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Evaluation of Evotherm as a WMA technology compaction and anti-strip additive

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CHAPTER 1: INTRODUCTION

Background

With the development of the global economy, how to address sharply increasing demand for fossil fuels and reduce gas emissions has become a critical issue for society. The asphalt industry is also always looking for an efficient way to reduce emissions and save energy. Evotherm Warm Mix Asphalt is one alternative to achieve that purpose in the asphalt paving industry. Evotherm is a new generation warm mix asphalt chemical additive which was invented by MeadWestvaco in 2003 (Buss, 2011), and it allows a temperature reduction in the range of 50 to 75 °C (100 to 130°F) lower than typical hot mix asphalt (MeadWestvaco, 2012). A considerable amount of related research summarized in the literature review points out many advantages to implementation of the Evotherm WMA, but those all do well out of the lower mixing and compaction temperatures, which can lead to save energy, reduce emissions and lower costs for contractors.

In 2008 MeadWestvaco released the latest version Evotherm called Evotherm 3G with its partner corporations Paragon Technical Services and Mathy Technology & Engineering (MeadWestvaco, 2012). The Evotherm 3G includes two products: Evotherm-J1 and Evotherm-M1. Both of have warm mix asphalt characters, but also can completely coat fine and coarse aggregate for many aggregate applications and can effectively make use of binder from reclaimed asphalt pavement (RAP) materials. Moreover, Evotherm-J1 can be widely and efficiently mixed with mineral aggregate, and Evotherm-M1 exhibits excellent moisture resistance with high tensile strength ratio values (Evotherm J1 Product data Bulletin, 2012) & (Evotherm M1 Product Data Bulletin, 2012).

Problem Statement

Whether in HMA or WMA, moisture damage has been a major concern for asphalt concrete pavement. Moisture susceptibility can lead to stripping which can seriously damage a pavement structure by the loss in bond strength between the asphalt cement and the aggregate (Roberts, et al., 2009). As new generation WMA additives evolve, many owner agencies are concerned about these technologies contribute to moisture susceptibility. In addition, it is important for owner/agencies to know that if adding WMA technologies will affect asphalt mixture stability at different compaction temperatures.

Objectives

There are two main objectives to be addressed through this research. The first is to evaluate performance of the Evotherm–J1 and the Evotherm–M1 as a compaction technology additive. The second objective is to study the effect of moisture anti-strip of these two types Evotherm 3G products.

Methodology

In order to achieve the first objective, test results from MeadWestvaco were obtained including the compaction force index (CFI), and the traffic force index (TFI) to analyze the stability of the asphalt mixtures which were mixed and compacted at three different temperature combinations. The second objective of this research was achieved by running indirect tensile strength (ITS), dynamic modulus and Hamburg wheel track tests. A statistical analysis of the performance test results will help to determine which Evotherm 3G product ability to mitigate moisture sensitivity and the optimum dosing.

Hypothesis

In order to achieve the research objectives, the following hypotheses were developed with ensuing statistical analysis:

- Each mixture type has different performance results due to either a change in Evotherm type or Evotherm content.
- The Evotherm WMA mix performance is dependent on a temperature combination of mixing and compaction temperature.

Based on the extensive laboratory testing, some additional hypotheses were developed including:

- What is optimal Evotherm 3G content for each type Evotherm 3G product?
- Which mix type has the best performance on moisture anti-stripping?
- As a WMA technology compaction additive, which type Evotherm proportioning performances better on the WMA compaction stability?

Thesis Organization

This thesis is divided into five chapters. The first chapter is an introduction that provides background information about warm mix asphalt technology including Evotherm. In this chapter, the problem statement, objectives, methodology, and hypothesis are also briefly described to address to the research. Chapter 2 is the literature review, which summarizes a considerable amount literature on WMA technology and moisture susceptibility. The chapter also highlights the history of Evotherm and discusses the Superpave gyratory compaction method associated with mix compatibility. Chapter 3 outlines the experimental plan and introduces the specimen preparation procedures and the three proposed tests. Chapter 4 presents the results and statistical analysis of each set of tests. Chapter 5 is the summary, conclusions, and recommendations for further research.

CHAPTER 2: LITERATURE REVIEW

Background of Warm Mix Asphalt Technology

Warm mix asphalt technology is identified as an asphalt mix technology that allows a temperature reduction in the range of 35°F to 100°F (20 to 55°C) lower than typical hot mix asphalt by reducing the viscosity of the asphalt binder at a certain temperature range. By this way, aggregate could be fully coated at a lower temperature by the reduced viscosity asphalt binder. (Kristjansdottir, 2006)

The concept of WMA was proposed first time in the German Bitumen Forum in 1997 and then has been widely developed in Europe after these countries signed the Kyoto Agreement on greenhouse gas reduction (Newcomb, 2007). In 2007, the Federal Highway Administration's International Technology Scanning Program organized a U.S. expert team to visit four European countries to evaluate the feasibility of WMA in U.S. After the trip, the scan team suggested that the WMA technology can be recommended for use in the United States (D'Angelo, 2008).

Compared to HMA, there are several major reasons why warm mix asphalt technology is getting more and more popular and used more widely (D'Angelo, 2008):

- Reduced emissions: WMA expected emission reductions are: 30% to 40% for CO_2, 50% for VOC, 10% to 30% for CO, 60% to 70% for NO_X, 20% to 25% for dust.
- Reduced fuel and energy usage: WMA expected fuel savings range from 11% to 35%.
- Paving benefits: works for cooler temperature areas; longer haul distance; higher reclaimed asphalt paving (RAP) material mix proportion.
- Reduced worker exposure: reduction in asphalt aerosols and polycyclic aromatic hydrocarbons (PAHs) which can cause cancer.

Two ways can be accessed to classify the WMA technology. One method is by the degree of temperature reduction. Figure 1 shows a detailed temperature classification for different asphalt mixes. The other way is differentiated by the amount of water or additives to be added (D'Angelo, 2008).

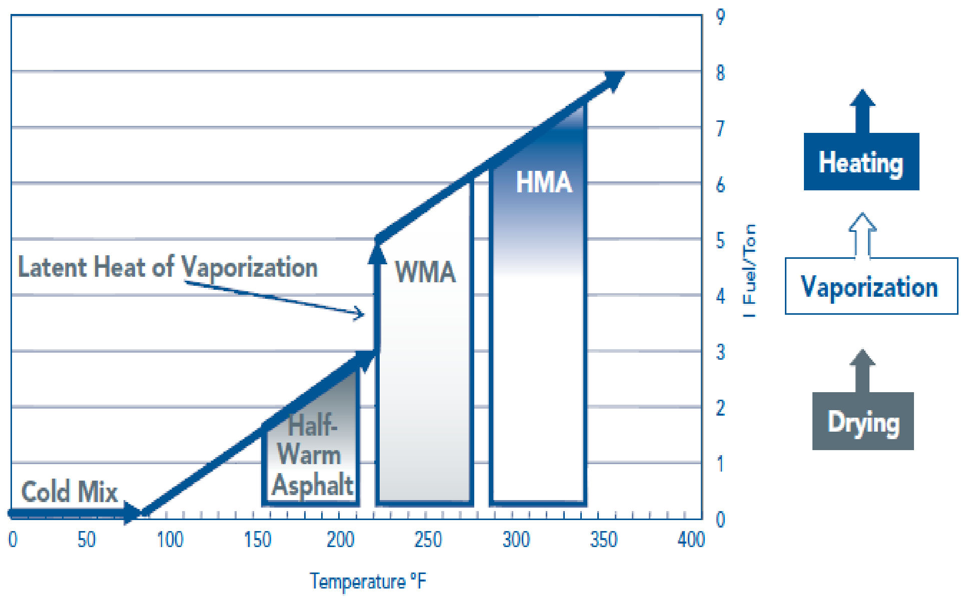


Figure 1. Mix Type Classifications by Temperature Range and Fuel Usage

The ultimate goal of adding water or an organic additive is to reduce the viscosity of the asphalt binder which results in a temperature reduction during asphalt mixing and compaction. When small amounts of water are injected into hot asphalt, it gets in touch with the asphalt binder first and is then vaporized at a high temperature. Meanwhile, the binder expands as water in the form of steam expands which results in a reduction of viscosity. Similar theories works for additives, but the melting point of the organic additives must be higher than the asphalt temperature to avoid asphalt embrittlement (D'Angelo, 2008).

There are five mature warm mix asphalt technologies that have been developed and used in Europe and the United States. WAM-Foam® (Warm Asphalt Mix Foam) is a two-component binder system which includes soft and hard bitumen. The WAM-Foam® was developed by Shell Global Soultions and Lolo Veidekke in Norway and it can lead to a 30 percent fuel savings and 30 percent CO_2 emission reduction. Aspha-min is a zeolite and is an artificial natrium-aluminum silicate which has been hydro-thermally crystallized. Aspha-min is a German warm mix asphalt technology, and it reduces the temperature by about 30°C (54°F) in asphalt mix production. In 1997, Sasol Wax International released Sasobit wax that is refined from coal gasification and is an oxidable and ageing stable fine crystalline. Use of Sasobit wax leads to 18° - 54°F temperature reduction in paving project temperatures. Advera WMA is a type of U.S WMA technology developed by PQ Corporation in Malvern, PA. It is a manufactured synthetic zeolite like Aspha-min and its production temperatures are typically 50° F – 70° F lower than traditional HMA. Last one technology is Evotherm, the focus of this research and is discussed in more detail in the following section (United States Department of Transportation, 2011). A summary of the WMA technologies is presented in Table 1 below.

Table 1. WMA Technologies (United States Department of Transportation, 2011)

Added to Binder or Mix			Foaming Processes			Emerging U.S. Technologies		
WMA Process	Additive	Production Temperature (at plant) °C	WMA Process	Additive	Production Temperature (at plant) °C	WMA Process	Additive	Production Temperature (at plant) °C
Sasobit (Fischer-Tropsch wax)	Yes, in Germany Added on average at 2.5% by weight of binder; lower doses, 1.0–1.5%, used in U.S.	Varies, 20–30 C° (36–54F°) drop from HMA. German guideline recommends 130–170 °C (266 to 338 °F), depending on binder stiffness	Aspha-min (zeolite)	Yes, about 0.3% by total weight of mix	Varies, 20–30 C° (36–54 F°) drop from HMA. German guideline recommends 130–170 °C (266–338 °F), depending on binder stiffness	Evotherm ™ (hot aggregate coated with emulsion)	Yes	85–115 °C (185–239 °F)
Asphaltan-B (Montan wax)	Yes, in Germany added on average at 2.5% by weight of binder	Varies, 20–30 C° (36–54 F°) drop from HMA. German guideline recommends 130–170 °C depending on binder stiffness	LEA, also EBE and EBT (from portion of aggregate fraction)	Yes, 0.2–0.5% by weight of binder of a coating and adhesion agent	<100 °C (212 °F)	Double-Barrel Green	Not necessary; an antistripping agent may be added similar to normal HMA	116–135 °C (240–275 °F)
Licomont BS 100 (additive) or Sübit (binder) (fatty acid amides)	Yes, about 3% by weight of binder	Varies, 20–30 C° (36–54 F°) drop from HMA. German guideline recommends 130–170 °C depending on binder stiffness	LEAB® (direct foam with binder additive)	Yes, added at 0.1% by weight of binder	90 °C (194 °F)	Advera (zeolite)	Yes, about 0.25% by total weight of mix	Varies, 20–30 C° (36–54 F°) drop from HMA.

Background of Evotherm

With the development of the global economy, how to address sharply increasing fossil fuel demands and reduce gas emissions has become a critical issue for society. The asphalt industry is also always looking for an efficient way to reduce emissions and save energy. As a newer innovative technology, Evotherm contributes to the asphalt concrete pavement industry by reducing fuel demand and greenhouse gas emissions by reducing the mixing and compaction temperatures of the asphalt mixture without affecting the properties of the mix.

Evotherm is a new generation warm mix asphalt chemical additive which was invented by MeadWestvaco in 2003 (Buss, 2011). Evotherm allows traditional hot mix asphalt to work at a comparable warm mix temperature which is 50 to 75 °C (100 to 130°F) lower than HMA (Evotherm® Warm Mix Asphalt, 2012). The advantages of utilizing Evotherm include (MeadWestvaco, 2012):

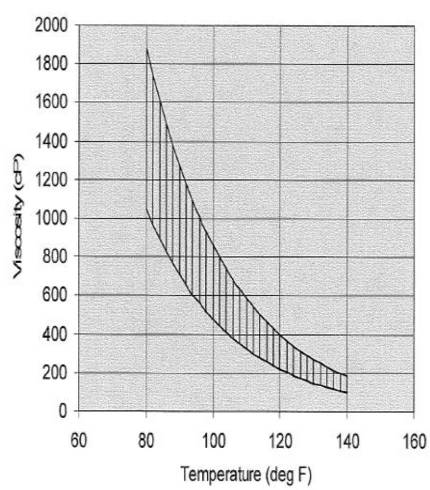
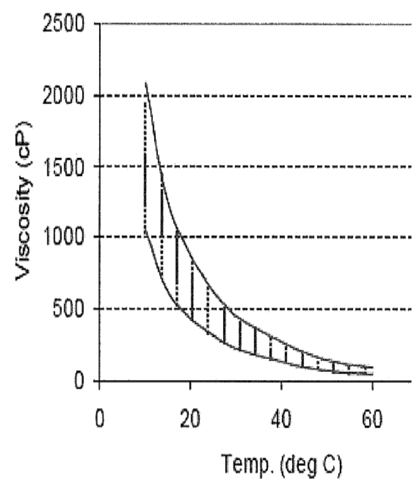
- Reduced air pollution including a reduction of 46% in CO_2, 63% in CO, 30% in VOC, 34%PM, 58% in NO_x and 81% in SO_x emission, respectively.
- Evotherm projects require less energy.
- Asphalt with Evotherm is easier to compact than traditional HMA.
- Asphalt mixes with Evotherm could extend the construction season in northern climates.
- Adding Evotherm could increase mixing facilities' throughput and increase the economic benefits.
- The lower production and compaction temperature of Evotherm could protect paving equipment from operating wear and tear.
- For asphalt concrete, the lower temperature means less oxidation which could extend pavement service life and lead to faster pavement construction and a more comfortable working environment for employees.
- Evotherm can easily be integrated with recycled asphalt materials.

