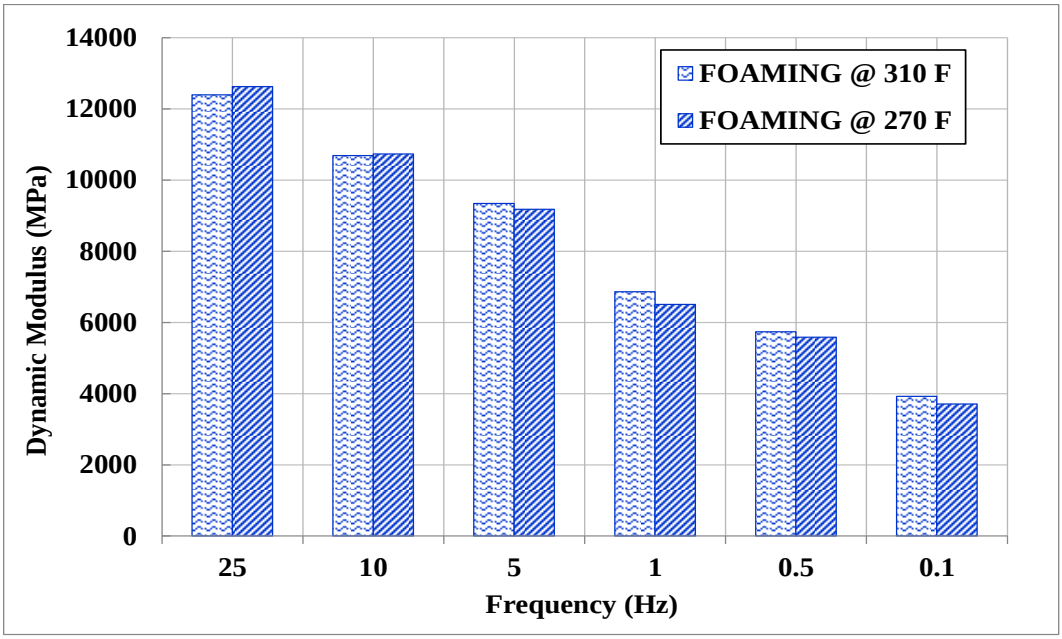

FIGURE 18 E* testing results for lab specimens of the foaming-based mix.

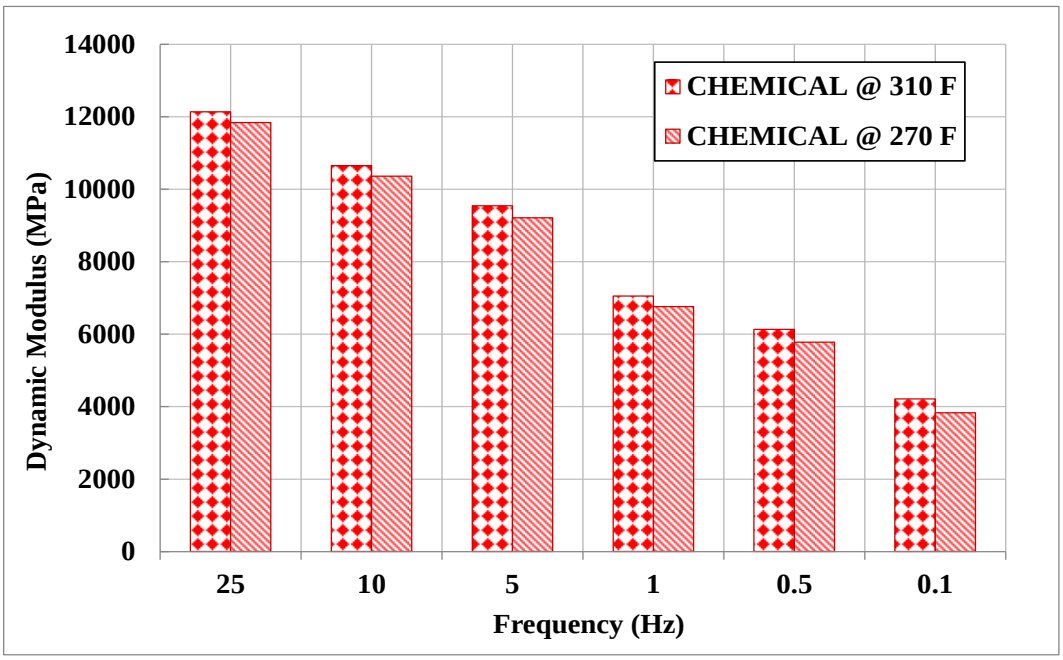

FIGURE 19 E* testing results for lab specimens of the chemical-based mix.

The dynamic modulus values for the three mixtures at different compaction temperatures are shown combined in FIGURE 20**Error! Reference ource not found.**. It can be observed that, at the 310 °F compaction temperature, the control HMA mixture showed slightly higher moduli values when compared to both WMA mixtures, which showed about the same moduli values. For the 270 °F compaction temperature, the dynamic moduli values for the three mixtures were about the same. This means that decreasing the compaction temperature from 310 °F to 270 °F would reduce the material's stiffness of the control HMA mixtures. The chemical-based WMA mixture showed a similar trend as the control HMA mix, but at a lesser extent; while the foaming-based WMA was not affected at all with the compaction temperature reduction.

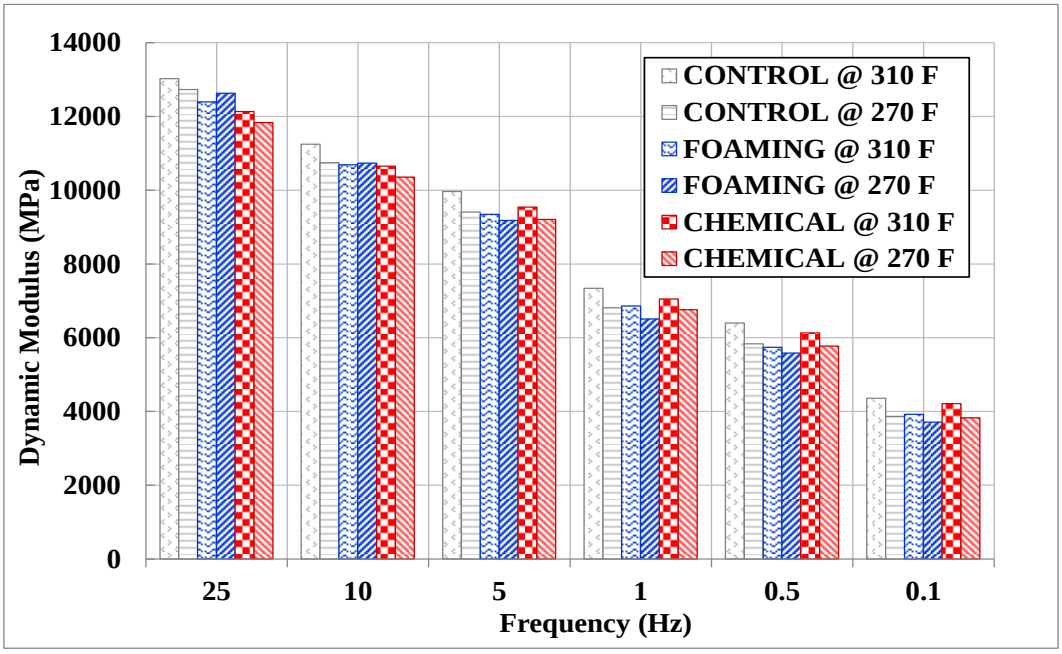

FIGURE 20 E* testing results for lab specimens of all three mixes.

The dynamic modulus test results of the laboratory compacted specimens didn't show any unusual increase in the dynamic modulus for the chemical-based WMA mixture; the dynamic moduli were around and/or slightly less than the control HMA and the foaming-based WMA mixtures. This outcome may point out an important consideration when sampling certain types of WMA mixtures from the field to be compacted and evaluated in the laboratory. This is mainly the question whether the WMA mixture properties will change when samples are reheated and compacted in the laboratory due to the release of the WMA additive. It may be best to compact future laboratory specimens directly after sampling either at the asphalt plant or at the paving site.

Statistical analyses were performed for the three mixtures for statistical significance. The statistical analyses used a paired t-distribution for two variables.

A statistical hypothesis, two-population test (Ho: $\mu 1 = \mu 2$ {Null Hypothesis} and H1: $\mu 1 \neq \mu 2$ {Alternative Hypothesis}) were conducted. The critical assumptions of the analysis were that the mean values of the two samples were unknown and equal. In addition, a significance level α of 5% was assumed, and the acceptance criterion for a given hypothesis was when $t_{critical} \leq t_{stat\ \alpha/2,\upsilon}$ where υ is the degree of freedom.

TABLE 8 presents the statistical hypothesis testing results for the E* dynamic moduli of each mixture type at the two different compaction temperatures. The results of the statistical analysis support that there is a significant difference between the dynamic moduli when the compaction temperature was decreased for the control HMA as well as the chemical-based WMA mixture. On the other hand, there was no statistical significant difference of the dynamic modulus values due to reduction in temperature for the foaming-based WMA mixture.

TABLE 8 Paired T-test for E* Results for Laboratory Mixes

Frequency (Hz)	Control lab @ 270F	Control lab @ 310F	Foaming lab @ 270F	Foaming lab @ 310F	Chemical lab @ 270F	Chemical lab @ 310F
25	12729	13026	12629	12397	11834	12132
10	10743	11249	10736	10688	10354	10650
5	9407	9966	9177	9346	9205	9541
1	6810	7339	6508	6860	6760	7051
0.5	5836	6397	5586	5739	5775	6129
0.1	3869	4361	3711	3922	3829	4211
df	5		5		5	
t Stat	-12.18		-1.19		-21.44	
t Critical one-tail	2.02		2.02		2.02	
t Critical two-tail	2.57		2.57		2.57	
Statistical status	**Significant**		**Insignificant**		**Significant**	

4.3 Indirect Diametral Tensile Strength Testing (IDT)

The IDT experiment also included the testing of field cores as well as laboratory compacted specimens for the control HMA mixture and the WMA mixtures. The IDT tested field cores were obtained by un-stacking the E* specimens since no damage occurred during the E* test. For the laboratory test specimens, specimens were obtained by cutting the E* tested specimens into three discs. The laboratory test specimens included also specimens compacted at two different temperatures (310 °F and 270 °F).

4.3.1 IDT Test Results for the Control Mix

TABLE 9 summarizes the IDT results for the control mixture including field stacked cores, lab-compacted specimens at 270 °F and lab-compacted specimens at 310 ºF.

TABLE 9 IDT Results for the Control Mix

Specimen Type	Specimen ID	Average Thickness (mm)	Specimen Air Voids (%)	Peak Tensile Strength (kPa)	Mean Peak Tensile Strength (kPa)	Variance (σ2)
Field-cores	H1	58.10	9.92	641	836	44693
	H2	55.10	8.58	698		
	H3	58.01	8.67	576		
	H4	58.20	9.34	692		
	HM1	56.50	8.36	894		
	HM8	53.68	7.60	1139		
	HM9	52.65	7.74	981		
	HM10	56.62	8.12	1064		
Compacted @ 270F	2C8_01 B	48.98	8.53	1481	1503	453
	2C8_02 B	49.89	9.24	1512		
	2C9_01 B	47.67	9.49	1490		
	2C9_02 T	49.39	9.03	1528		
Compacted @ 310F	3C8_01 B	47.66	9.05	1752	1641	6577
	3C8_01 T	49.79	8.54	1592		
	3C8_02 M	48.14	7.33	1648		
	3C9_01 T	49.01	9.84	1571		

4.3.2 IDT Test Results for the Laboratory Specimen of the Foaming-based Mix

TABLE 10 summarizes the IDT results for the foaming-based mix including field stacked cores, lab-compacted specimens at 270 °F and lab-compacted specimens at 310 ºF. Laboratory specimens involve mix that has the WMA additive (Advera) been added on the lab (AAL) as well as mix that has the WMA additive (Advera) been added on the plant (AAP).

TABLE 10 IDT Results for the Foaming-based Mix

Specimen Type	Specimen ID	Average Thickness (mm)	Specimen Air Voids (%)	Peak Tensile Strength (kPa)	Mean Peak Tensile Strength (kPa)	Variance (σ2)
Field-cores	W1	53.70	9.85	742	760	647
	W2	56.34	7.94	778		
AAP Compacted @ 270F	2A9_02 B	47.43	9.99	1489	1491	337
	2A9_04 T	47.54	9.23	1472		
	2A9_02 T	47.90	9.07	1487		
	2A9_02 M	49.67	8.96	1516		
AAP Compacted @ 310F	3A9_01 B	48.45	9.91	1297	1495	22430
	3A9_01 M	49.77	9.60	1610		
	3A9_03 B	51.74	10.32	1462		
	3A9_01 T	47.08	9.50	1612		

4.3.3 IDT Test Results for the Laboratory Specimen of the Chemical-based Mix

TABLE 11 summarizes the IDT results for the chemical-based mix including field stacked cores, lab-compacted specimens at 270 °F and lab-compacted specimens at 310 ºF. Laboratory specimens involve mix that has the WMA additive (Evotherm) been added on the plant (EAP).

TABLE 11 IDT Results for the Chemical-based Mix

Specimen Type	Specimen ID	Average Thickness (mm)	Specimen Air Voids (%)	Peak Tensile Strength (kPa)	Mean Peak Tensile Strength (kPa)	Variance (σ2)
Field-cores	WM3	42.86	8.98	1388	1303	14672
	WM10	67.05	7.41	1217		
Compacted @ 270F	2E8_01 M	47.58	8.55	1347	1283	3963
	2E8_01 B	49.51	9.61	1222		
	2E8_04 T	48.90	8.14	1280		
Compacted @ 310F	3E8_02 T	54.27	9.59	1419	1306	9450
	3E8_02 B	47.31	9.48	1252		
	3E8_04 T	47.16	8.67	1249		

As shown in FIGURE 21, the IDT test results for the field cores showed a similar trend to the E* test results, where the chemical-based WMA mixture showed higher tensile strength values compared to both the control HMA mixture and the foaming-based WMA mixture.

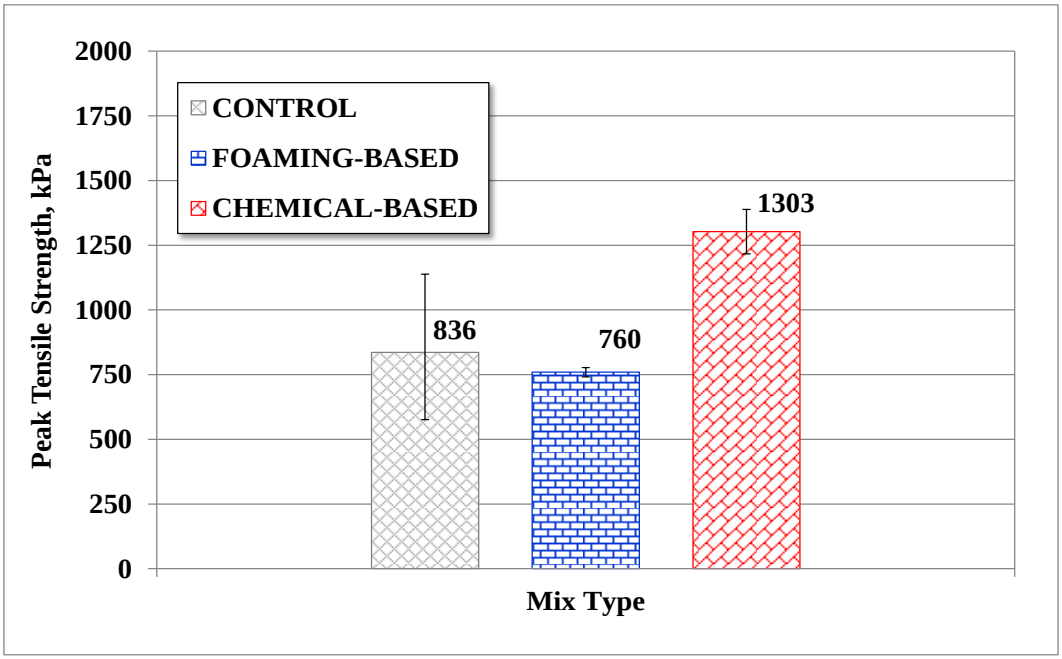

FIGURE 19 IDT testing results for field cores of all three mixes.

The average tensile strength values were plotted for the three mixtures at both compaction temperatures in FIGURE 22. The plotted results at 310 °F compaction temperature showed that the control HMA mixture has higher indirect tensile strength values as compared to both WMA mixtures. At 270 °F compaction temperature, the control HMA mixture showed a noticeable drop of the IDT value while the other two WMA mixtures have almost the same IDT compared to those at 310 °F. This finding reflects the fact that WMA additives maintained the mixture properties at lower compaction temperatures. The IDT test

results for field cores showed the same trend as the E* test results, while the laboratory test results showed lower indirect tensile strength for the chemical-based WMA mixture, which contradicted with the results from the field cores. This result confirmed the concern that the chemical-based WMA mixture properties may have changed by reheating the mixture in the laboratory.

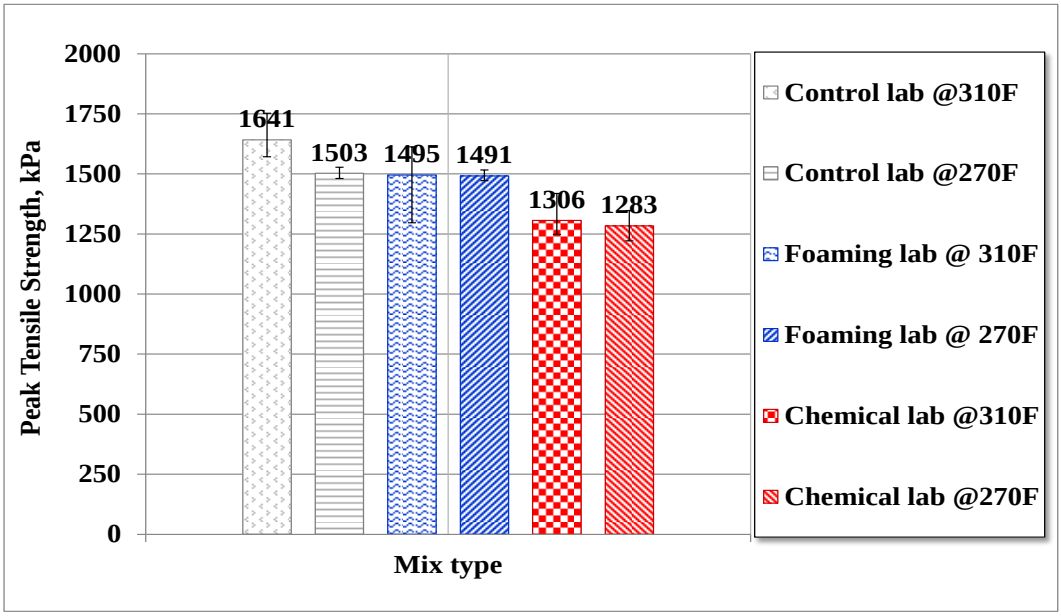

FIGURE 20 IDT testing results for lab cores of all three mixes.