Evotherm asphalt projects had been performed in many countries including China, France, and Canada. Over nineteen states have done over 100 Evotherm projects in the United States (MeadWestvaco, 2012). At present, MeadWestvaco has generated three versions of Evotherm warm mix asphalt technologies. Evotherm ET is a water-based asphalt emulsion and it can reduce production temperatures by 55 °C (100°F) without any plant modifications. Evotherm DAT is a dispersed asphalt technology which could be in-line injected directly with a drop in production temperatures of 45-55°C (85-100°F). Evotherm 3G is the third generation Evotherm technology. It is a water-free chemical additive that can reduce mix temperatures 33-45°C (60-85°F) by directly adding it into the terminal asphalt binder. (MeadWestvaco, 2012).

2008 MeadWestvaco released the latest version --- Evotherm 3G with its partner corporation Paragon Technical Services and Mathy Technology & Engineering (MeadWestvaco, 2012). The recommended Evotherm 3G additive dosages is from 0.25 to 0.75% by weight of the total binder, and the total binder means the sum of virgin binder plus binder derived from recycled materials. Research by Hurley indicates that the optimal Evotherm 3G content is 0.5 percent by the weight of total binder (Hurley & Prowell, 2006).

Both of Evotherm-J1 and Evotherm-M1 are two major types of Evotherm 3G products (Contractor, 2011). They are technologies that can completely coat fine and coarse aggregates for any aggregate gradations and can effectively make use of binder of reclaimed asphalt pavement (RAP) materials. Moreover, Evotherm-J1 can be widely and efficiently mixed with mineral aggregate. In addition, Evotherm-M1 exhibits excellent moisture resistance with high tensile strength ratio values (, Evotherm J1 Product data Bulletin, 2012 & Evotherm M1 Product Data Bulletin, 2012). A tabulated property comparison between the J1and M1 technologies is provided as follows (Evotherm J1 Product data Bulletin, 2012 & Evotherm M1 Product Data Bulletin, 2012) in Table 2.

Table 2. Comparison between the Evotherm-J 1 and Evotherm-M 1

	Evotherm-J1	Evotherm-M1
Physical Form	Dark Liquid	Dark Amber liquid
Density at 25°C	8.25 lb/gal	8.35 lb/gal
Specific Gravity at 25°C	0.999	0.97
Conductivity at 25°C	4.3 µS/cm	2.2 µS/cm
Dielectric Constant at 25°C	2-10	2-10
Recommended Dosage Rate	0.25-0.75 by weight asphalt cement	0.25-0.75 by weight asphalt cement
Recommended Mixing Temperature Range	>220 °F	>220 °F
Recommended Compaction Temperature Range	>220 °F	>220 °F
Typical Viscosity Range		

Superpave Gyratory Compaction

The intent of this part of literature review is to present information about using the Superpave Gyratory to estimate asphalt mixture stability which mainly focuses on shear capability and resistance.

The selected Superpave Gyratory Compactor is the Pine AFG2 which is a newer generation gyrator compactor invented by Pine Instrument Company. Several advanced functions are developed in AFG2. First, the machine can setup a programmable gyratory external or internal angle. Second, the machine could optionally measure the force and shear capability applied on the specimen. In addition, the AFG2 has a taller compaction mold with 150mm diameter *200 mm size than previous gyratory compactors. Finally, all the data information created by the AFG2 can be stored automatically and saved to a USB drive (Pine Instrument, 2009).

Figure 2. Images of AFG2 Superpave Gyratory Compactor (Pine Instrument, 2009)

Using a Pine AFG2 Superpave Gyratory Compactor to estimate the stability of asphalt mixtures can be outlined as two steps. The first stage is taking advantage of the construction densification index (CDI) to indicate how much roller work is required for compacting an asphalt pavement during construction. The second stage is utilizing the traffic densification index (TDI) to reflect how much densification can be applied by traffic loading to approach the pavement plastic failure. The CDI and TDI are all densification values and are hard to identify. Therefore, the compaction force index (CFI) and the traffic force index (TFI) are developed to visually demonstrate the shear force effect from contraction and traffic on asphalt pavements. Resistive effort curves are employed to identify the CDI, TDI, CFI and TFI. The resistive effort curves are illustrated in Figure 3 (Faheem & Bahia, 2005).

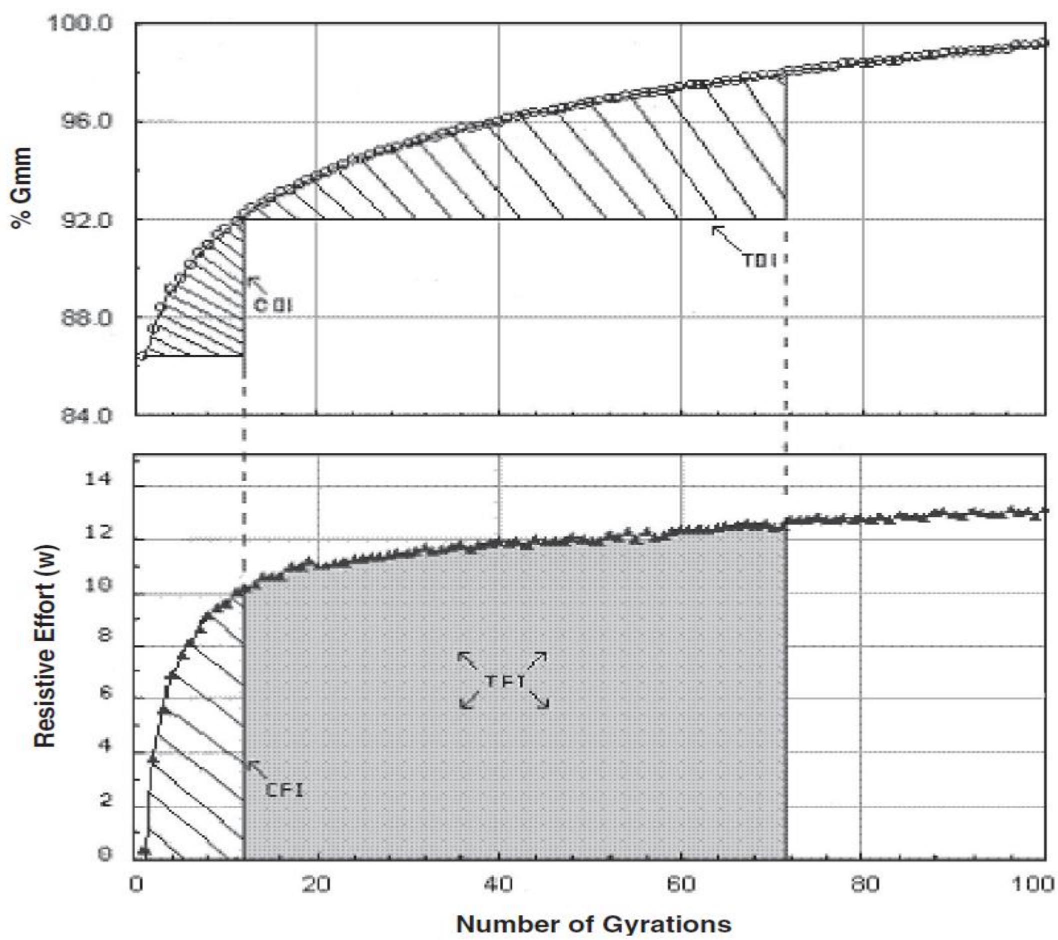


Figure 3. Resistive Effort Curves

In Surperpave, the number of gyrations is a function to control and check the asphalt mixture compactibility. For asphalt pavement, the number of gyrations (the initial (N_{ini}), maximum (N_{max}) or design number of gyration (N_{des})), can be used to evaluate traffic level or check plastic failure (Asphalt Institute, 2001). The gyrations are the number of Superpave Gyratory Compactor gyrations utilized to simulate the effort applied by a typical paver during the asphalt pavement construction. Thus, asphalt mixture density is identified by the percent of the maximum theoretical specific gravity (G_{mm}) and indirectly demonstrated by the number of gyrations. The CDI and TDI also are performed by the number of gyration at varied percent of G_{mm} values. Correspondingly, the CFI and TFI are presented by the different areas under the resistive effort curve (Faheem & Bahia, 2005).

The resistive effort curve is separated at 92% of the asphalt mixture maximum theoretical specific gravity (G_{mm}) into a construction effect zone and a traffic effect zone. The CFI refers the left construction side and relates to the area under the resistive effort curve below 92% G_{mm}. For the right traffic effect zone, the TFI is measured by the area between 92% and 98% G_{mm} under the resistive effort curve. In essence, low resistive effort is desirable for contractor to easily compact an asphalt pavement, saving compaction time/effort and reducing cost. Therefore for an asphalt mixture, lower values of CFI are desired to get better constructability. Inversely, higher TFI values are desired for asphalt mixtures to resist the stress from traffic loading and to reduce pavement rutting. A higher TFI value also means the pavement could take more traffic during its service life and extend its service life (Abed, 2011).

Moisture Susceptibility

Moisture susceptibility is an indispensable issue needed to be considered for asphalt concrete pavement. Moisture damage is a loss of strength due to the effects of moisture. Moisture susceptibility could lead to stripping which could seriously damage the pavement structure by the loss in bond strength between the asphalt cement and the aggregate (Roberts, et al., 2009). Moisture damage often can result in thermal cracking, fatigue cracking and permanent deformation, and it is affected by a variety of factors including the pavement drainage condition, mix composition, material properties, traffic loading, and environment characteristics (Lu, 2005).

Moisture damage is a comprehensive process which is not only related to physical characteristics but also to chemical composition. Moisture stripping can occur due to the following main mechanisms: detachment, displacement, spontaneous emulsification, pore pressure, hydraulic scour, pH instability, and environmental effects on the aggregate–asphalt system. Improving the chemical bonding between asphalt cements and aggregates is an efficient way to reduce moisture damage and stripping in asphalt pavement. Net charges exist in interfacial transition zones between the aggregate and the asphalt cement and are significantly affected by the ability of the chemical bonding to attract or repel water molecules (Transportation Research Board, 2003).

Due to the significance of moisture susceptibility, dozens of test methods have been developed to evaluate the potential moisture damage for flexible pavements. The methods are divided into two types: testing loose mixtures and compacted asphalt mixes. Those methods are all intended to simulate field conditions in the lab from different aspects such as traffic (loading), climate (temperature) and pavement structure (Transportation Research Board, 2003). Three of the most popular moisture susceptibility tests are described in Chapter 3 as they were used in this thesis research.

CHAPTER 3: EXPERIMENTAL PLAN AND TEST SETUP

Experimental Plan

This section provides the experimental plan to evaluate the performance of the Evotherm as a WMA compaction technology and as an anti-strip additive. Two types of Evotherm, J-1 and M-1, from the MeadWestvaco Company were selected, and their added amounts are by weight of binder: 0%, 0.5% and 1 %. A PG 64-22 original asphalt binder was used to blend with the two types of Evotherm and the optimal binder content is 5.3%. Six types of aggregates from different sources were provided for the mixture design which included 3/8 CL Chip, Eagle City limestone, manufactured sand, and quartzite from South Dakota; natural sand from Hallet Materials corporation and hydrated lime product from Voluntary Purchasing Group, Inc. All samples had the same aggregate gradation but the two different types of Evotherm with three different blend contents were varied. Therefore, six mix types were developed and are abbreviated as J1-0%, J1-0.5%, J1-1%, M1-0%, M1-0.5% and M1-1% for further discussion.

The SUPERPAVE design method was implemented for the mix design development. The test required by the SUPERPAVE design method include the aggregate washed gradation test, coarse and fine aggregate angularity test, flat and elongated particle analysis, crush count, bulk specific gravity testing, theoretical maximum specific gravity testing, and optimal binder content determination. The mix design level was 10,000,000 ESALs with a 12.5 mm nominal maximum aggregate size (NMAS) being used.

One of the objectives of the research is to evaluate performance of the Evotherm 3G products as WMA compaction technology additive. The MeadWestvaco Company produced and tested all specimens which were used in this part of the research project to measure the specimens' shear capability. The samples were compacted using a Pine AFG2 Superpave Gyratory Compactor at three different mixing/compaction temperature: 160/145°C, 145/130°C, and 130/115°C, respectively. The selected design number of gyrations (N_{des}) is 96 and the maximum number of gyrations (N_{max}) is 152. A detailed testing plan is summarized by Table 3.

Table 3. Performance Testing Plan of WMA Compaction Technology Additive

	Additive	0%(Control)	M1-0.5%	M1-1%	J1-0.5%	J1-1%
Temperature (°C)	160/145	xxx	xxx	xxx	xxx	xxx
	145/130	xxx	xxx	xxx	xxx	xxx
	130/115	xxx	xxx	xxx	xxx	xxx

[a] "X" represents one sample and x within each cell represents sample size.

In order to evaluate the contribution of Evotherm as an anti-strip, Indirect Tensile Strength Testing, Dynamic Modulus Testing and Hamburg Wheel Track Testing were conducted to evaluate mixture moisture damage susceptibility. All of three sets of test samples were compacted using a Pine Superpave Gyratory Compactor to 7%±0.5 air voids. The sample sizes (diameter × height) of three above tests were: 100 × 63.5±2.5 mm, 100 × 150 ±2.5 mm, 100 × 61±1 mm, respectively. A detailed testing plan is summarized by Table 4.

Table 4. Performance Testing Plan of Moisture Anti-strip Additive

		Unconditioned						Conditioned					
Evotherm Type		J-1			M-1			J-1			M-1		
Evotherm Content (%)		0	0.5	1	0	0.5	1	0	0.5	1	0	0.5	1
Anti-Strip Tests	TSR	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
	E*	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
	Hamburg WTD	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx

[a] "X" represents one sample and x within each cell represents sample size.