4.4 TSR Test Results for the Laboratory Specimens compacted at 270 °F for the three Mixes

In order to assess the moisture susceptibility of the control HMA and both WMA mixtures, three replicates from each mixture type were conditioned according to the AASHTO T 283-89 procedure. The replicates represented the laboratory specimens compacted at only 270 °F. As mentioned earlier, the TSR value represents the ratio of conditioned (wet) IDT to the unconditioned (dry) IDT. However, the test procedure indicates to run the test on specimens with average

air voids of 7%, the air voids level of the tested specimens was targeted to be 9% in order to simulate the average field-cores air voids. TABLE 12 summarizes the conditioned IDT test results after passing a freezing/thaw cycle. The results of the conditioned IDT test showed almost the same trend compared to those of the dry IDT results at 270 °F, where the control and foaming-based mixtures showed almost the same indirect tensile strength values and slightly higher than the chemical-based WMA mixture.

TABLE 12 IDT Results for Dry and Wet Conditions for All Three Mixes

Specimen Type		Specimen ID	Average Thickness (mm)	Sample Air Voids (%)	Peak Tensile Stress (kPa)	Mean (μ)	Variance (σ2)
Dry Condition	Foaming based Compacted @ 270F	2A9_02 B	47.43	9.99	**1489**	1491	337
		2A9_04 T	47.54	9.23	**1472**		
		2A9_02 T	47.90	9.07	**1487**		
		2A9_02 M	49.67	8.96	**1516**		
	Chemical based Compacted @ 270F	2E8_01 M	47.58	8.55	**1347**	1283	3963
		2E8_01 B	49.51	9.61	**1222**		
		2E8_04 T	48.90	8.14	**1280**		
	Control Compacted @ 270F	2C8_01 B	48.98	8.53	**1481**	1503	453
		2C8_02 B	49.89	9.24	**1512**		
		2C9_01 B	47.67	9.49	**1490**		
		2C9_02 T	49.39	9.03	**1528**		
Wet Condition	Foaming Compacted @ 270F	GBH50B	45.78	8.30	**1076**	903	22977
		GBH50M	51.50	7.84	**840**		
		GBH52B	48.35	9.26	**792**		
	Chemical Compacted @ 270F	2E8_01 T	48.61	9.34	**741**	804	6914
		2E8_04 M	48.41	7.48	**898**		
		2E8_04 B	49.23	9.25	**773**		
	Control Compacted @ 270F	2C9_01 T	48.46	8.98	**897**	898	35
		2C9_02 M	47.15	9.04	**905**		
		2C9_02 B	48.75	9.03	**893**		

FIGURE 23 illustrates the TSR values for the three mixtures compacted at 270 °F. As it was expected for the control mixture compacted at lower temperature, the TSR value didn't exceed 0.6. On the other hand, the WMA mixtures showed slightly higher TSR values compared to the control HMA mixture. However the TSR values of the three mixtures were low. The high air voids level of the tested specimens, 9%, compared to the 7% specified by the test procedure could have significant effect in lowering the overall TSR values. Additional future investigation is needed to address this issue. Almost 1.5 year after construction, none of the mixtures showed any sign of distress or moisture damage in the field.

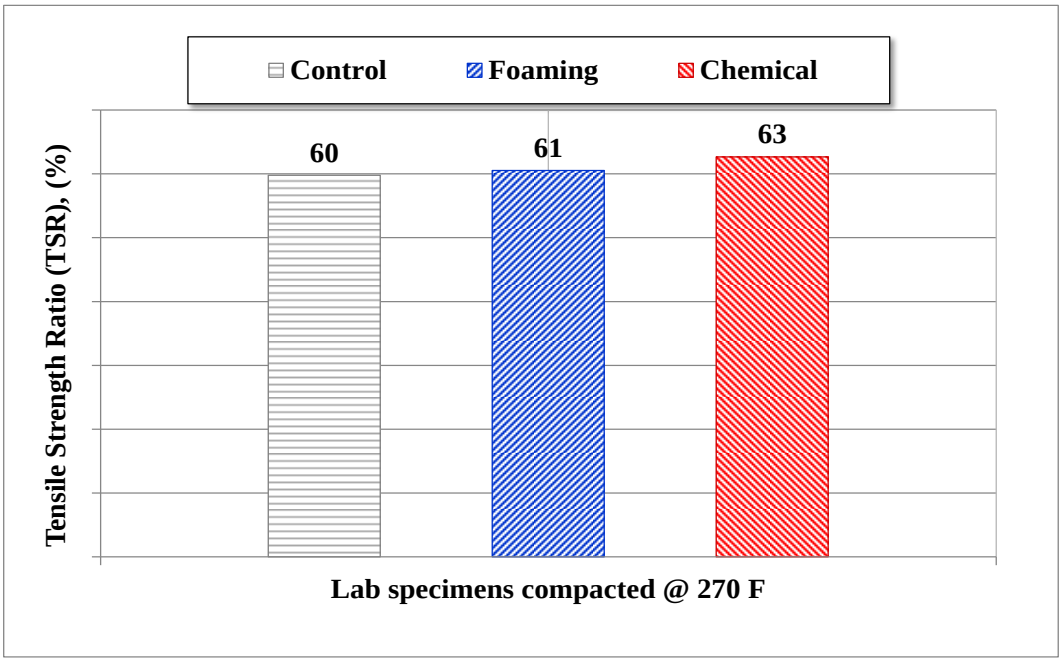

FIGURE 21 TSR results for all three mixes.

4.5 Hamburg Wheel Tracking Test Results

4.5.1 Hamburg Wheel Track Test Results for Three Mixes Compacted at 270 °F

For both WMA mixtures, two slab replicates were prepared by re-heating and compacting loose mix using the kneading compactor at two temperatures; 270 ºF (132 ºC) and 310 ºF (154 ºC) to the designated 7% air-voids. The Compaction temperatures were intended to be parallel with other testing. All details for volumetric and results calculations were conducted by ADOT Pavement Materials group and are attached on Appendix B. As per protocol, the specimens were mounted and then conditioned for 30 minutes prior to testing. The process of conditioning and testing lasted approximately for 6 hours for each mix. All mixes showed a good potential of moisture resistance. FIGURE 24 shows the rutting versus cycles relationship for the mixtures compacted at 270 ºF.

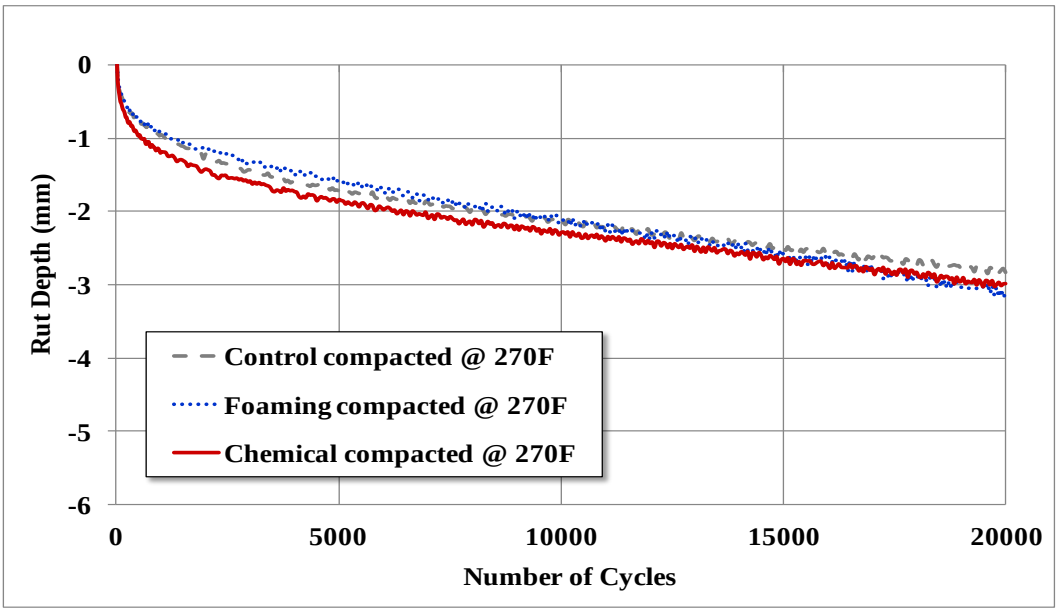

FIGURE 22 Hamburg testing results for all three mixes compacted at 270 ºF.

4.5.2 Hamburg Wheel Track Test Results for Three Mixes Compacted at 310 °F

FIGURE 25 shows the rutting versus cycles relationship for the mixtures compacted at 270 ºF.

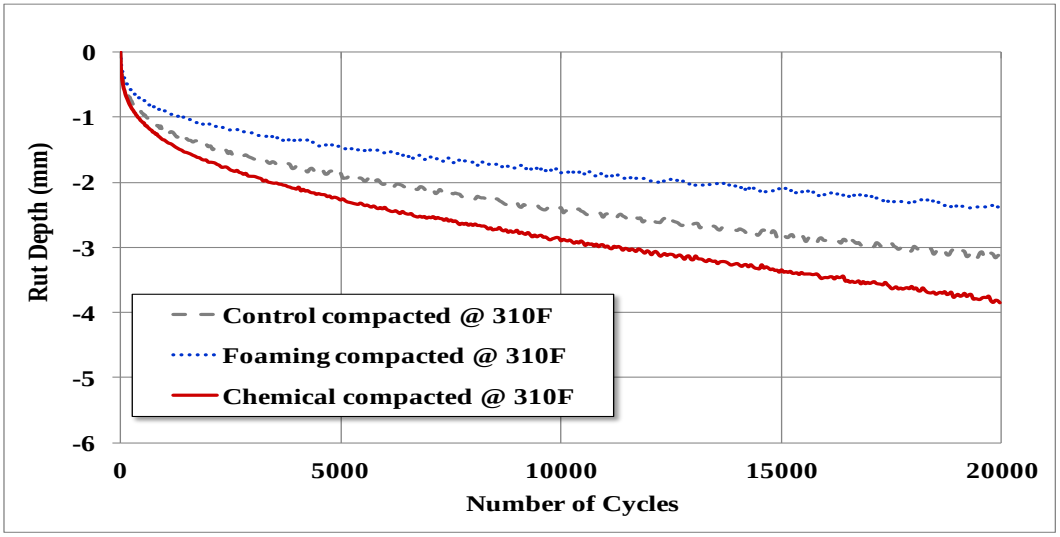

FIGURE 23 Hamburg testing results for all three mixes compacted at 310 ºF.

FIGURE 24 and FIGURE 25 show the rut depth-cycle relationship for all replicates. The rut depth was measured on the middle third along the slab specimen. It is quiet noticeable that all replicates did not pass the falling criteria of 0.787 in (20mm). In fact, the maximum rut depth was centered about 0.118 in (3 mm) which indicates a very good performance. This can be observed also by checking the rut-cycle relationship for the three mixtures where none of them showed any inflection points, which is a sign for the stripping. On the other hand, the results for both WMA mixtures compacted at 270 ºF (132 ºC) are almost identical to the control mixture compacted at 310 ºF (154 ºC), which means that the WMA mixtures are performing well and comparable to the control mixture. Based on the results of the TSR and the rut-cycle relationships, it can be

concluded that the three mixtures have a comparable moisture susceptibility level. However, the TSR values implied that theses mixtures may have problem with the moisture damage, which is contradicted with the Hamburg Wheel-Track test results. This may be due to the fact that the AASHTO T283 includes both freezing and thawing conditions. Which can be more damaging compared to the Hamburg Wheel-Track test.

4.6 The Effect of WMA Additives on the Compaction Efforts

4.6.1 Compaction Energy

All laboratory specimens were compacted using the gyratory compactor machine. The most important two factors to be considered during the compaction are the total number of gyrations, and the shear stress. Those two factors are important indicators to assess how easy the material is compacted. FIGURE 26 shows the average calculated air-voids for both WMA and control mixtures. The average air-voids for each mixture group look comparable and all the values are around the target 9%. FIGURE 27 shows the compaction details for the foaming admixture added at lab and plant for specimens compacted at 270 °F (132 ºC), and 310 °F (154 ºC). The results showed that adding the foaming admixture at plant required relatively lower number of gyrations compared to the case when adding the admixture at lab for both 270 °F (132 ºC) and 310 °F (154 ºC) compaction temperatures. Meanwhile, WMA mixtures showed a clear reduction on the number of gyration compared to the control mixture. This fact indicates the role of the WMA additive to allow for compacting at lower temperatures, and less

compaction efforts. The outcomes from this study supported the conclusion from the re-heating study, where the foaming-based mixtures that were re-heated at the lab showed a comparable number of gyrations compared to the one created in the lab. This can be also noticed by comparing the number of gyrations of the control mix to the plant foaming-based mix, where the later mix showed less number of gyration compared to the earlier mix. This means that the WMA additives are still effective after laboratory storage and the re-heating before the laboratory compaction. It was expected based on the foaming manufacturer opinion and the product literature that the effect of the foaming admixture may be minimal or not existent after the WMA mixture got cold. This statement was based on the fact that the reheating of material would release the moisture and lift the minerals which would act as filler in the binder. However, the results from E* as well as the compaction effort studies showed that the WMA is still effective even after the reheating.

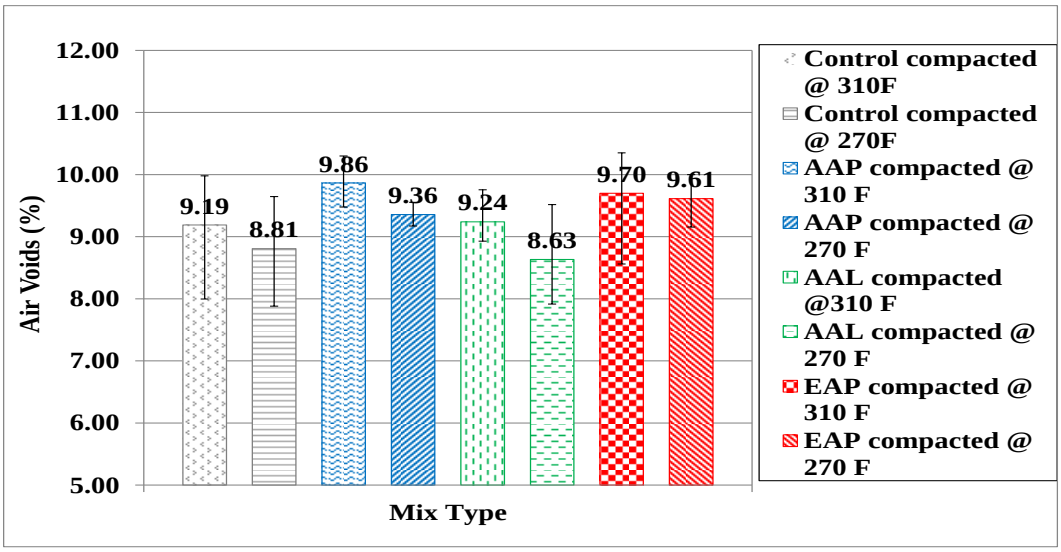

FIGURE 24 Calculated air voids for the WMA and control mixtures.

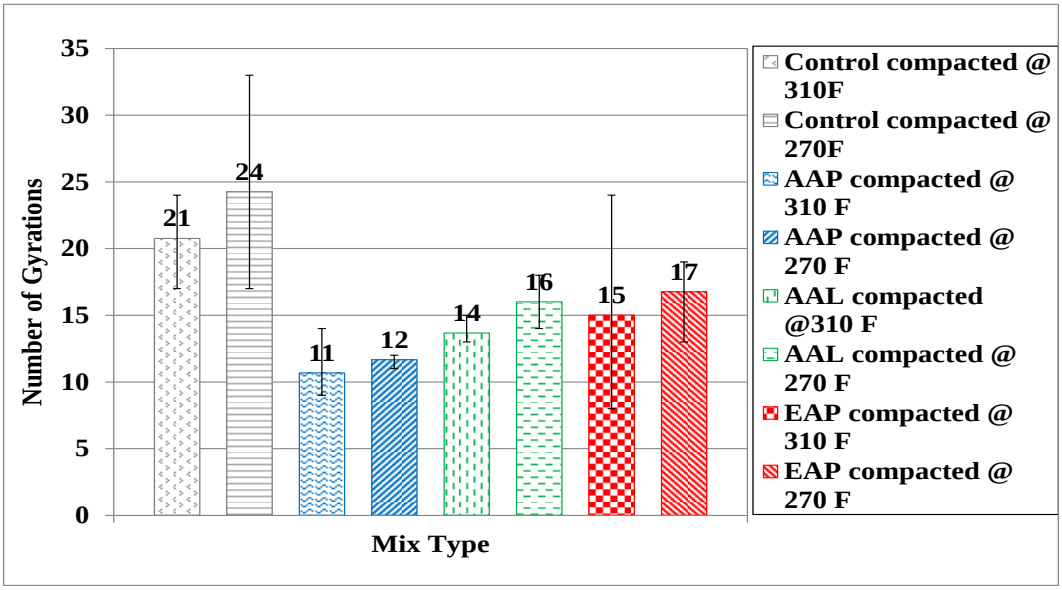

FIGURE 25 Compaction efforts for the WMA and control mixtures.

4.7 Re-Heating Study for WMA Mixtures - Case Study for the Foaming-Based Mixture

Laboratory testing for asphalt mixtures usually requires the sampling of material either at the paving site or at the asphalt plant. The issue of re-heating asphalt mixtures in lab has recently been a matter of concern. WMA mixtures are thought to be more susceptible to properties change when re-heated in the lab due to the possibility of losing the benefit of the WMA additive.

This part of the study intended to capture the effect of re-heating on WMA by conducting the complex modulus test on the foaming-based mixture. Two sets of material were sampled from the paving site and brought back to the laboratory; this included the control and foaming-based mixtures. The foaming-based WMA plant mixture was re-heated, compacted and eventually tested in the lab. On the other hand, the foaming additive was added to the control mixture in the lab after

being re-heated. The foaming additive was added at a dosage of 0.25% by the weight of the asphalt mix according to the manufacture recommendations. Both set of specimens were prepared and tested for the E* at 70 °F (21.1°C).

4.7.1 Dynamic Modulus Test Results

To investigate the effect of the compaction temperature for both plant WMA mixture (AAL) and the mixture that had the foaming additive added to the control mixture in the laboratory (AAP), the specimens were compacted at two different temperatures. The first compaction temperature was selected to be around the normal compaction temperature of conventional HMA mixtures 310 °F (154 °C); while the second one was lower 270 °F (132°C). The laboratory-compacted specimens for the four combinations were manufactured at three replicates for each combination. The dynamic modulus values for the two mixtures were determined at 6 different frequencies and at two different compaction temperatures as shown in FIGURE 28.