Sample Conditioning

According to the above experimental plan, all of the samples for each of three of TSR, dynamic modulus and Hamburg WTD tests were prepared according to AASHTO T 283 specification: "Resistance of Compacted Bituminous Mixture to Moisture Induced Damage." For each test, all samples were randomly assigned into two subsets so that they are similar in average air voids. As a control group (non-moisture conditioned group), one of two subsets was selected to be tested under the dry condition. They were placed in a 25 ± 0.5 °C (77±1 °F) water bath for two hours and then stored in an environmental chamber at 25°C prior to testing. However, the moisture-conditioned specimens had to undergo vacuum saturation. The degree of saturation was between 70 and 80 percent for the tested specimens and they were each wrapped with a plastic film and then placed in a plastic bag which contained 10 ± 0.5 ml of water and sealed. Afterwards, the sealed samples were stored in a freezer at a temperature of -18± 3°C (0 ± 5 °F). After a minimum of 16 hours, all of samples were removed from the freezer and put into a water bath at 60 ± 1 °C (140±2 °F) for 24 ±1 hours. Meanwhile, all samples must be removed from the plastic bags and film, and submerged with 25mm of water above their surface. The next step before testing is same as control group samples as all of conditioned samples were placed in a 25 ± 0.5 °C (77±1 °F) water bath for two hours and then stored in an environmental chamber at 25°C prior to testing. After all of the above steps, all of unconditioned and conditioned specimens are ready for testing.

Indirect Tensile Strength Testing

The indirect tensile strength (IDT) test, according to AASHTO T 283-07 “Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage”, was performed for both non-moisture and moisture-conditioned samples to evaluate the mixture sensitivity to moisture damage. AASHTO T 283-07 describes the IDT testing procedure that “place one specimen between the steel loading strips and then place the specimen and loading strips between the two bearing plates in the testing machine. Apply the load to the specimen, by means of the constant rate of movement of the testing machine head, at 50 mm/min.” Finally, the maximum compressive load was recorded to calculate tensile strength.

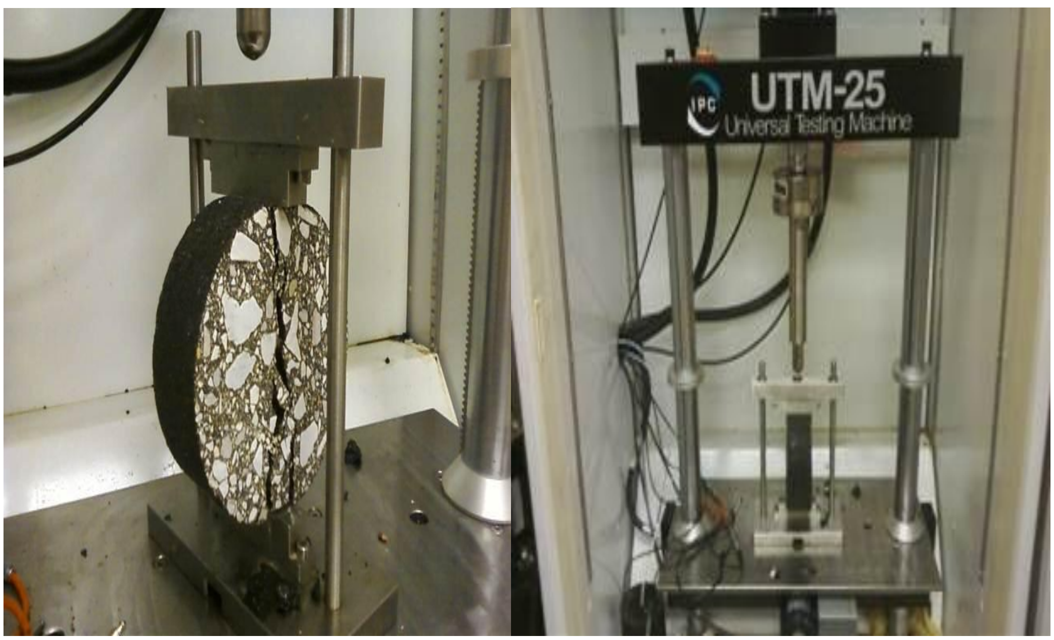


Figure 4. Images of Indirect Tensile Strength Testing

Stripping is a process that could be influenced by moisture and will result in a loss of strength through the weakening of the bond between the asphalt cement and the aggregate (Roberts et al., 2009).The loss of strength can be reflected from the tensile strength ratio (TSR) because that express the numerical index of resistance of HMA to the detrimental effect of water as the ratio of retained strength after moisture and freeze-thaw conditioning to that of the original strength (AASHTO, 1997). The flowing is the calculation for determining the tensile strength ratio:

$$Tensile\ Stegth\ Ratio\ (TSR) = \frac{S_2}{S_1}$$

where:

S_1= average tensile strength of the dry subset, kPa (psi); and

S_2= average tensile strength of the conditioned subset, kPa (psi).

The tensile strength (S_1, S_2) is as follows (SI Units):

$$S_t = \frac{200P}{\pi t D}$$

where:

St = tensile strength, kPa;

P = maximum load, N;

t = specimen thickness, mm; and

D = specimen diameter, mm.

Dynamic Modulus Test

The dynamic modulus |E*|, is a complex number that relates stress to strain for linear viscoelastic materials such as HMA mixtures subjected to a continuously applied sinusoidal cyclic loading in the frequency domain (Schwartz, 2005). It is a test used to evaluate the stiffness of a material. Stiffness as characterized by the dynamic modulus is a fundamental engineering material property of asphalt concrete that is essential to predicting the performance of asphalt pavements. The dynamic modulus is used to quantify the stiffness of asphalt pavements because asphalt materials are viscoelastic, meaning the ability for it to recover from induced stresses is dependent upon temperature and loading frequency. Besides, the dynamic modulus test has also been evaluated as a simple performance test for predicting moisture-susceptibility in asphalt mixture (Bausano et al., 2007). As expected, the dynamic modulus decreases as the temperature increases and the loading frequency decreases. Meanwhile, HMA mixes which have high stiffness modulus value at low temperatures have a greater resistance to permanent deformation (Roberts et al., 2009).

The AASHTO TP 62-07 procedure was followed for specimen preparation and test setup. In order to obtain a high degree of accuracy, three LVDTs were used and fixed by six brackets which were attached using epoxy glue. All the samples were tested under three different temperatures (4^{o}C, 21^{o}C and 37^{o}C) starting with the lowest temperature and proceeding to the highest and 9 different frequencies (0.1, 0.2, 0.5, 1, 2, 5, 10, 20 and 25 Hz). During the dynamic modulus test, a sinusoidal (haversine) axial compressive stress is applied to a specimen of asphalt concrete as presented in Figure 5 at a given temperature and loading frequency.

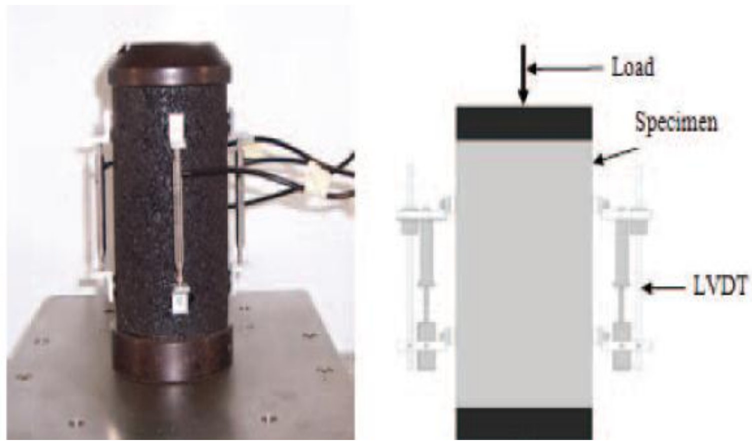


Figure 5. Dynamic Modulus Test Setup (Transportation Research Board, 2003)

The applied stress and the resulting recoverable axial strain response of the specimen is measured and used to calculate the dynamic modulus and phase angle (AASHTO, 2009). The angle by which the peak recoverable strain lags behind the peak dynamic stress is referred to as the phase angle, φ. The phase angle is an indicator of the viscous properties of the material being evaluated.

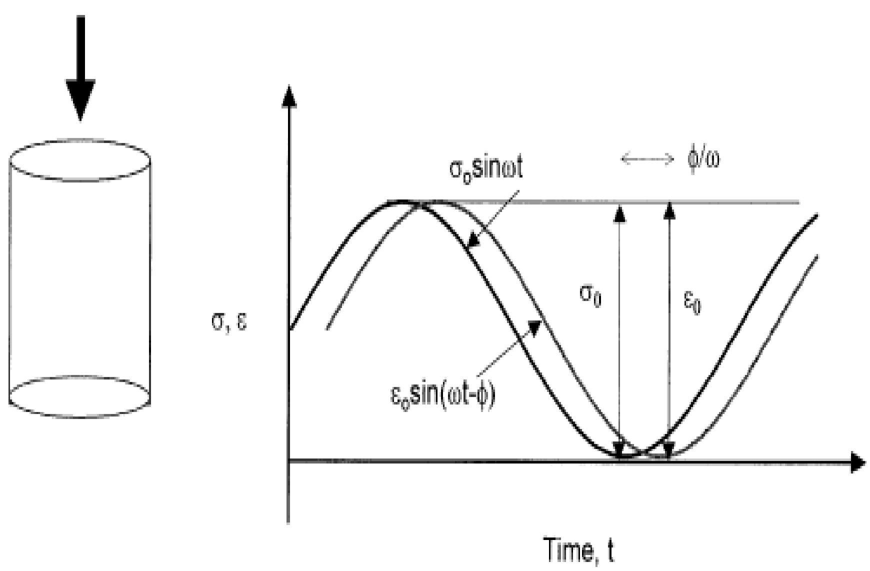


Figure 6. Haversine Loading for the Dynamic Modulus Test (Witczak, 2005)

By applying a continuous sinusoidal load to asphalt materials, the viscoelastic behavior of the asphalt sample can be described through “complex” mathematics. The dynamic modulus is calculated by dividing the stress amplitude as maximum dynamic stress (σ_o) by the strain amplitude as the peak recoverable axial strain (ε_o) (See Figure 6).

$$|E^*| = \frac{\sigma_o}{\varepsilon_o}$$

The dynamic modulus (*E**) is the absolute value of the complex modulus |E*|. |E*| is composed by a storage modulus E’ and a loss modulus E”. The storage modulus refers to the elastic behavior of the material and the loss modulus refers to the viscous behavior of the material.

$$E^* = E' + iE''$$

The proportions of the storage modulus and the loss modulus for a dynamic modulus value can be defined with the phase angle (θ) which can be described mathematical as:

$$E^* = |E^*| \cos\theta + i|E^*| \sin\theta$$

The phase angle describes the amount of time the strain responses occur after the stresses have been applied is defined by the following equation.

$$\theta = \frac{t_i}{t_p}(360)$$

where:

t_i = time lag between a cycle of stress and strain (s);

t_p = time for a stress cycle (s); and

i = imaginary number.

For a pure elastic material, the phase angle is zero degrees and for a pure viscous material the phase angle is equal to 90 degrees.

Development of Master Curves

Based on the concept of the time –temperature superposition principle, a master curve is constructed at a reference temperature (normally 70°F (21.1°C)) to describe the dynamic modulus at different temperatures/frequencies of loading and is developed to characterize asphalt concrete for pavement thickness design and performance analysis. An advantage of the master curve is that it can characterize how a mix may perform at a frequency or temperature which was not tested (Buss, 2011) and can provide an approach to comparing the results obtain by two laboratories with different sets of tests conditions, such as moisture conditioned and unconditioned, respectively (Pellinen & Witczak, 2002).

Through a master curve it is possible to integrate traffic speed, climatic effects, and aging for pavement responses and distress models (Roberts et al., 2009). The use of the dynamic modulus master curve permits the elastic modulus of the HMA layers to be varied by temperature, speed, and layer depth in pavement designs. Master curves for asphalt mixtures can be mathematically modeled by the following sigmoidal function (Garcia & Thompson, 2007):

$$\mathrm{Log}|E^*| = \delta + \frac{\alpha}{1+e^{\beta+\gamma(\log f_r)}}$$

where:

fr = reduced frequency at the reference temperature;

δ = minimum value of E*;

δ + α = maximum value of E*; and

β, γ = parameters describing the shape of the sigmoidal function.

The following second-order polynomial equation can be used to calculate the shift factors for each frequency sweep at a fixed temperature.

$$\log f_r = \log f + a_1(T_R - T) + a_2(T_R - T)^2$$

where:

f_r = reduced frequency at the reference temperature;

f = loading frequency at the test temperature;

a_1, a_2 = the fitting coefficients;

T_R = the reference temperature, °C; and

T = the test temperature, °C.

Hamburg Wheel Track Test

The Hamburg Wheel Tracking Test Device (HWTD) is one of several wheel tracking tests have been used in the United States. It was developed in the 1970s by Esso A.G of Hamburg, Germany (Aschenbrener, 1995). The major purpose of the HWTD is to test an asphalt mixture's susceptibility to moisture damage. The test is conducted with hot water and results can be utilized to evaluate the potential of stripping (Roberts et al., 2009).

The AASHTO T 324-04 procedure was followed for specimen preparation and test setup. Two cylindrical specimens were butted into molds which were filled with water at 50°C and two solid steel wheels with 0.73 MPa (145psi) contact stress were loaded on the samples and repeated 20,000 times of 1.1km/h wheel passes for about 6.5 hours or until failure. The test ended automatically when 50 mm (1.6 in.). Rut depth occurs or the preset number of 20,000 wheel cycles is reached (Roberts et al., 2009).