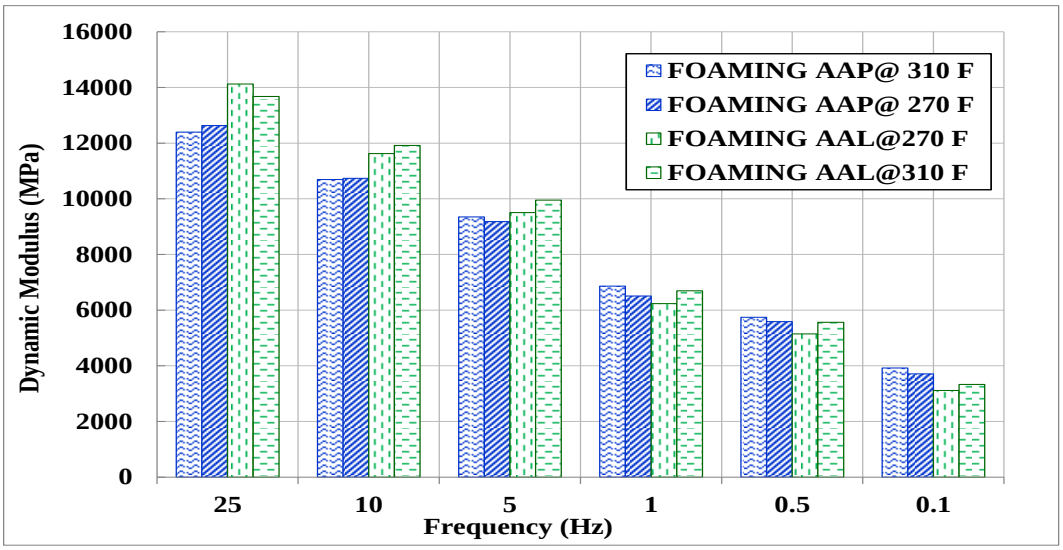

FIGURE 26 Comparison of dynamic modulus of AAP and AAL mixtures.

From FIGURE 28, it can be observed that there is no substantial difference between the two foaming mixtures. Both foaming added at the lab and plant had almost the same dynamic modulus values. It can be observed that, at the 310 °F (154 °C) compaction temperature, both foaming-based mixtures showed slightly higher modulus values when compared to the ones compacted at 270 ºF (132 °C).

Statistical significance analysis was performed for the two mixtures. The statistical analyses used a paired t-distribution for two variables. A statistical hypothesis, two-population test (Ho: $\mu 1 = \mu 2$ {Null Hypothesis} and H1: $\mu 1 \neq \mu 2$ {Alternative Hypothesis}) were conducted. The critical assumptions of the analysis were that the mean values of the two samples were unknown and equal. In addition, a significance level α of 5% was assumed, and the acceptance criterion for a given hypothesis was when $t_{critical} \leq t_{stat\ \alpha/2,\upsilon}$ where υ is the degree of freedom. Table 13 presents the statistical hypothesis testing results for the E* dynamic moduli of each mixture type at the two different compaction temperatures. Both methods of adding the admixture either at the plant or at the lab gave similar modulus values. Thus, the re-heating process of the WMA seems not to have any negative effects on the material properties.

TABLE 13 Statistical Comparison Between AAL and AAP Using T-paired Test

Frequency (Hz)	Dynamic Modulus (MPa)							
	AAL @270	AAL @310	AAP @270	AAP @310	AAL @270	AAP @270	AAL @310	AAP @310
25	14119	13677	12843	13590	14119	12843	13677	13590
10	11623	11913	10936	11315	11623	10936	11913	11315
5	9503	9953	9339	9774	9503	9339	9953	9774
1	6231	6693	6518	7149	6231	6518	6693	7149
0.5	5147	5562	5567	5894	5147	5567	5562	5894
0.1	3110	3330	3633	3972	3110	3633	3330	3972
df	5		5		5		5	
t Stat	-1.65		-6.755		0.52		-0.50	
t Critical one-tail	2.02		2.02		2.02		2.02	
t Critical two-tail	2.57		2.57		2.57		2.57	
Statistical Diff. Between Sample means	**Insignificant**		**Significant**		**Insignificant**		**Insignificant**	

The results of the statistical analysis supported that there was no statistical significance of the dynamic modulus values between the foaming-lab and foaming-plant specimens at both compaction temperatures; in fact the reduction in temperature did not statistically reduce the modulus values for the foaming-based WMA mixture. However, there was a statistical difference between the foaming added at plant specimens compacted at 270 ºF (132 ºC) and compacted at 310 ºF (154 ºC).

4.8 Field Evaluation Trip

Field evaluation trip was held to the project site on January 10, 2011 with coordination with ADOT materials and testing section. The pavement by that time was 1½ year old. From the visual inspection of the three sections; control, foaming-based and chemical-based, all the three sections was doing quite excellent. The pavement had an Open-graded friction coarse layer on top of the control and WMA sections that was laid recently. Despite the low TSR values of the laboratory specimens for all mixtures, no evidence of stripping or cracking was noticed on the pavement. This could be due to the dry weather of the Phoenix area which minimizes the risk of moisture damage. FIGURE 29 shows photos from the field evaluation trip.

FIGURE 27 Field evaluation trip.

CHAPTER 5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Warm Mix Asphalt (WMA) technology has been growing significantly in the last decade and the future is promising for further improvements and implementations. The main goal of WMA is to produce asphalt mixtures at lower mixing temperatures compared to the classic Hot Mix Asphalt (HMA) mixing temperatures, and maintaining similar strength, durability and performance characteristics. Many agencies and state Department of Transportation (DOT's) across the country have put a tremendous effort on implementing the benefit of lowering the mixing temperature of asphalt mixtures to reduce the emissions and reduce production costs. The Arizona Department of Transportation (ADOT) has been on track in this area and constructed several trial sections using different WMA additives. This study utilized materials from actual ADOT paving sections where field-cores and loose materials were sampled and tested at the ASU's Advanced Pavement Laboratory. The study evaluated the laboratory performance of two different WMA mixtures (foaming-based and chemical-based) compared to a control HMA mixture used in field test sections. The scope of work included laboratory testing of field cored specimens as well as laboratory specimens compacted at two different temperatures. The laboratory testing program included the dynamic modulus E* test, the Indirect Diametral Tensile strength test, and the moisture sensitivity test. Because of the limited amount of mixtures and field

cores sampled, in general, the study was conducted with partial testing plan and laboratory evaluation.

5.2 Conclusions

From the laboratory evaluation of the three mixtures; control, foaming-based and chemical-based mixtures, several conclusions were drawn from each testing results. Summary of conclusions for the four tests are summarized in the following sections. In order, they are: dynamic modulus (E*), indirect diametral tensile strength (IDT), tensile strength ratio (TSR) and Hamburg wheel-track test. The Hamburg wheel-track test was conducted at the ADOT laboratories with data analysis conducted at ASU.

5.2.1 Dynamic Modulus (E) Test*

The dynamic modulus results of the field cores for both the control HMA and foaming-based WMA mixtures showed a comparable E* values at 70 °F; however, E* values of the chemical-based WMA mixture were much higher.

For the laboratory compacted specimens of the three mixes, E* results indicated that decreasing the compaction temperatures from 310 °F to 270 °F didn't have any negative effect on the material stiffness or strength for both WMA mixtures, while the control HMA strength was affected to some extent. Based on the average E* values for the six loading frequencies, (laboratory specimens comapcted at 310 ºF to specimens compacted at 270 ºF), the percentages of reduction on the dynamic modulus are summarized as follows:

- Control: strength reduced by 8% between compaction temperatures
- Foaming-based: strength reduced by 2%
- Chemical-based: strength reduced by 5%

5.2.2 Indirect Diametral Tensile Strength (IDT) Test

IDT test results of the field cores showed similar findings to the E* results. For the laboratory compacted specimens, the IDT results indicated that decreasing the compaction temperatures from 310 °F to 270 °F didn't have any negative effect on the material strength for both WMA mixtures, while the control HMA strength was affected to some extent. Based on the average IDT values for the laboratory specimens, the percentages of reduction on the IDT for specimens comapcted at 310 ºF to specimens compacted at 270 ºF are summarized as follows:

- Control: strength reduced by 10% between compaction temperatures
- Foaming-based: strength reduced by 0.5%
- Chemical-based: strength reduced by 1.8%

5.2.3 Tensile Strength Ratio (TSR) Test

The moisture sensitivity test results based on the TSR values for specimens compacted at 270 ºF for all three mixtures indicated that the WMA mixtures and the control mixture had comparable TSR values. However all TSR results were below the specification limit of 70%. Having the TSR specimens being tested at higher air voids level than specification (9% instead of 7%) could potentially affect the TSR values in comparison to specifications. Moreover, the inclusion of

a freezing cycle as part of the test could also be a possible cause of lowering the TSR values due to harsh conditioning of the freezing cycle.

5.2.4 Hamburg Wheel-track Test

The Hamburg Wheel-Track test results disagreed with the TSR results; in that the Hamburg results indicated good performance for all three mixtures at both compaction temperatures 270 °F (132 ºC) and 310 °F (154 ºC).

5.2.5 The Effect of WMA Additives on the Compaction Efforts and the Effect of Re-heating

The number of gyrations to achieve the same air void level for the different mixtures was lower for both WMA mixes compared to the control mixture. The compaction study results also showed that there is no significant difference between the re-heated Advera WMA mixture and the one prepared in the laboratory. Also, E* results for the re-heating study agreed with those from the compaction effort study.

5.3 Recommendations

- The validity of collecting field WMA mixtures, re-heating and comapacting them in the laboratory was questionable for some WMA processes especially those of foaming-based approach; however, this research study showed no significant difference in performance for WMA reheated mixtures at least from the E* stand point and based on the dynamic modulus results for Advera added at lab (AAL) and Advera added at plant (AAP) mixtures.

- Since the re-heating study was conducted for only the foaming-based mixture, the issue of re-heating needs to be carefully evaluated. This could be done through extended field and laboratory evaluation for each WMA process to make sure that the effectivness of the additive is not demolished in the process. More investigation is needed to determine if the reheating of WMA mixtures would reduce the effect of WMA additives. This can be achieved by compacting the laboratory specimens directly at the mix plant or at the paving site. A portable gyratory compactor can be used at the asphalt plant in order to avoid reheating the WMA mixtures.
- Collection of future performance data from the field test sections is needed to provide the actual field performance of the WMA mixtures and compare them to the control HMA mixture.