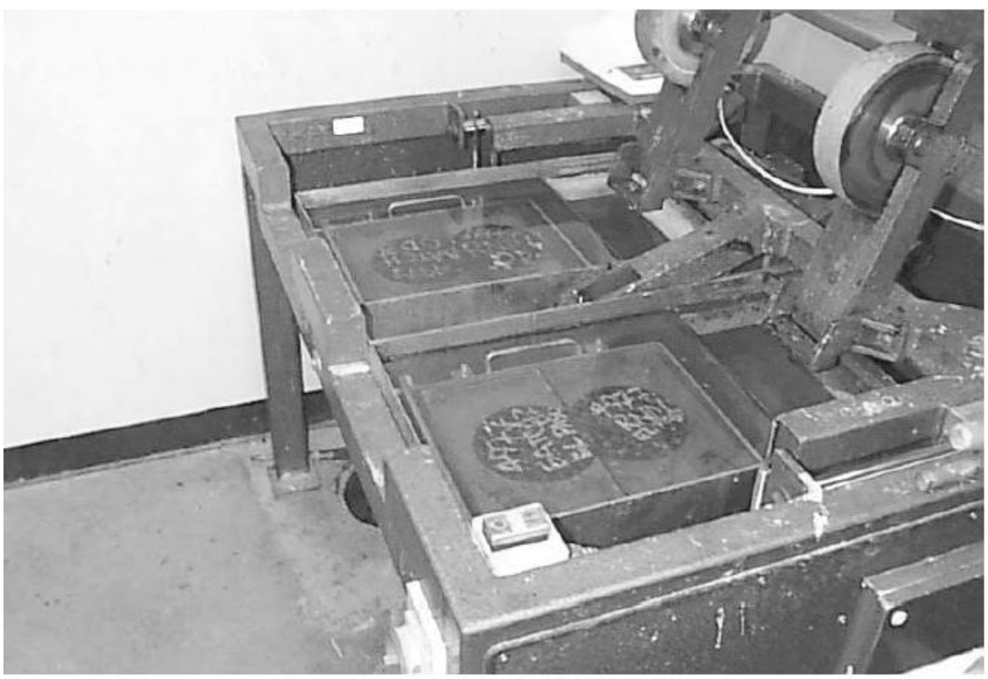


Figure 7. Hamburg Wheel Track Test Setup (Transportation Research Board, 2003)

A curve can be plotted as shown in Figure 8 after the test. In the figure, there are three turning points. After the first 1,000 wheel passes, the first turning point occurred and called the post-compaction consolidation to assume that the wheel is to density the mixture. The next turning point brings out the creep slope and it reflects rutting which primarily from plastic flow other than moisture damage. The third one is the stripping slope that indicates moisture damage. The accumulation of permanent deformation due to moisture damage can be measures by the stripping slope, which is the inverse of the rate of deformation (wheel passes per 1-mm rut depth) after the stripping inflection point (SIP). Besides, higher stripping slope and SIP indicate less moisture damage (Federal Highway Administration, 2011). Although the curve have the three characteristic variables, some mixes will only show the creep slope while some mixes show the stripping slope immediately after the post compaction stage (Lu, 2005).

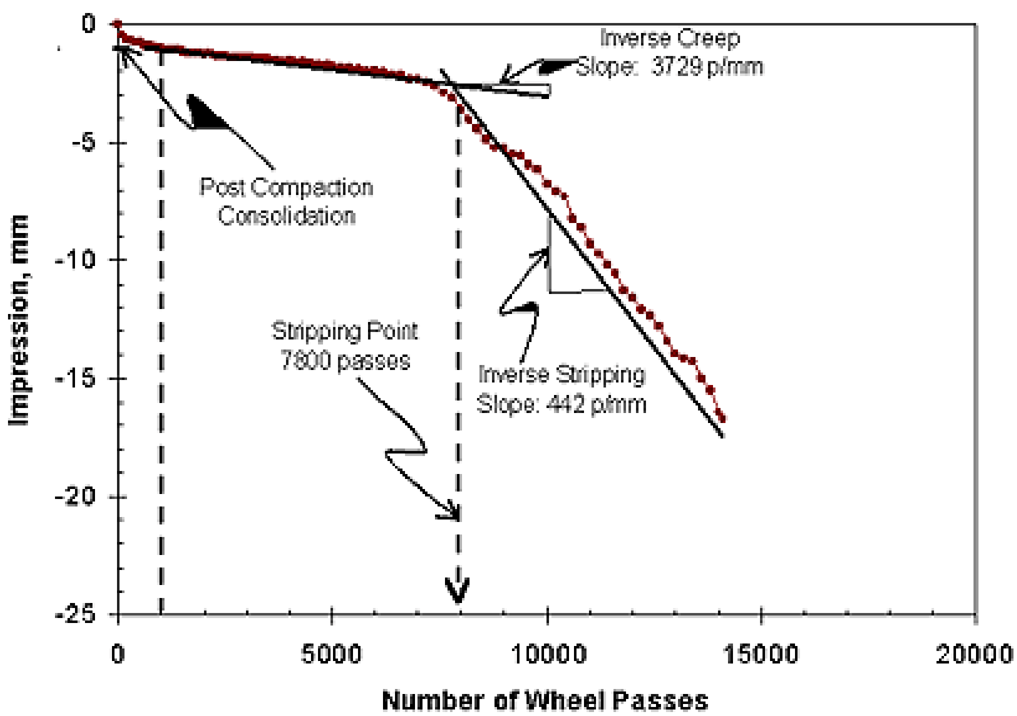


Figure 8. Rut Depth vs. Number of Wheel Passes (Federal Highway Administration, 2011)

An important point which could indicate moisture damage called stripping inflection point (SIP). It is a point that the number of wheel passes at the intersection of the creep slope and the stripping slope. After the number of wheel passes at that point, the moisture damage tends to dominate performance (Federal Highway Administration, 2011). The Colorado Department of Transportation (CDOT) points out that any inflection point below 10,000 wheel passes is an indication of moisture susceptibility (Aschenbrener, 1994). Mathematically, the SIP is calculated as shown in the following equation:

$$\text{Stripping Inflection Point (SIP)} = \frac{\text{Intercept (creep section)} - \text{Intercept (stripping section)}}{\text{Slpoe (stripping section)} - \text{slope (creep section)}}$$

(Roberts, 2009).

In general, the test rutting result is defined by the rut depth at 20,000 wheel passes. At present, there is no a specification to limit the maximum rut depth for the HWTD testing in U.S. However, The Texas Department of Transportation (TxDOT) uses 12.5 mm after 20,000 passes and The Colorado Department of Transportation (CDOT) suggested that a rut depth of 10 mm after 20,000 passes as the criterion (Lu, 2005).

CHAPTER 4: PERFORMANCE TESTING RESULTS AND ANALYSIS

WMA Compaction Shear Capability Testing Results and Analysis

In this section, the test results were evaluated, namely how the two types of Evotherms (J1, M1) contribute to the stability of the asphalt mixtures which were mixed and compacted at three different temperature combinations. As described in Chapter 3, each mix type involves three samples and each mix type was tested at three different temperature combinations. According to the temperature range classification mentioned in Chapter 2, the mixing and compaction temperature combination of 160/145°C is associated with the HMA, however, the combination of 145/130°C and130/115°C are classified to WMA. Table 5 shows a summary of the test result and the detailed testing data are located in Appendix A.

As shown in Table 5, average values of the compaction force index (CFI), and the traffic force index (TFI), the air voids @ N_{des} and the air voids @ N_{max} are presented regardless of compaction temperature, it is clear that the air voids @ N_{des} of each mix type is close to 3.0% and decrease when the number of gyrations increases to the maximum. That is because when the gyrations increased, the density of the asphalt mix increases and the air voids decreases. In addition, visually, M1-1% has the lowest CFI value at 130°C and the control group has the highest TFI value at 115°C. Figures 1 and Figure 2 visually shows the CFI and TFI tendencies with error bars. The error bars with standard deviation show the difference between the two mean (CFI, TFI) is not statistically significant difference ($p<0.05$) as evidence by the error bars overlapping. In addition, some raw data were removed as outliers which are out of a range that between average (CFI, TFI) values plus and minus two standard deviation values. The one-way analysis plot for outliers is located in Appendix A.

Table 5. Summary of WMA Compaction Shear Capability Testing Results

Additive	Control			M1-0.5%			M1-1.0%			J1-0.5%			J1-1.0%		
Compaction Temp.	145	130	115	145	130	115	145	130	115	145	130	115	145	130	115
Va @ N_{de}	2.6	3.0	2.9	3.0	2.6	3.1	2.9	2.5	2.8	2.6	2.8	2.8	2.5	2.8	2.6
Standard Deviation	0.1	0.1	0.2	0.2	0.1	0.0	0.2	0.1	0.1	0.2	0.2	0.0	0.2	0.2	0.2
95% CI	0.1	0.1	0.3	0.3	0.1	0.0	0.3	0.2	0.2	0.3	0.3	0.1	0.3	0.3	0.3
Va @N_{max}	1.5	1.8	1.7	1.7	1.5	1.7	1.8	1.4	1.6	1.4	1.6	1.7	1.3	1.6	1.5
Standard Deviation	0.1	0.1	0.2	0.2	0.0	0.1	0.2	0.1	0.1	0.1	0.3	0.1	0.2	0.2	0.2
95% CI	0.1	0.1	0.3	0.2	N/A	0.1	0.3	0.2	0.1	0.2	0.4	0.1	0.3	0.3	0.2
CFI Average	541	543	646	554	545	640	595	482	599	580	504	609	579	594	599
Standard Deviation	23.3	43.6	50.5	88.6	20.7	17.7	55.3	38.5	23.9	33.3	9.8	48.1	40.7	53.0	45.5
95% CI	32.2	60.4	70.0	123	28.6	24.5	76.6	53.3	33.1	46.1	13.6	66.6	56.4	73.5	63.1
TFI Average	3189.0	3669.8	3966.3	3501.5	3286.0	3705.3	3661.0	3019.3	3584.8	3318.6	3210.0	3628.2	3270.9	3542.2	3484.9
Standard Deviation	109.5	238.2	361.4	277.4	22.1	53.4	212.9	106.6	118.9	184.6	152.8	136.5	220.2	456.6	264.4
95% CI	151.7	330.2	500.9	384.5	30.7	74.1	295.1	147.7	164.8	255.9	211.7	189.2	305.1	632.9	366.4