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APPENDIX A

MIX DESIGN

Arizona Department of Transportation
Asphalt Mix Design

Project Number:	H595507C	MA. Producer:	MISSION MATERIALS COMPA
Mat Type:	3/4" Asphaltic Concrete	Mix Code:	C008-08
Date Submitted:	04/07/2009	Date Verified:	04/29/2009
Date Approved:	04/29/2009	Asphalt Source:	ERGON ASPHALT PRODUCTS
Effective Date:	07/13/2009 05:00 am	Admix Source:	CHEMICAL LIME COMPANY
AC Spec Type:	416	Producer Code:	C008-08
with RAP':	No	Mix Design Lab:	WESTERN TECH. INC.

	W/O Add Mixture (%)	W/ Add Mixture (%)
Admixture Type:		Lime
Admixture Spec Gravity:		2.2
Admixture:		1.0 %

Sieve	W/O % Passing	W/ % Passing
1 1/2"	100	100
1"	100	100
3/4"	100	100
1/2"	86	86
3/8"	76	76
1/4"	64	65
#4	57	57
#8	41	41
#10	37	38
#16	29	30
#30	21	21
#40	16	17
#50	12	13
#100	7	8
#200	4	5

Aggregate	
O.D. SP. GR. Coarse:	2.600
O.D. SP. GR Fine:	2.606
O.D. SP. GR. Comb. (w/ admix):	2.599
Crushed Faces:	93 %
Mix Design S.E.:	75
Adot S.E. Target:	
Abrasion:	
100 Revs:	4
500 Revs:	19
%RAP Agg. (by wt of total agg)	
%RAP Binder (by wt of total binder)	

Mix	
Asphalt Pct:	4.8%
Asphalt Grade:	PG 76-16
Asphalt SP. GR.:	1.037
Asphalt Absorption:	0.48
Bulk Density PCF:	144.2
Max Theo. Density:	152.6
Marshall Stability:	4196
Flow:	13
Retained Strength:	99%
Vma:	15.2%
Air Voids:	5.5%
Voids Filled:	63.7%
Wet Strength Psi:	487

APPENDIX B

HAMBURG WHEEL TRACKING TESTING RESULTS

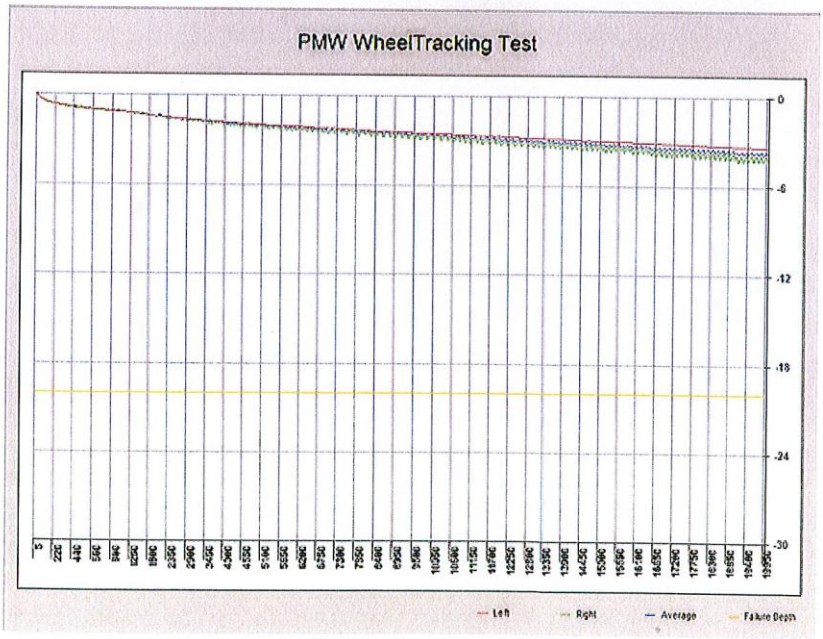
1. Control Mixture

a. Control Mix Compacted at 270 °F

WheelTracker Report

Project Name:	MP 130-MP 138	Date:	5/20/11
Project Number:	NH-085-B(011)	Date Sampled:	6/17/09
Job Number:	LOT 21	Lab Number:	
Project Engineer:	BOBBY LALL	Mix Type:	416 3/4 1% LIME
Submitted By:	YUMA	Asphalt Grade:	76-16
Temperature:	55	Pit Source:	ERGON
Comments:	TEST#78, LV=7.5, RV=7.5, IMC=99, 40MM SLAB Control HMA		

	Left	Right	Average
Max Impression:	-3.40 mm	-4.31 mm	-3.86 mm
	Pass #: 20000 / Pt: 1	Pass #: 20000 / Pt: 11	
Fail Depth: 20mm	PASS	PASS	PASS



CC: STATION 5891 CONTROL

Rut Data Report			
Performed: 5/18/2011	Test #77		Fail Depth: -20mm
Pass #	**Left Wheel**	**Right Wheel**	**Pass #**
5,000	-2.49	-2.09	**5,000**
10,000	-3.16	-2.46	**10,000**
15,000	-3.72	-2.76	**15,000**
20,000	-4.14	-3.07	**20,000**
Tested	9,10,11	9,10,11	**Tested**

THEORETICAL SAMPLE WEIGHT
Weight (g) = 0.93 x R ÷ 62.3 x V x 16.4;
Voids = 7.0 ± 0.5

Date	Sample Number	Rice Density (from fast) (R)	Sample Size (inch) (L X W X H) V = 10.26 X 13.12 X 1.700	Sample Size (gram)
5/19/11	LOT 21 CONTROL	152.9	228.84	8567

BULK DENSITY TEST

Date	Sample Number	Sample Size L X W X H (inch)	Air Weight	SSD Weight	H_2o Weight	Specific Gravity	Density	Air Void
5/19	1		8432.7	8478.0	4757.4	2.266	141.2	7.5
5/19	2		8413.2	8463.7	4752.3	2.266	141.2	7.5

Specimen Compacted at Temperature (°F) 270 Test_____ Check_____

5/27/11
NH-085-B(011)
LOT 21
STATION 5891
TEST# 78
LEFT
Rut Depth 3.40MM

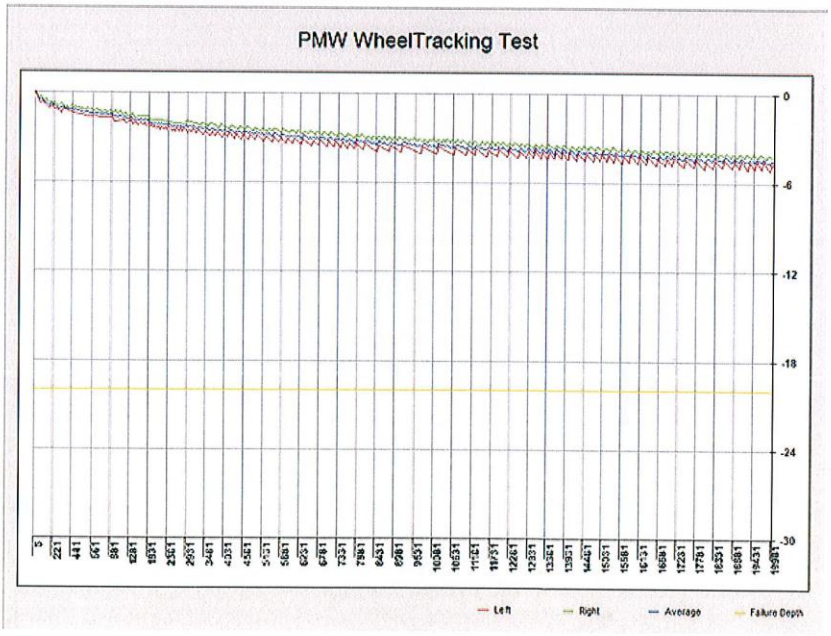
5/27/11
NH-085-B(011)
LOT 21
STATION 5891
TEST# 78
RIGHT
Rut Depth 4.31MM

b. Control Mix Compacted at 310 °F

WheelTracker Report

Project Name:	MP 130-MP138	Date:	6/30/11
Project Number:	H595507C	Date Sampled:	6/17/09
Job Number:	LOT 21	Lab Number:	STATION 5856
Project Engineer:	B LALL	Mix Type:	416 3/4 1% LIME
Submitted By:		Asphalt Grade:	PG 76-16
Temperature:	55	Pit Source:	ERGON ASPHALT
Comments:	TEST#83, LV=7.5, RV=7.5, IMC=99, 40MM SLAB Control HMA		

	Left	Right	Average
Max Impression:	-5.16 mm	-4.34 mm	-4.75 mm
	Pass #: 19881 / Pt: 2	Pass #: 19781 / Pt: 11	
Fail Depth: 20mm	PASS	PASS	PASS



CC:

Compacted @ 310 F

Rut Data Report			
Performed: 6/30/2011	Test #83		Fail Depth: -20mm
Pass #	**Left Wheel**	**Right Wheel**	**Pass #**
5,000	-2.86	-2.38	**5,000**
10,000	-3.68	-2.99	**10,000**
15,000	-4.15	-3.53	**15,000**
19,981	-4.71	-4.04	**19,981**
Tested	1,2,3	9,10,11	**Tested**

THEORETICAL SAMPLE WEIGHT
Weight (g) = 0.93 x R ÷ 62.3 x V x 16.4;
Voids = 7.0 ± 0.5

Date	Sample Number	Rice Density (from fast) (R)	Sample Size (inch) (L X W X H) V = 10.26 X 13.12 X 1.700	Sample Size (gram)
06-29-11	lot 21 station 5856	152.9	228.84	8566

BULK DENSITY TEST

Date	Sample Number	Sample Size L X W X H (inch)	Air Weight	SSD Weight	H_2o Weight	Specific Gravity	Density	Air Void
06-29-11	1		8465.3	8519.5	4791.9	2.271	141.5	7.5
06-29-11	2		8506.4	8549.3	4804.6	2.272	141.5	7.5