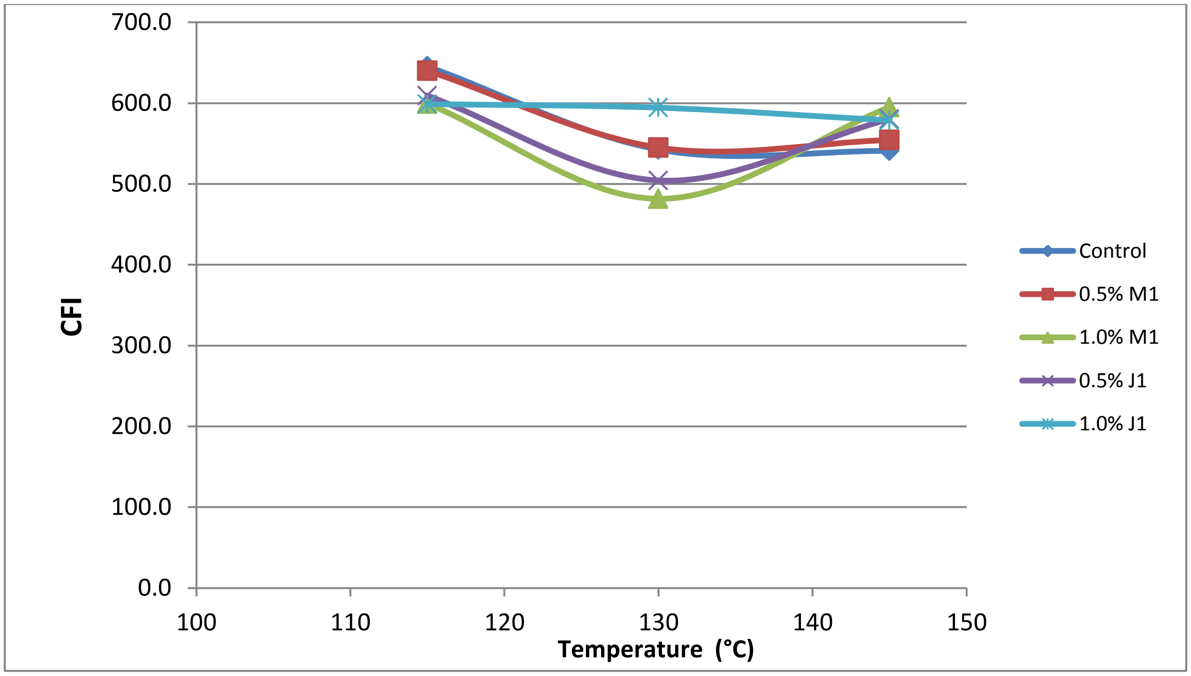


Figure 9. CFI Tendencies at Different Compaction Temperatures

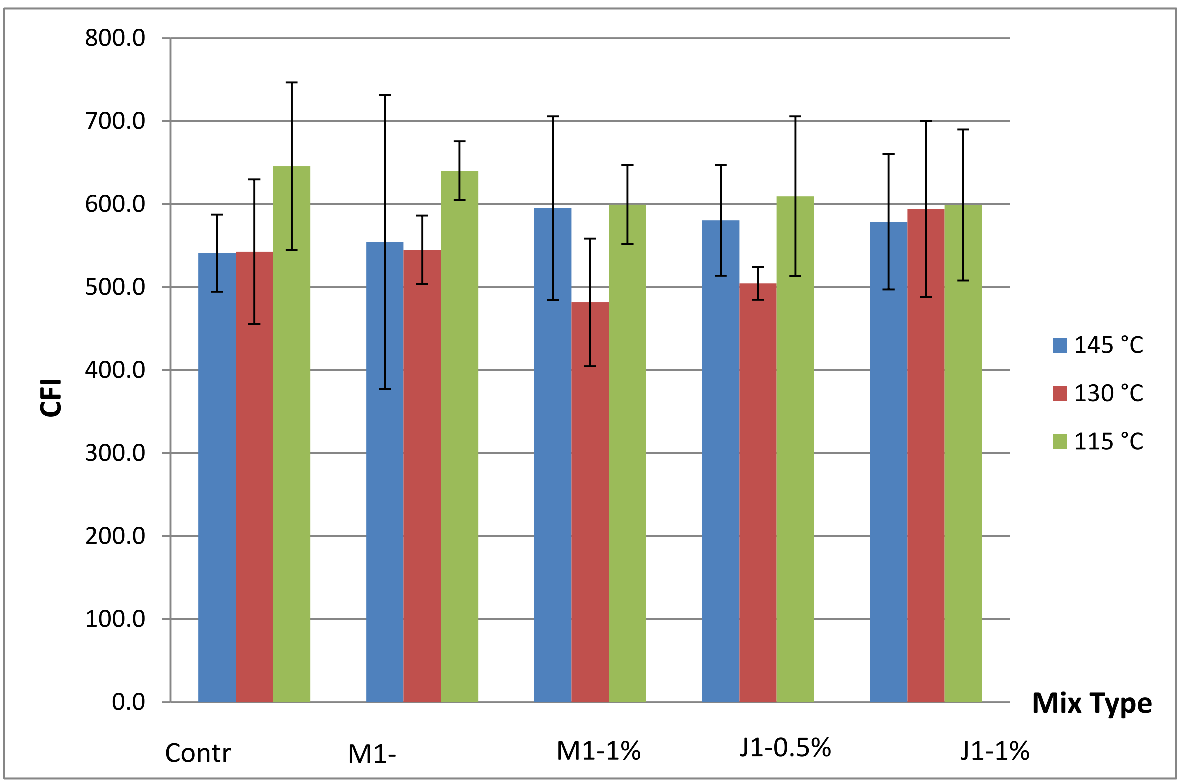


Figure 10. Effects of Different Additives on CFI

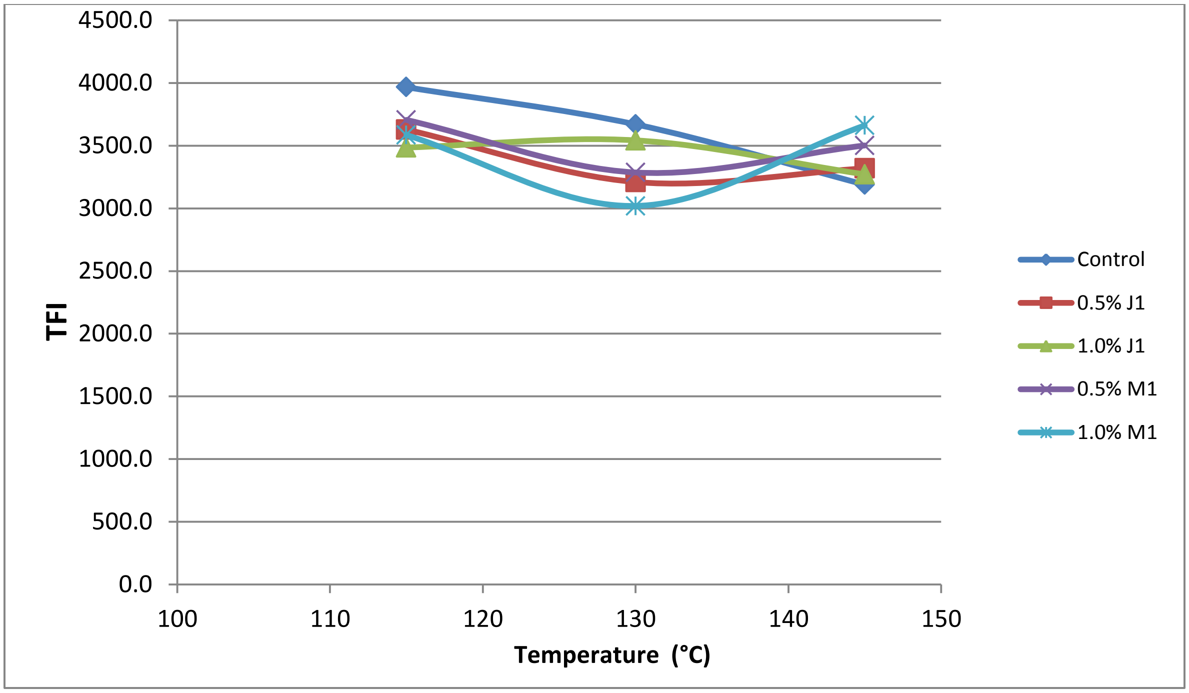


Figure 11. TFI Tendencies at Different Compaction Temperatures

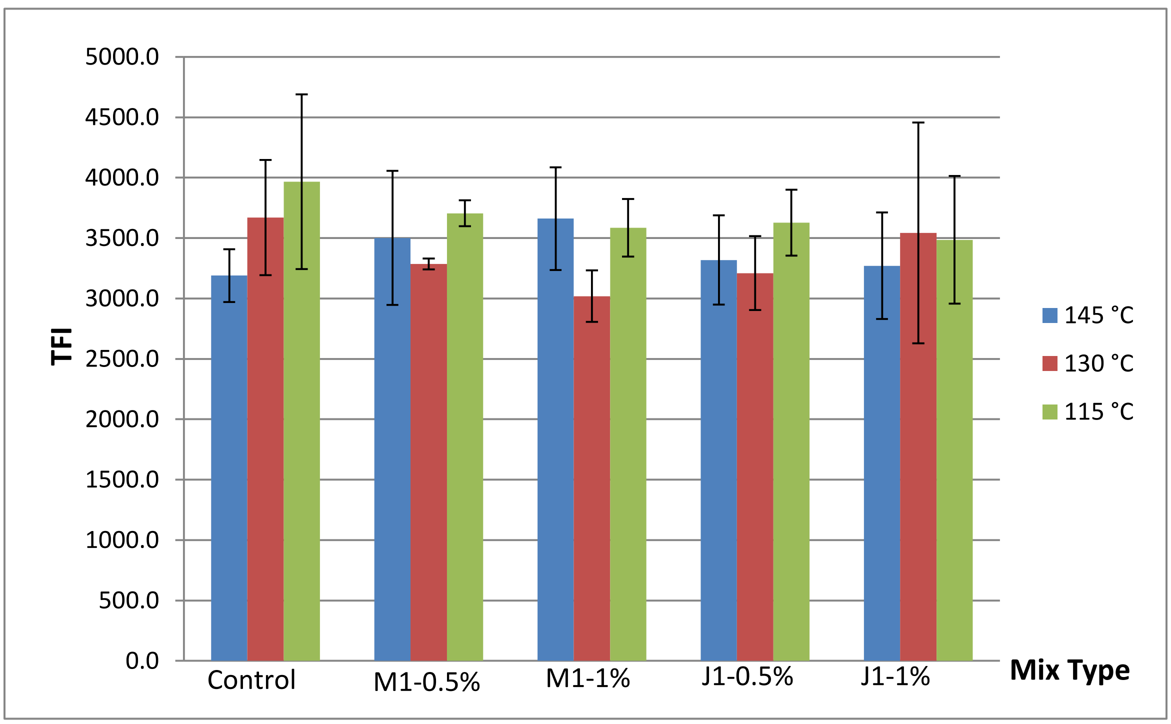


Figure 12. Effects of Different Additives on TFI

Analysis of the Compaction Force Index (CFI)

A Completely Randomized Design (CRD) was adopted in this experiment. The statistical analysis response of the experiment is the compaction force index (CFI) for each mix type. There are two factors of interest: mix type (Control, M1-0.5%, M1-1%, J1-0.5%, J1-1%), and compaction temperature (145°C, 130°C, 115°C). In order to evaluate how the two variables affect CFI, the two following statistical hypotheses were considered:

- Comparison of all J1/M1 samples
  - J1 (0% vs.0.5% vs.1%)
  - M1 (0% vs.0.5% vs.1%)
- Comparison between J1 and M1 samples
  - J1-0.5% vs. M1-0.5%
  - J1-1% vs. M1-1%

Hypothesis Test 1 for CFI

H_0:A_1=A_2=A_3, vs. H_a: At least one of the A_i is not equal (A_i means the CFI of one type Evotherm (J1/M1) with three different Evotherm contents)

A three-way factorial analysis of variance (ANOVA) statistical technique was used to test whether there are statistically significant differences in the mean CFI for each specific mix among the different treatments. For each type of Evotherm, there is an ANOVA table to match as follows in Tables 6 and 7.

Table 6. Effect Test ANOVA Table for the CFI of J1

Source	DF	Sum of Squares	F Ratio	Prob > F
Mix Type	2	2456.600	0.6745	0.5252
Temperature	2	20516.469	5.6332	0.0160
Mix Type & Temperature	4	13974.788	0.9185	0.1632

Table 7. Effect Test ANOVA Table for the CFI of M1

Source	DF	Sum of Squares	F Ratio	Prob > F
Mix Type	2	1749.793	0.3342	0.7219
Temperature	2	38128.059	7.2824	0.0076
Mix Type & Temperature	4	11568.676	1.1048	0.3954

Base on the above ANOVA tables, it is clear that there are no statistically significant differences in mix type and the interaction factor of mix type and temperature among J1/M1 mix types at an α=0.05 level. However, for both mix types, coincidentally there are the same significant differences in temperature. 145°C is not significantly different with 115°C and 130°C, but 115°C is significantly different with 130 °C.

Hypothesis Test 2 for CFI

This hypothesis includes two sub-hypothesis, one subset is: H_0:E_1=E_2, vs. Ha: At least one of E_i is not equal (E_i means the CFI of J1/M1 with 0.5% Evotherm). Another one is H_0:E_1=E_2, vs. Ha: At least one of E_i is not equal (E_i means the CFI of J1/M1 with 1% Evotherm). A three-way factorial ANOVA statistical technique was used to test whether there are statically significant differences in the mean CFI betweenJ1-0.5% and M1-0.5%, or between J1-1% and M1-1%. For each comparison, there is an ANOVA table to match as follows in Table 8 and 9.

Table 8. Effect Test ANOVA Table for the J1-0.5 vs. M1-0.5

Source	DF	Sum of Squares	F Ratio	Prob > F
Mix Type	1	781.471	0.2969	0.6007
Temperature	2	20215.021	3.8399	0.0678
Mix Type & Temperature	2	3309.906	0.6287	0.5577

Table 9. Effect Test ANOVA Table for the J1-1% vs. M1-1%

Source	DF	Sum of Squares	F Ratio	Prob > F
Mix Type	1	3665.948	1.6836	0.2267
Temperature	2	10039.180	2.3053	0.1555
Mix Type & Temperature	2	11919.404	2.7370	0.1179

For the comparison between J1-0.5% and M1-0.5%, there are no statistically significant differences in the mix type, temperature and the interaction factor of the mix type and temperature at an α=0.05 level.

Similar to the comparison between J1-0.5% and M1-0.5%, there also are no statistically significant differences in the factors of mix type, temperature and the interaction factor of the mix type and temperature in the comparison between J1-1% and M1-1%.

Analysis of the Traffic Force Index (TFI)

A Completely Randomized Design (CRD) was adopted in this experiment as well. The statistical analysis response of the experiment is the traffic force index (TFI) for each mix type. There are two factors of interest: mix type (Control, M1-0.5%, M1-1%, J1-0.5%, J1-1%), and compaction temperature (145°C, 130°C, 115°C). In order to evaluate how the two variables effect on TFI, the two following statistical hypotheses were considered:

- Comparison of all J1/M1 samples
  - ➢ J1 (0% vs.0.5% vs.1%)
  - ➢ M1 (0% vs.0.5% vs.1%)
- Comparison between J1 and M1 samples
  - ➢ J1-0.5% vs. M1-0.5%
  - ➢ J1-1% vs. M1-1%

Hypothesis Test 1 for TFI

The hypothesis for the TFI is as follows: H_0:A_1=A_2=A_3, vs. H_a: At least one of the A_i is not equal (A_i means the TFI of one type Evotherm (J1/M1) with three different Evotherm contents)

A three-way factorial ANOVA statistical technique was used to test whether there are statically significant differences in the mean TFI for each specific mix among the different treatments. For each type Evotherm, there is an ANOVA table to match as follows in Tables 10 and 11.

Table 10. Effect Test ANOVA Table for the TFI of J1

Source	DF	Sum of Squares	F Ratio	Prob > F
Mix Type	2	204495.26	1.2987	0.3038
Temperature	2	678318.53	4.3079	0.0348
Mix Type & Temperature	4	395370.83	1.2555	0.3332

Table 11. Effect Test ANOVA Table for the TFI of M1

Source	DF	Sum of Squares	F Ratio	Prob > F
Mix Type	2	128022.27	1.2604	0.3160
Temperature	2	653718.25	6.4359	0.0114
Mix Type & Temperature	4	837531.66	4.1228	0.0226

Base on the above ANOVA tables, it is clear that there are no statistically significant differences in mix type and the interaction factor at an α=0.05 level for all J1 mixtures. The highest mean TFI is at 115 °C and it is statistically significant different with the mean of TFI at 145°C. For the M1 mixtures, there are statistically significant differences in temperature and interaction factor but in mix type.

Hypothesis Test 2 for TFI

This hypothesis includes two sub-hypothesis, one subset is: H_0:E_1=E_2, vs. Ha: At least one of E_i is not equal (E_i means the TFI of J1/M1 with 0.5% Evotherm). Another one is H_0:E_1=E_2, vs. Ha: At least one of E_i is not equal (E_i means the TFI of J1/M1 with 1% Evotherm). A three-way factorial ANOVA statistical technique was used to test whether there are statically significant differences in the mean TFI between J1-0.5% and M1-0.5%, or between J1-1% and M1-1%. For each comparison, there is a special ANOVA table to match as follows in Tables 12 and 13.

Table 12. Effect Test ANOVA Table for the J1-0.5% vs. M1-0.5%

Source	DF	Sum of Squares	F Ratio	Prob > F
Mix Type	1	42306.61	1.2656	0.2932
Temperature	2	358260.39	5.3585	0.0334
Mix Type & Temperature	2	9687.52	0.1449	0.8673

Table 13. Effect Test ANOVA Table for J1-1% vs. M1-1%

Source	DF	Sum of Squares	F Ratio	Prob > F
Mix Type	1	433.40	0.0054	0.9430
Temperature	2	165839.47	1.0343	0.3942
Mix Type & Temperature	2	522286.43	3.2574	0.0862

For comparison between J1-0.5% and M1-0.5%, there are no statistically significant differences in mix type and in the interaction factor of the mix type and temperature. The highest mean TFI is at 115 °C and it is statistically significant different with the mean of TFI at 130°C.

For comparison between J1-1% and M1-1%, there are no statistically significant differences in the factors of mix type, temperature and the interaction factor of the mix type and temperature.

Indirect Tensile Strength (ITS) Testing Results and Analysis

Indirect tensile strength test was conducted by the methodology described in Chapter 3. Both the unconditioned (control group) and moisture-conditioned experimental groups were tested with the three specimens in each group. As mentioned in Chapter 3, based on two types of additives and three content levels, there are six unconditioned groups and six conditioned groups that have been tested. The detailed group information and results are presented in Appendix B. Table 14 provides a summary of the TSR result obtained from ITS testing.

For each group, average tensile strength values and TSR ratios are determined on the group averages. The mixes with the highest and lowest average strength are the J1-0% and J1-0.5% mixtures which were conducted without moisture conditioning. The TSR ratios were calculated following the methods described in Chapter 3 and they are all greater than the acceptable minimum ration of 0.80. The IDOT TSR ratio was also calculated according to Iowa DOT specification which is taking the ratio of conditioned mix strength with an additive and dividing by the unconditioned mix strength without any additive. Thus, for one type of additive, the denominator of the IDOT TSR ratio always was the dry strength of the 0% additive content mix. By keeping a consistent denominator, the data does not add a confounding factor. By this way, the TSR value could effectively reflect the moisture damage effect and eliminate the additive effect in the asphalt mixture. For the further analysis, only the IDOT TSR ratios were considered. All of above data were analyzed by the JMP statistical software (SAS, 2009) and the statistical analysis results are discussed in the following sections.

Table 14. Tensile Strength Ratios

	Unconditioned	Load (KN)	Strength	Ave. Strength (kpa)	Conditioned	Load (KN)	Strength	Ave. Strength (kpa)	TSR	IDOT TSR
	S56	14.045	1444.04		S21	11.838	1229.2			
J1-0%	S53	12.609	1293.87	1340.82	S23	11.542	1180.5	1202.42	0.90	0.90
	S59	12.599	1284.55		S25	11.616	1197.6			
	S66	7.823	803.33		S6	12.971	1323.6			
J1-0.5%	S67	8.855	907.61	880.84	S12	13.414	1370.3	1340.79	1.52	1.00
	S68	9.08	931.60		S11	13.02	1328.5			
	S69	8.001	821.24		S15	10.1	1035.9			
J1-1%	S70	8.625	885.68	926.57	S17	11.365	1175.0	1137.51	1.23	0.85
	S71	10.441	1072.80		S19	11.778	1201.6			
	S60	12.508	1288.84		S31	10.494	1071.0			
M1-0%	S58	10.534	1077.45	1224.85	S27	11.849	1208.6	1190.38	0.97	0.97
	S55	12.774	1308.27		S29	12.291	1291.5			
	S49	10.545	1082.29		S35	13.044	1332.1			
M1-0.5%	S40	12.86	1346.65	1233.67	S38	13.129	1343.8	1269.23	1.03	1.04
	S52	12.271	1272.07		S50	10.994	1131.8			
	S72	10.104	1036.24		S46	11.9	1215.98			
M1-1%	S73	9.512	972.43	999.22	S42	11.189	1137.31	1178.07	1.18	0.96
	S74	9.64	988.98		S45	11.488	1180.90			

Analysis of Indirect Tensile Strength (ITS)

A completely Randomized Design (CRD) was adopted in this experiment. The statistical response of the experiment is the indirect tensile strength for each mix and it includes three factors of interest which are additive type (2 kinds: J-1; M-1), additive content (3 levels: 0%; 0.5%; and 1% by weight of original binder), and conditioning (2 kinds: moisture and non-moisture). According to the research objective, five statistical hypotheses were considered as follows:

Hypothesis 1: Strength $_{conditioned}$ = Strength $_{unconditioned}$ for

- all of J1 and M1 mixes

Hypothesis 2: Strength $_{unconditioned}$ = Strength $_{unconditioned}$ for

- J1-0% vs. J1-0.5%, J1-0% vs. J1-1%, J1-0.5% vs. J1-1%;
- M1-0% vs. M1-0.5%, M1-0% vs. M1-1%, M1-0.5% vs. M1-1%;

Hypothesis 3: Strength $_{conditioned}$ = Strength $_{conditioned}$ for

- J1-0% vs. J1-0.5%, J1-0% vs. J1-1%, J1-0.5% vs. J1-1%;
- M1-0% vs. M1-0.5%, M1-0% vs. M1-1%, M1-0.5% vs. M1-1%;

Hypothesis 4: Strength $_{unconditioned}$ = Strength $_{unconditioned}$ for

- J1-0.5% vs. M1-0.5%;
- J1-1% vs. M1-1%;

Hypothesis 5: Strength $_{conditioned}$ = Strength $_{conditioned}$ for

- J1-0.5% vs. M1-0.5%;
- J1-1% vs. M1-1%.

All samples were randomly assigned in the experimental plan for moisture/non-moisture conditioning. Finally, the analysis of variance or ANOVA was done with an α=0.05.

Hypothesis Test 1 for ITS

H0:AC_{11}=AC_{12}=AC_{21}=AC_{22}, vs. Ha: At least one of the ACij is not equal (ACij means the strength of one type additive J1/M1 with different conditioning)

The statistical analysis had two factors of interest: the moisture conditioning which had two levels: moisture and non-moisture conditioned. Another factor was the additive type that included J1 and M1. In addition, "student's t-test" was also utilized to identify whether the factors are statistically significantly or not. As shown in Appendix B, it is clear that there are statistically significant differences between the conditioned and unconditioned sets but there is no statistically significant difference in additive types and in interaction factor.

Table 15. ITS Effect Test ANOVA Table for the M1/J1 Mixtures

Source	DF	Sum of Squares	F Ratio	Prob > F
Additive Type	1	17750.68	0.7311	0.3989*
Conditioning	1	126901.00	5.2268	0.0290
Additive Type* Conditioning	1	31082.28	1.2802	0.2663

Hypothesis Test 2 for ITS

H0:A_1=A_2=A_3, vs. Ha: At least one of the Ai is not equal (A_i means the strength of one type additive J1/M1 with three different additive contents under non-moisture conditioning).

One factors of interest in this statistical analysis was one type Evotherm J1 or M1. This factor included three Evotherm contents (0%, 0.5% 1.0%). For each type of additive, there is an ANOVA table as shown in Table 16 and17.

Table 16. ITS Effect Test ANOVA Table for the Unconditioned J1 Mixtures

Source	DF	Sum of Squares	F Ratio	Prob > F
Additive J1 Content	2	385250.13	19.4306	0.0024

Table 17. ITS Effect Test ANOVA Table for the Unconditioned M1 Mixtures

Source	DF	Sum of Squares	F Ratio	Prob > F
Additive M1 Content	2	105979.27	4.4065	0.0665

For the J1 mixes, the F-ratio is 19.4306, the p-value equals 0.0024, which is smaller than 0.05, so the hypothesis of H_0 was rejected at $\alpha=0.05$. Therefore, it could be concluded that statistically significant differences exist among unconditioned mixes J1-0%, J-0.5% and J1-1%, whereas, there are no significant statistical differences among unconditioned mixes M1-0%, M-0.5% and M1-1%. Tukey HSD illustrates that J1-0% mix have the highest Least Square Mean value and it is significantly different with J1-0.5% and J-1%. However, it shows no evidence of differences between J1-0.5% and J1-1%. The Tukey HSD detailed results are shown in Appendix B.

Hypothesis Test 3 for ITS

H_0:A_1=A_2=A_3, vs. Ha: At least one of the Ai is not equal (Ai means the strength of one type additive J1/M1 with three different additive contents under moisture conditioning)

One factor of interest in this statistical analysis was among the two additives J1 and M1. This factor included three additive contents (0%, 0.5% 1.0%). This factor was abbreviated as "Additive Type & Content". For each additive, there is an ANOVA table to match as follows in Table 18 and19.

Table 18. ITS Effect Test ANOVA Table for the Conditioned J1 Mixtures

Source	DF	Sum of Squares	F Ratio	Prob > F
Additive J1 & Content	2	64692.562	10.5615	0.0108

Table 19. ITS Effect Test ANOVA Table for the Conditioned M1 Mixtures

Source	DF	Sum of Squares	F Ratio	Prob > F
AdditiveM1 & Content	2	14683.292	0.7822	0.4990

For the J1 mixes, the F-ratio is 10.5615, the p-value equals 0.0108, which is smaller than 0.05, so the hypothesis of H_0 was rejected at α=0.05. Therefore, there are some statistically significant differences among conditioned mixes J1-0%, J-0.5% and J1-1%, whereas, there are no statistically significant differences among conditioned mixes M1-0%, M-0.5% and M1-1%. From the LS Means Differences Tukey HSD and LS Means Plot, the J1-0.5% mix has the highest mean tensile strength and is significantly different than the J1-1% mix which has the lowest mean tensile strength. However, the J1-1% has the lowest mean tensile strength which is not significantly different than the J1-0% mix. The JMP results for this analysis are located in Appendix B.

Hypothesis Test 4 for ITS

This hypothesis includes two sub-hypothesis, one subset is: H_0:E_1=E_2, vs. Ha: At least one of E_i is not equal (E_i means the strength of J1/M1 with 0.5% additive). Another one is H_0:E_1=E_2, vs. Ha: At least one of E_i is not equal (E_i means the strength of J1/M1 with 1% additive). Both subsets of samples were non-moisture conditioned. The factor of interest performed in both hypotheses is abbreviated as "Additive Type & Content". For each, there is an ANOVA table as shown in Table 20 and 21.

Table 20. ITS Effect Test ANOVA Table for the Unconditioned J1-0.5% vs. M1-0.5%

Source	DF	Sum of Squares	F Ratio	Prob > F
Additive Type & Content	1	186772.33	16.0766	0.0160

Table 21. ITS Effect Test ANOVA Table for the Unconditioned J1-1% vs. M1-1%

Source	DF	Sum of Squares	F Ratio	Prob > F
Additive Type & Content	1	7913.4017	0.8709	0.4035

Under the non-moisture condition, the M1-0.5% mix had higher mean tensile strength than the J1-0.5% mix, and they are significantly different between each other. However, at same condition, there was no evidence indicating that the M1-1% mix had a significantly different mean tensile strength compared to the J1-1% mix. The JMP analysis for this hypothesis is attached in Appendix B.

Hypothesis Test 5 for ITS

There are two hypotheses associated with this section and both of sets of samples were moisture-conditioned. One set is: H_0:E_1=E_2, vs. Ha: At least one of E_i is not equal (Ei means the strength of J1/M1 with 0.5% additive). Another one is H_0:E_1=E_2, vs. Ha: At least one of E_i is not equal (E_i means the strength of J1/M1 with 1% additive). These are the factors of interest and were performed for both hypotheses, and it was abbreviated as "Additive Type & Content". For each subset, there is a special ANOVA table as follows in Table 22 and 23.

Table 22. ITS Effect Test ANOVA Table for the Conditioned J1-0.5% vs. M1-0.5%

Source	DF	Sum of Squares	F Ratio	Prob > F
Additive Type & Content	1	7682.6817	1.0341	0.3667

Table 23. ITS Effect Test ANOVA Table for the Conditioned J1-1% vs. M1-1%

Source	DF	Sum of Squares	F Ratio	Prob > F
Additive Type & Content	1	2468.0760	0.5211	0.5103

JMP output results are located in Appendix B. After freeze-thaw cycling, the mean tensile strength of J1-0.5% mix and J1-1% mix were not significantly different with the mean strength of M1-0.5% and M1-1% mixes, respectively.

Analysis of Tensile Strength Ratio (TSR)

A Completely Randomized Design (CRD) was applied in this experiment. The statistical response of the experiment is the IDOT TSR ratio for each mix and it includes two factors of interest: additive type (J-1; M-1) and additive content (0%, 0.5%, and 1% by weight of the total binder). In total six combinations were analyzed, and all samples were randomly assigned to experience moisture/non-moisture conditioning. Finally, all of data were analyzed using analysis of variance or ANOVA with an $\alpha=0.05$.

The R-square value is 0.5816, which means 58.16% of the variation in IDOT TSR can be explained by this model.

Table 24. ANOVA Table for TSR

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Model	5	0.06997778	0.013996	3.3367	0.0405*
Error	12	0.05033333	0.004194		
C. Total	17	0.12031111			

Table 25. Effect Tests for TSR

Source	DF	Sum of Squares	F Ratio	Prob > F
Additive Type	1	0.02420000	5.7695	0.0334*
Additive Content	2	0.04174444	4.9762	0.0267*
Additive Type* Additive Content	2	0.00403333	0.4808	0.6297

Hypothesis Test of Additive Type

The hypothesis for the factor of additive type is as follows: H_0: A_1=A_2, vs H_a: At least one of the Ai is not equal (A_i means different additive type)

Since the F-ratio = 5.7695, the P-value is 0.0334 which is less than 0.05, H_0 is rejected at α=0.05. Therefore, there are statistically significant differences between the additive types.

Table 26. TSR Estimated Effects for the Additive Type

Level	Mean	Estimated Effects
J-1	0.915556	-0.03667
M-1	0.988889	0.036667
The grand mean of response is 0.952222		

In this table of estimated effects, a positive sign illustrates the effect of the additive type level is greater than the grand mean; negative sign means the mean of the additive type level is less than the grand mean. As indicated in Figure13, the additive M-1 has higher mean of IDOT TSR ratios than another additive type.