Specimen Compacted at Temperature (°F) 310 Test_____ Check_____

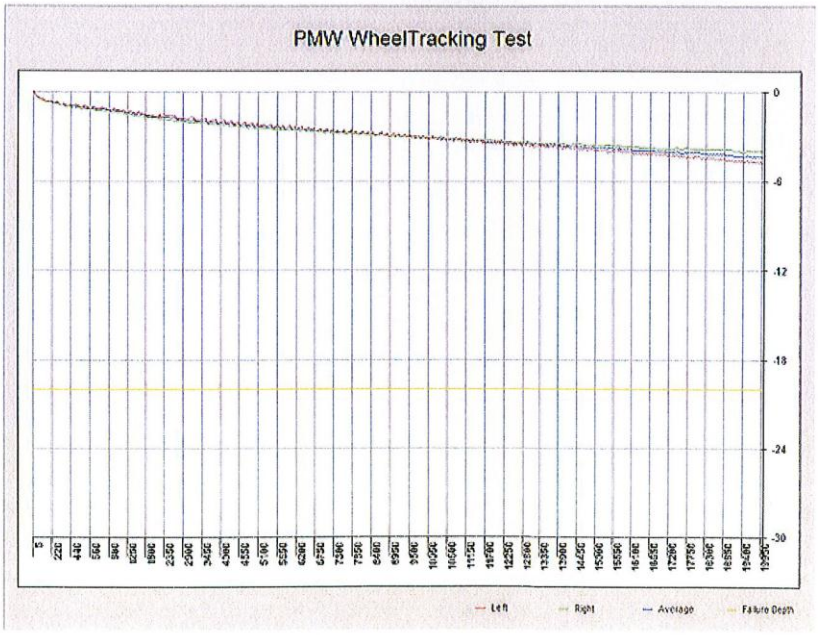
2. Foaming-based (Advera) Mixture

a. Foaming-based Mix Compacted at 270 °F

WheelTracker Report

Project Name:	MP 130 - MP 138	Date:	5/25/11
Project Number:	NH-085-B(011)	Date Sampled:	6/17/09
Job Number:	LOT 20	Lab Number:	
Project Engineer:	BOBBY LALL	Mix Type:	416 3/4 1% LIME
Submitted By:	YUMA	Asphalt Grade:	PG 76-16
Temperature:	55	Pit Source:	ERGON
Comments:	TEST#79 LV=7.2, RV=7.2, IMC=99, 40MM SLAB Advera WMA		

	Left	Right	Average
Max Impression:	-4.79 mm	-4.01 mm	-4.40 mm
	Pass #: 19950 / Pt: 2	Pass #: 19400 / Pt: 1	
Fail Depth: 20mm	PASS	PASS	PASS



CC: STATION 5827

Rut Data Report			
Performed: 5/25/2011	Test #79		Fail Depth: -20mm
Pass #	**Left Wheel**	**Right Wheel**	**Pass #**
5,000	-2.14	-2.22	**5,000**
10,000	-2.95	-2.86	**10,000**
15,000	-3.76	-3.41	**15,000**
20,000	-4.58	-3.81	**20,000**
Tested	1,2,3	1,2,3	**Tested**

THEORETICAL SAMPLE WEIGHT

Weight (g) = 0.93 x R ÷ 62.3 x V x 16.4;
Voids = 7.0 ± 0.5

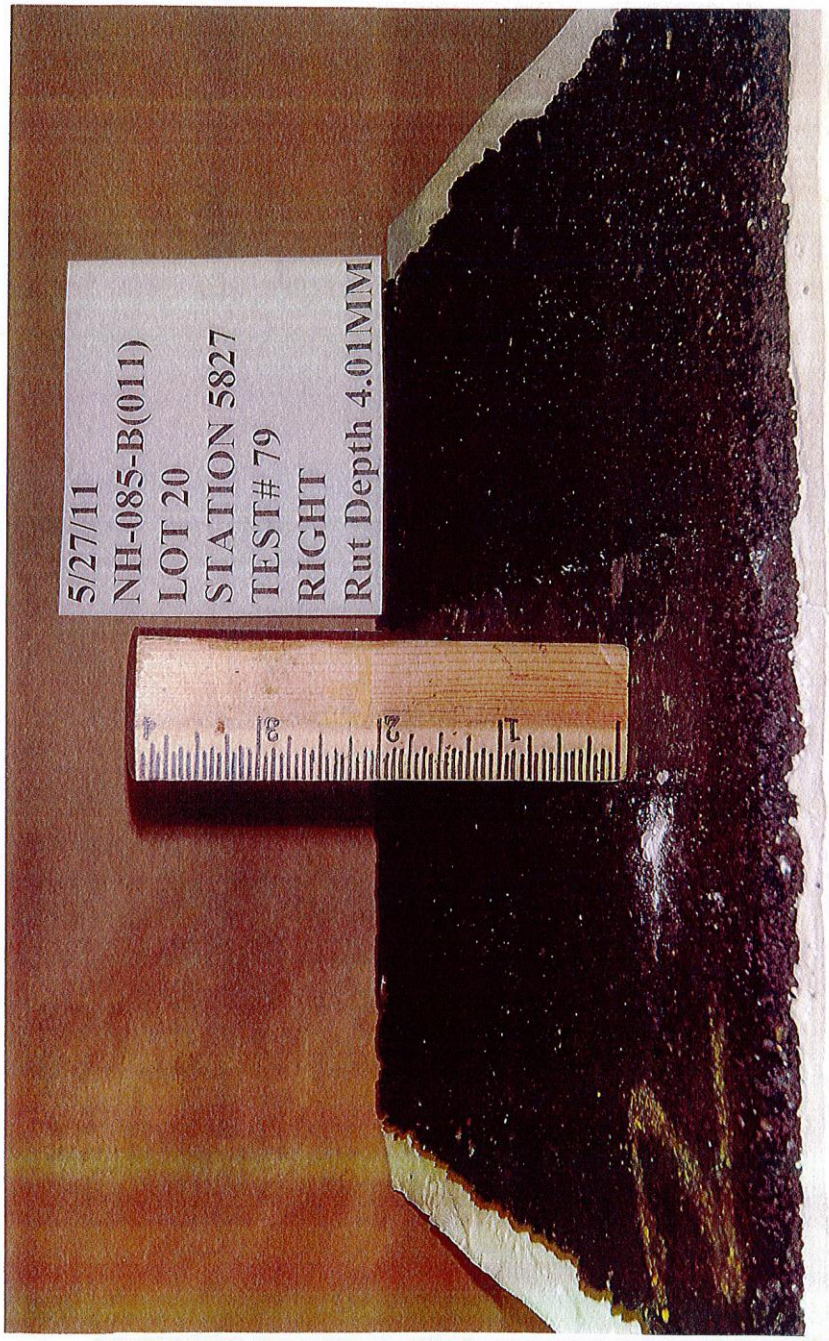
Date	Sample Number	Rice Density (from fast) (R)	Sample Size (inch) (L X W X H) V = 10.26 X 13.12 X 1.700	Sample Size (gram)
5/24/11	LOT 20 5827	152.4	228.84	8538

BULK DENSITY TEST

Date	Sample Number	Sample Size L X W X H (inch)	Air Weight	SSD Weight	H_2o Weight	Specific Gravity	Density	Air Void
5/24/11			8424.2	8467.5	4754.6	2.269	141.4	7.2
5/24/11			8404.0	8433.6	4729.0	2.269	141.4	7.2

Specimen Compacted at Temperature (°F) 270 Test _____ Check _____

5/27/11
NH-085-B(011)
LOT 20
STATION 5827
TEST# 79
LEFT
Rut Depth 4.79MM

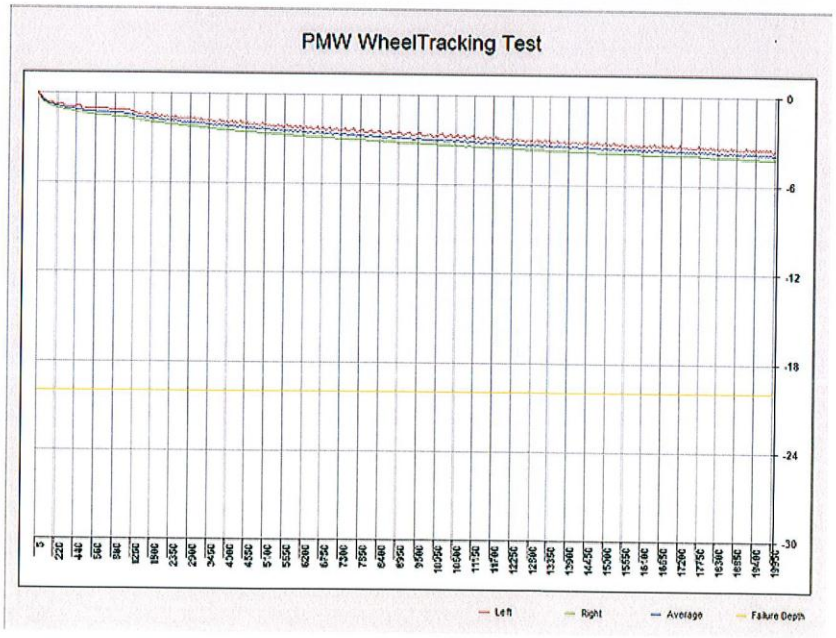

5/27/11
NH-085-B(011)
LOT 20
STATION 5827
TEST# 79
RIGHT
Rut Depth 4.01MM

b. Foaming-based Mix Compacted at 310 °F

WheelTracker Report

Project Name:	MP 130-138	Date:	7/1/11
Project Number:	H595507C	Date Sampled:	6/17/09
Job Number:	LOT 20	Lab Number:	STATION 5827
Project Engineer:	B LALL	Mix Type:	416 3/4 1% LIME
Submitted By:		Asphalt Grade:	PG 76-16
Temperature:	55	Pit Source:	ERGON ASPHALT
Comments:	TEST#84, LV=7.5, RV=6.6, IMC=99, 40MM SLAB Advera WMA		

	Left	Right	Average
Max Impression:	-3.71 mm	-4.23 mm	-3.97 mm
	Pass #: 19900 / Pt: 11	Pass #: 20000 / Pt: 1	
Fail Depth: 20mm	PASS	PASS	PASS



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Compacted @ 310 F

Rut Data Report			
Performed: 7/1/2011	Test #84		Fail Depth: -20mm
Pass #	**Left Wheel**	**Right Wheel**	**Pass #**
5,000	-1.85	-2.53	**5,000**
10,000	-2.38	-3.14	**10,000**
15,000	-2.84	-3.63	**15,000**
20,000	-3.12	-4.05	**20,000**
Tested	9,10,11	1,2,3	**Tested**

THEORETICAL SAMPLE WEIGHT

Weight (g) = 0.93 x R ÷ 62.3 x V x 16.4;
Voids = 7.0 ± 0.5

Date	Sample Number	Rice Density (from fast) (R)	Sample Size (inch) (L X W X H) V = 10.26 X 13.12 X 1.700	Sample Size (gram)
06-30 11	Lot 20 station 5827	152.4	228.84	8538.