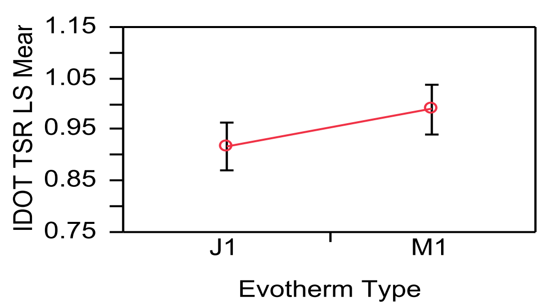


Figure 13. LS Means Plot for the Additive Type of TSR

From the plot above, the M-1 additive has a higher mean of tensile strength than the J-1 additive.

α=0.050 t=2.17881

LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	J1	M1
J1	0 0 0 0	-0.0733 0.03053 -0.1399 -0.0068
M1	0.07333 0.03053 0.00681 0.13985	0 0 0 0

Level			Least Sq Mean
M1	A		0.98888889
J1		B	0.91555556

Levels not connected by same letter are significantly different.

Figure 14. LS Means Differences Student's t for the Additive Type of TSR

The statistically significant difference in IDOT TSR ratio means additive M-1 has greater TSR value on average compared to the additive J-1, and additive M-1, and is summarized in Figure 14.

Hypothesis Test of Additive Content

The hypothesis for the factor of additive content is as follows: H_0: M_1=M_2=M_3, vs. H_a: At least one of the Mi is not equal (Mi means different additive content)

Since the F-ratio = 4.9762, the P-value = 0.0267, which is smaller than 0.05, H_0 is rejected at α=0.05. Therefore, there are statistically significant differences between the Evotherm contents.

Table 27. TSR Estimated Effects for Additive Content

Level	Mean	Estimated Effects
0%	0.93333	-0.01889
0.5%	1.01833	0.066108
1%	0.90500	-0.04722

The grand mean of response is 0.952222

In this table of estimated effects, a positive sign illustrates the mean of the additive content level is greater than the grand mean; anegative sign illustrates the mean of the additive content level is smaller than the grand mean. As indicated, the 0.5% content mixture has the highest mean IDOT TSR ratio.

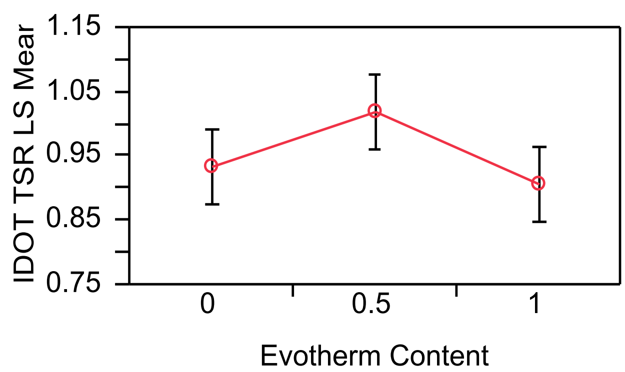


Figure 15. . LS Means Plot for the Additive Content of TSR

According to the Figure 15, the 0.5% and 1 % additive contents have the highest and lowest mean TSR values, respectively.

α=0.050 Q=2.66776

LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	0	0.5	1
0	0 0 0 0	-0.085 0.03739 -0.1848 0.01475	0.02833 0.03739 -0.0714 0.12809
0.5	0.085 0.03739 -0.0148 0.18475	0 0 0 0	0.11333 0.03739 0.01358 0.21309
1	-0.0283 0.03739 -0.1281 0.07142	-0.1133 0.03739 -0.2131 -0.0136	0 0 0 0

Level			**Least Sq Mean**
0.5	A		1.0183333
0	A	B	0.9333333
1		B	0.9050000

Levels not connected by same letter are significantly different.

Figure 16. LS Means Differences Tukey HSD for the Additive Content of TSR

As shown in Figure 16, there is a statistically significant difference in IDOT TSR ratio between 0.5% additive mix and 1% additive mixes. 0.5% additive has the highest TSR ratio on average and 1% additive mixes has the least TSR ratio on average. However, 0% additive mixes is not statistically significant than the others.

Hypothesis Test for the Interaction Factor of Additive Type & Additive Content

The hypothesis for the interaction factor is as follows: H_0: $AM_{11}=AM_{12}=AM_{13}=AM_{21}=AM_{22}=AM_{23}$, vs. H_a: At least one of the AM_{ij} is not equal (AM_{ij} means interactions between additive Type and additive Content). Since the F-ratio =0.4808, the P-value = 0.6297, which is greater than 0.05, H_0 stands at α=0.05. Therefore, there are no statistically significant differences between the additive type and the additive content.

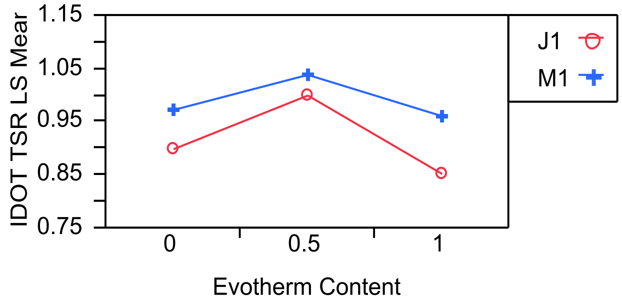


Figure 17. LS Means Plot for TSR Interaction Effect

Although there is no statistically significant difference between the additive type and the additive content, Figure 17 clearly shows that the M1 mixes have higher TSR ratio values than the J1 mixes. The M1-0.5% has the highest TSR ratio among the six combinations.

Dynamic Modulus Testing Results and Analysis

Analysis of E*

It is clear that temperature and frequency significantly influence the physical response of the materials and their properties are affected by temperature and or rate of loading. In order to study the effect of different variables on dynamic modulus values, a means comparison of E* data of different specific mixes to E* data of the other different specific mixes was done. The detailed dynamic modulus (E*) results are located in Appendix C. Five types of comparisons were considered as follows.

- Comparison of all J1/M1 samples.
  - ➢ Conditioned J1/M1 (0%, J1-0.5%, J1-1%) vs. Unconditioned J1/M1 (0%, J1-0.5%, J1-1%)
- Comparison of all J1/M1 unconditioned samples.
  - ➢ Unconditioned J1/M1 (0 % vs.0.5%, 0 vs.1.0%, 0.5vs.1%)
- Comparison of all J1/M1 conditioned samples.
  - ➢ Conditioned J1/M1 (0 % vs.0.5%, 0 vs.1.0%, 0.5vs.1%)
- Comparison of conditioned J1 samples and M1 samples.
  - ➢ Conditioned J1-0.5% / 1% vs. Conditioned M1-0.5% / 1%
- Comparison of unconditioned J1 samples and M1 samples.
  - ➢ Unconditioned J1-0.5% / 1% vs. Unconditioned M1-0.5% / 1%

Figure 18 through 25 present different comparisons with each plot were designed as a log-log space. Although master curves provide a visual mean to distinguish trends in E* values, the intercept coefficient can be used to examine how much E* changed for different comparisons. For each figure, there is an equation shown with a power value (exponent) and an intercept coefficient. All of the power values are close to one. Therefore, the intercept coefficient can be used to explain how much percent E* increased from E* of x-axial mix to E* of y-axial mix. The intercept coefficient was 3.247, and that means the average E* for the conditioned J1-0% mixtures is approximately 224.7% which is greater than the average E* of the unconditioned J1-0% mixes. The result indicates that a freeze-thaw cycle is good for retting resistance as it significantly increases the E* and improve stiffness for the J1-0% mixture.

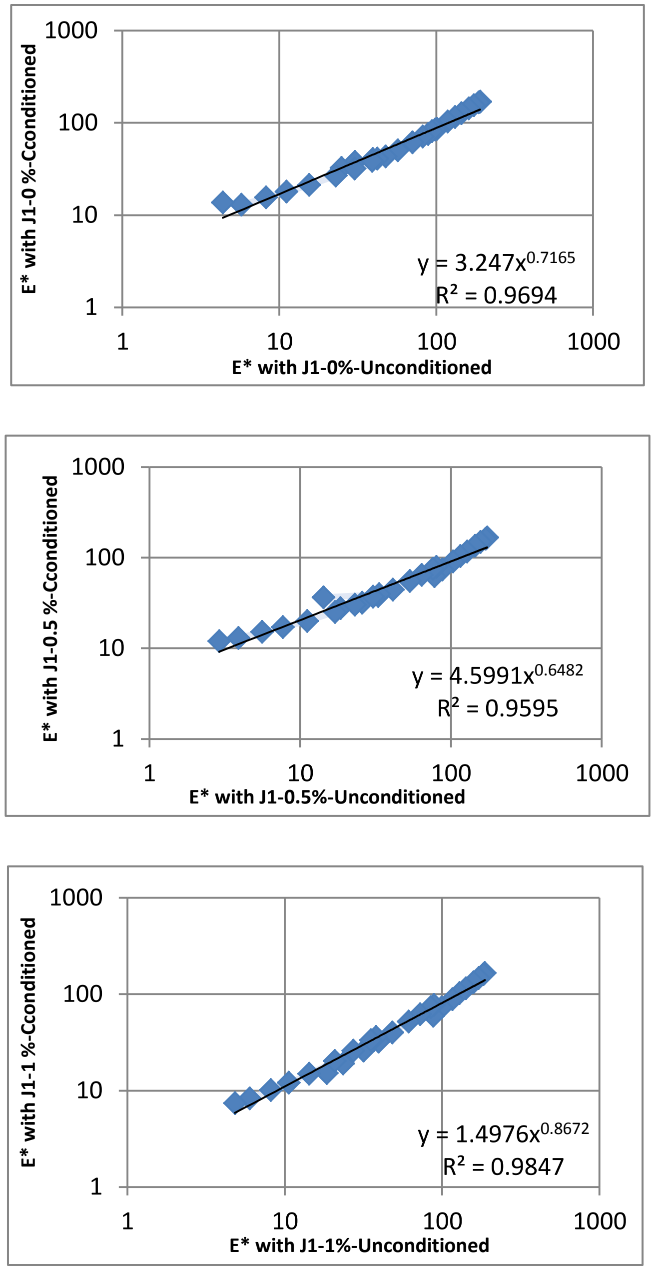
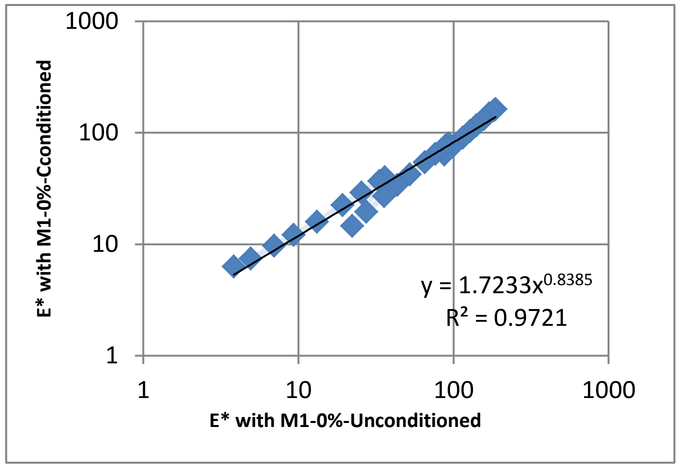
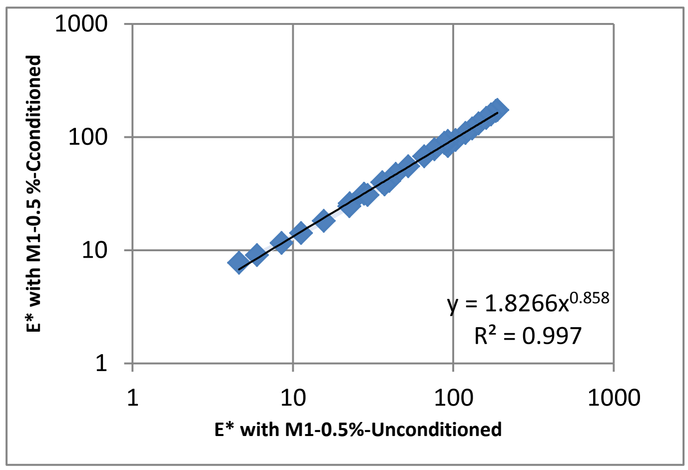


Figure 18. Conditioned vs. Unconditioned Intercept Coefficient Plots for the J1 Mixes





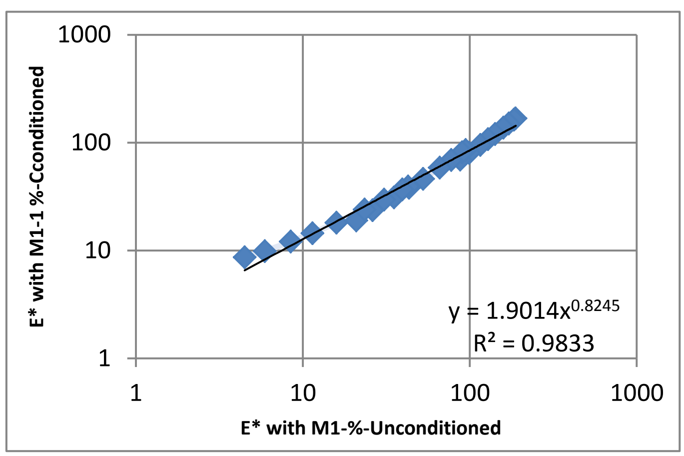


Figure 19. Conditioned vs. Unconditioned Intercept Coefficient Plots for the M1 Mixes