BULK DENSITY TEST

Date	Sample Number	Sample Size L X W X H (inch)	Air Weight	SSD Weight	H_2o Weight	Specific Gravity	Density	Air Void
06-30 11	1		8504.1	8543.1	4784.0	2.262	140.9	7.5
	2		8136.7	8201.5	4547.0	2.226	138.7	9.0
	2		8487.5	8517.4	4801.8	2.284	142.3	6.6

Specimen Compacted at Temperature (°F) 310 Test _____ Check _____

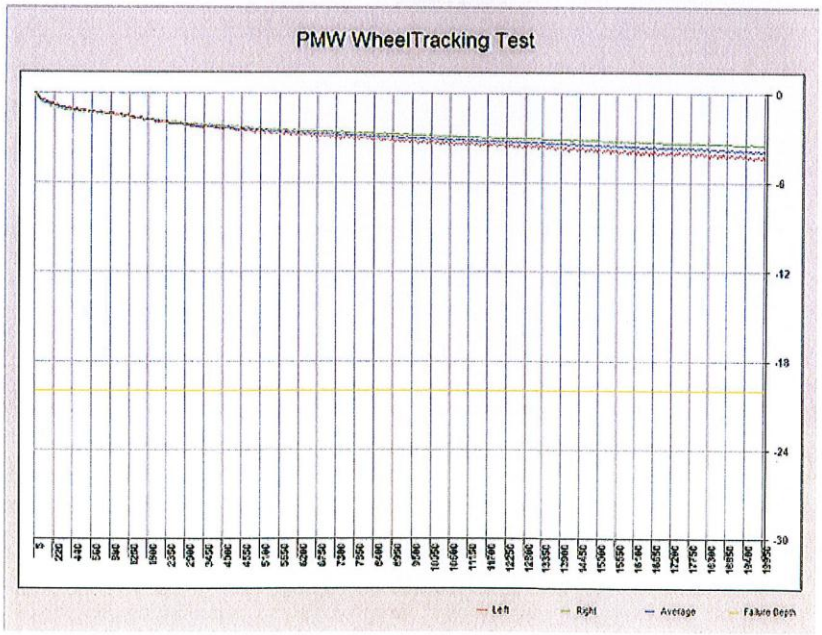
3. Chemical-based (Evotherm) Mixture

a. Chemical-based Mix Compacted at 270 °F

WheelTracker Report

Project Name:	MP 130-MP 138	Date:	5/18/11
Project Number:	NH-085-B(011)	Date Sampled:	7/22/09
Job Number:	LOT 41	Lab Number:	
Project Engineer:	BOBBY LALL	Mix Type:	416 3/4 1% LIME
Submitted By:	YUMA	Asphalt Grade:	PG 76-16
Temperature:	55	Pit Source:	ERGON
Comments:	TEST#77, LV=7.0, RV=7.0, IMC=99, 40MM SLAB Evotherm LIMA		

	Left	Right	Average
Max Impression:	-4.46 mm	-3.49 mm	-3.97 mm
	Pass #: 19600 / Pt: 11	Pass #: 20000 / Pt: 11	
Fail Depth: 20mm	PASS	PASS	PASS



CC: STATION 5994

Rut Data Report			
Performed: 5/20/2011	Test #78		Fail Depth: -20mm
Pass #	**Left Wheel**	**Right Wheel**	**Pass #**
5,000	-1.82	-1.87	**5,000**
10,000	-2.32	-2.37	**10,000**
15,000	-2.74	-2.94	**15,000**
20,000	-3.15	-3.51	**20,000**
Tested	1,2,3	9,10,11	**Tested**

THEORETICAL SAMPLE WEIGHT

Weight (g) = 0.93 x R ÷ 62.3 x V x 16.4;
Voids = 7.0 ± 0.5

Date	Sample Number	Rice Density (from fast) (R)	Sample Size (inch) (L X W X H) V = 10.26 X 13.12 X 1.700	Sample Size (gram)
5/17/11	LOT 41 4 OF 8	152.1	228.84	8521

BULK DENSITY TEST

Date	Sample Number	Sample Size L X W X H (inch)	Air Weight	SSD Weight	H_2o Weight	Specific Gravity	Density	Air Void
1			8393.4	8441.8	4742.0	2.269	141.4	7.0
2			8323.5	8387.2	4655.8	2.231	139.0	8.6
3			8383.1	8428.4	4738.0	2.272	141.5	7.0

Specimen Compacted at Temperature (°F) 275° Test_____ Check_____

5/27/11
NH-085-B(011)
LOT 41
STATION 5994
TEST# 77
LEFT
Rut Depth 4.46MM

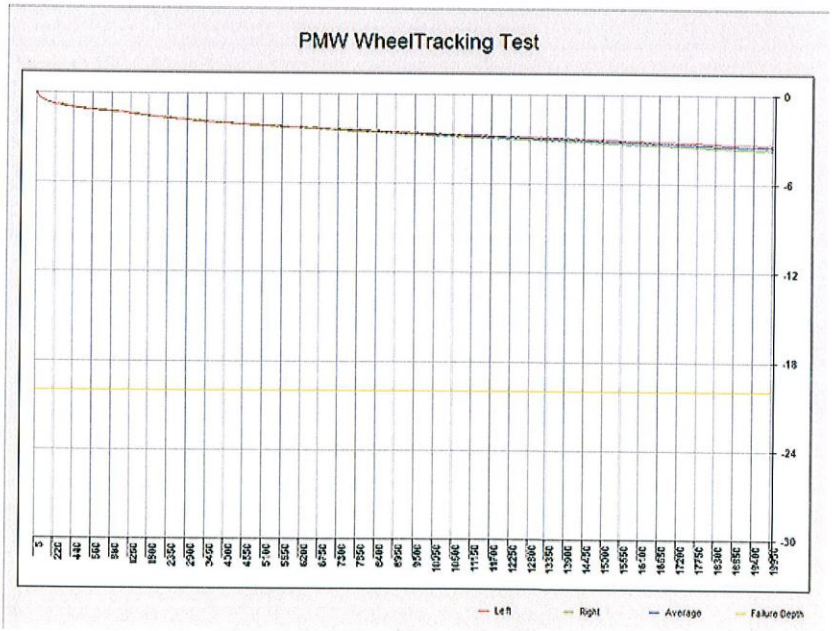
5/27/11
NH-085-B(011)
LOT 41
STATION 5994
TEST# 77
RIGHT
Rut Depth 3.49MM

b. Chemical-based Mix Compacted at 310 °F

WheelTracker Report

Project Name:	MP130-138	Date:	6/28/11
Project Number:	H595507C	Date Sampled:	7/22/09
Job Number:	LOT 41 (5 of 8)	Lab Number:	STATION 5994
Project Engineer:	B LALL	Mix Type:	416 3/4 1% LIME
Submitted By:		Asphalt Grade:	PG 76-16
Temperature:	55	Pit Source:	ERGON ASPHALT
Comments:	TEST#81, LV=6.5, RV=7.0, IMC=99, 40MM SLAB Evotherm WMA		

	Left	Right	Average
Max Impression:	-3.38 mm	-3.71 mm	-3.55 mm
	Pass #: 20000 / Pt: 1	Pass #: 19950 / Pt: 1	
Fail Depth: 20mm	PASS	PASS	PASS



CC:

Compacted @ 310 F

Rut Data Report			
Performed: 6/28/2011	Test #81		Fail Depth: -20mm
Pass #	**Left Wheel**	**Right Wheel**	**Pass #**
5,000	-1.96	-2.02	**5,000**
10,000	-2.45	-2.62	**10,000**
15,000	-2.84	-3.11	**15,000**
20,000	-3.12	-3.55	**20,000**
Tested	1,2,3	1,2,3	**Tested**

THEORETICAL SAMPLE WEIGHT

Weight (g) = 0.93 x R ÷ 62.3 x V x 16.4;
Voids = 7.0 ± 0.5

Date	Sample Number	Rice Density (from fast) (R)	Sample Size (inch) (L X W X H) V = 10.26 X 13.12 X 1.700	Sample Size (gram)
06-27-11	lot 41 5 of 8	152.1	228.84	8521.

BULK DENSITY TEST

Date	Sample Number	Sample Size L X W X H (inch)	Air Weight	SSD Weight	H_2o Weight	Specific Gravity	Density	Air Void
1			8508.7	8558.7	4830.2	2.282	142.2	6.5
2			8476.1	8519.0	4785.9	2.271	141.5	7.0

Specimen Compacted at Temperature (°F) 310° Test_____ Check_____