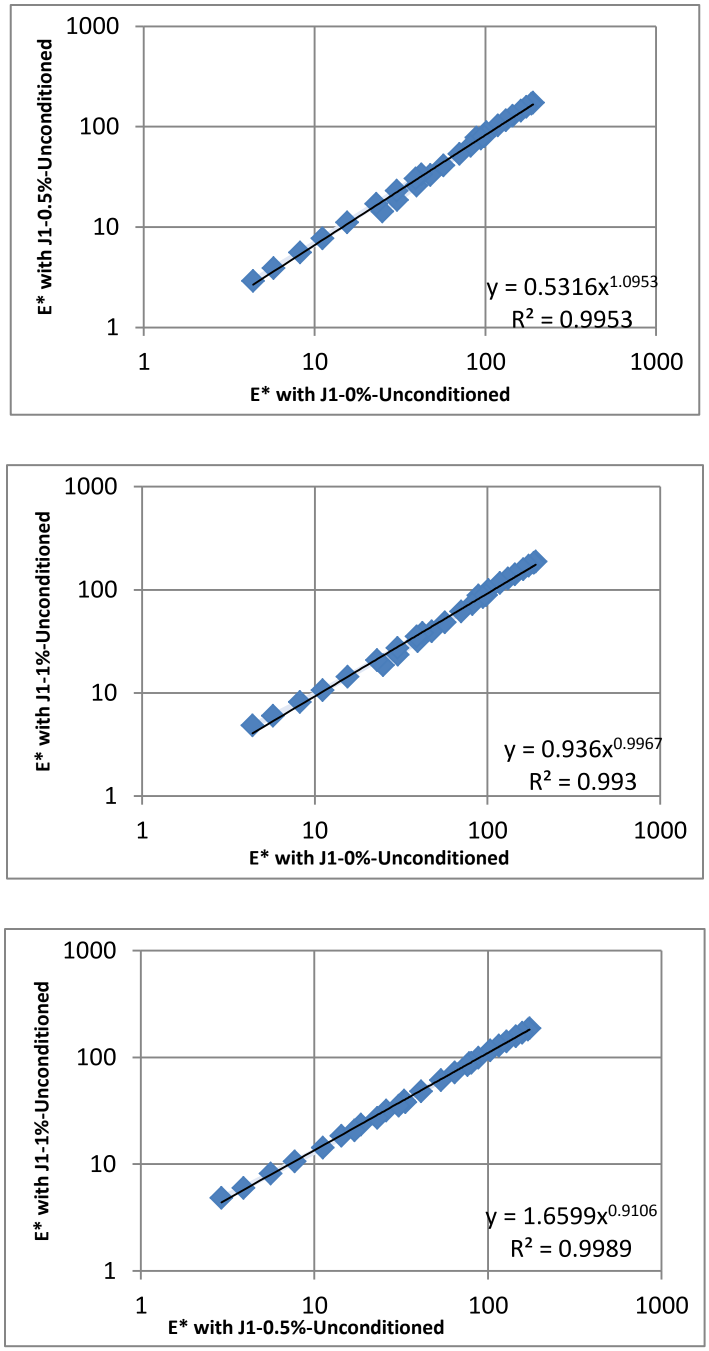


Figure 20. Comparison of Intercept Coefficients for the J1 Unconditioned Mixes

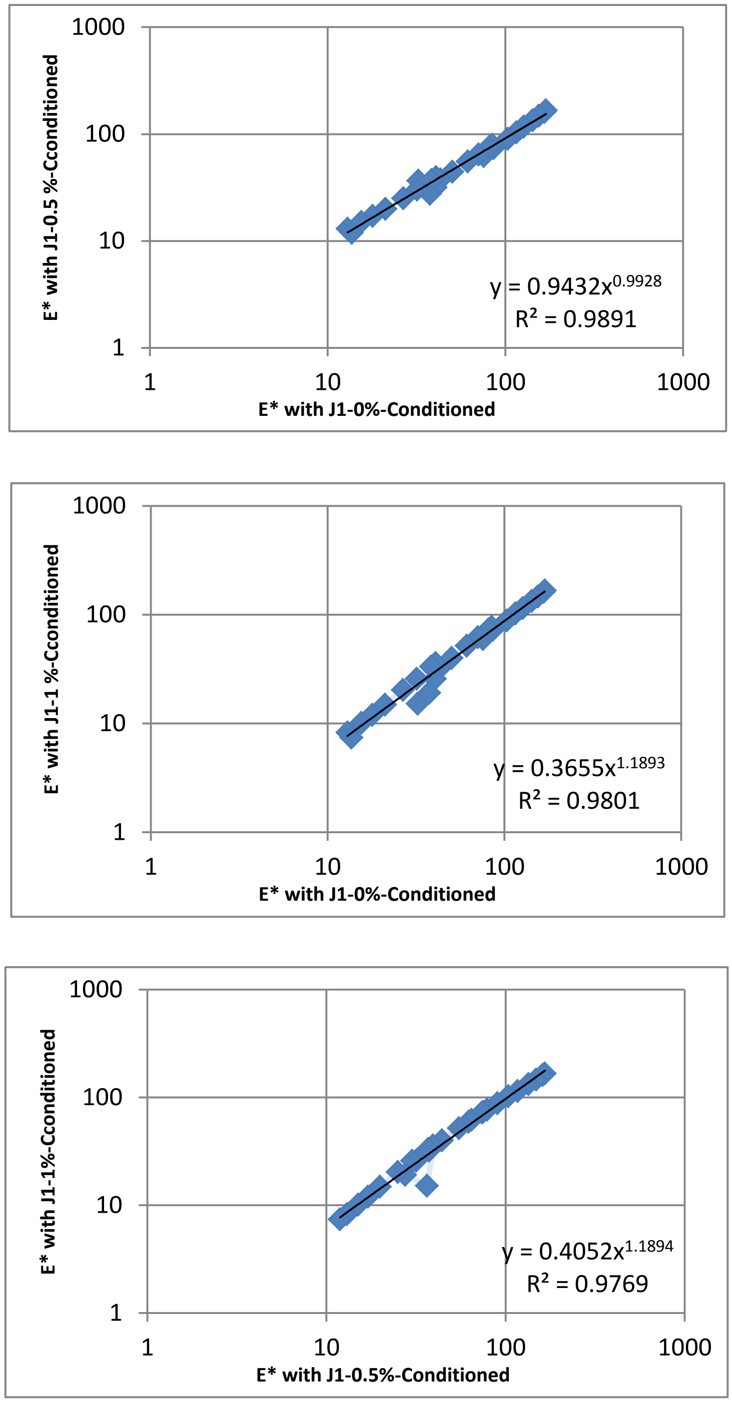


Figure 21. Comparison of Intercept Coefficients for the J1 Conditioned Mixes

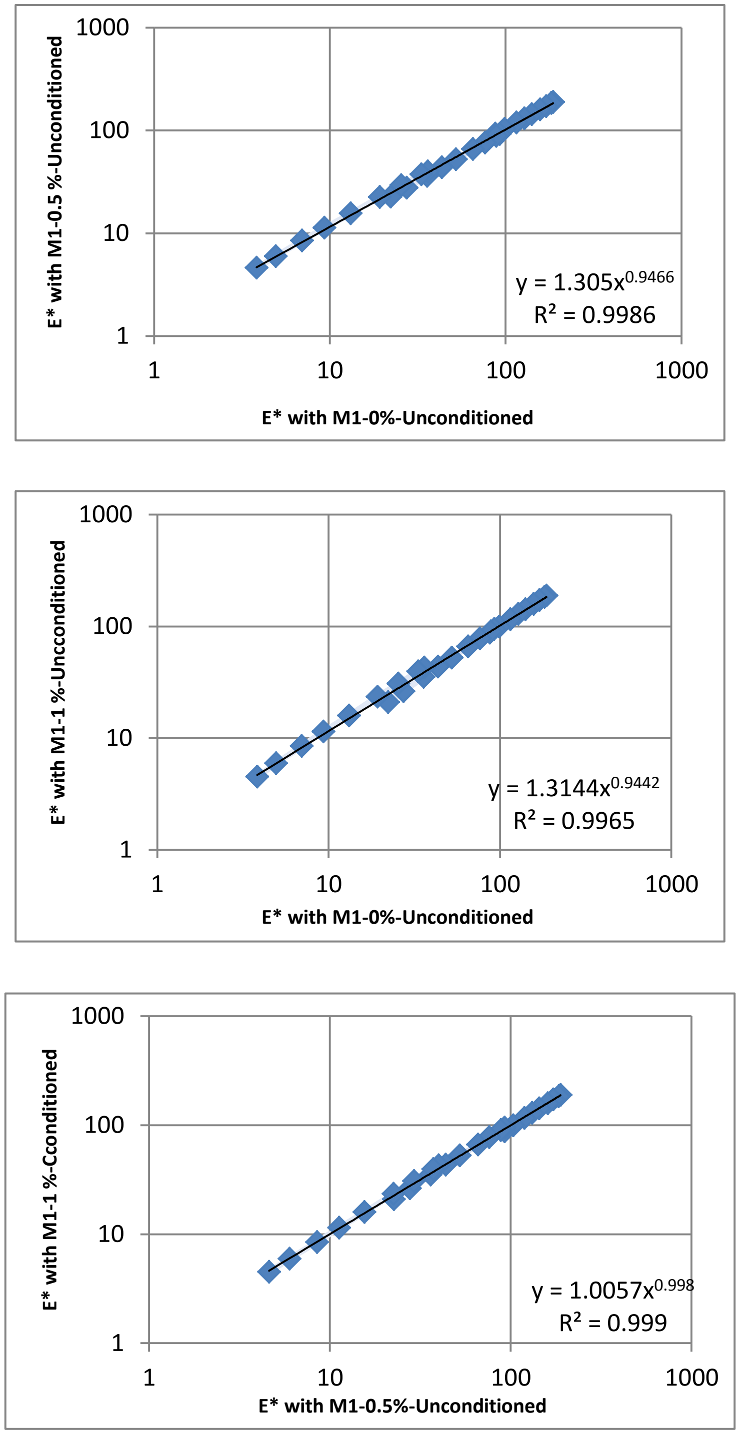
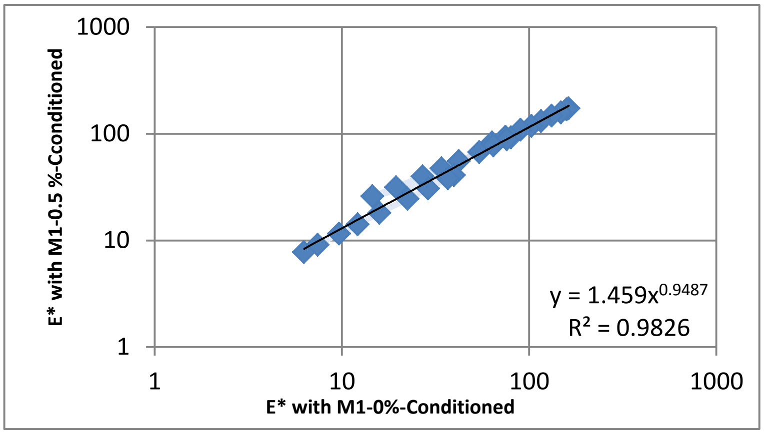
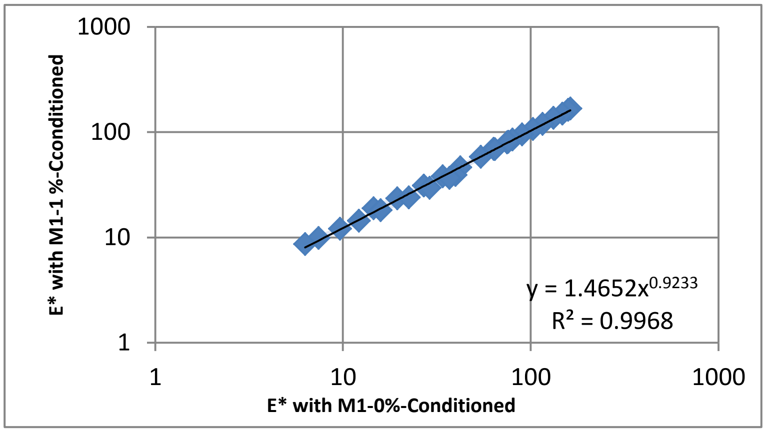


Figure 22. Comparison of Intercept Coefficients for the M1 Unconditioned Mixes





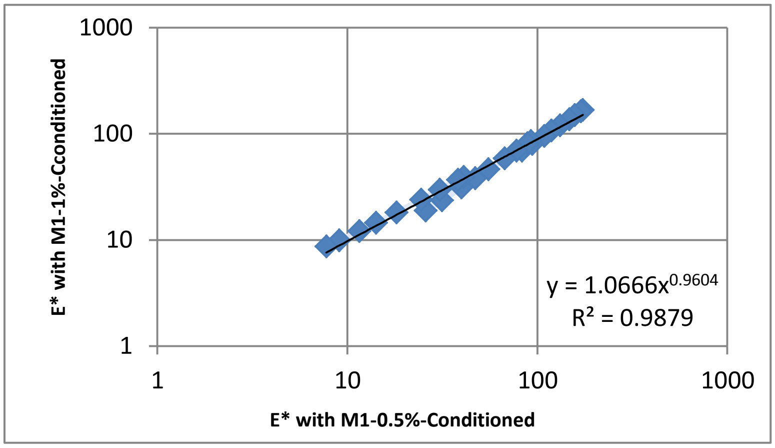


Figure 23. Comparison of Intercept Coefficients for the M1 Conditioned Mixes

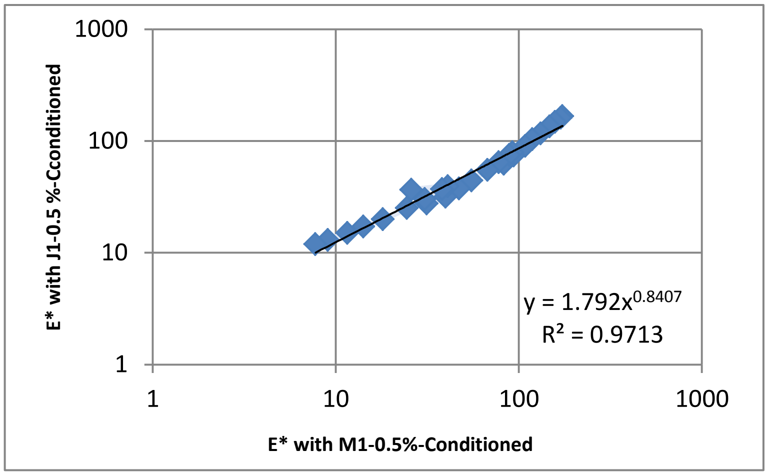


Figure 24. Comparison of Intercept Coefficients for the Conditioned J1-0.5% and M1-0.5%

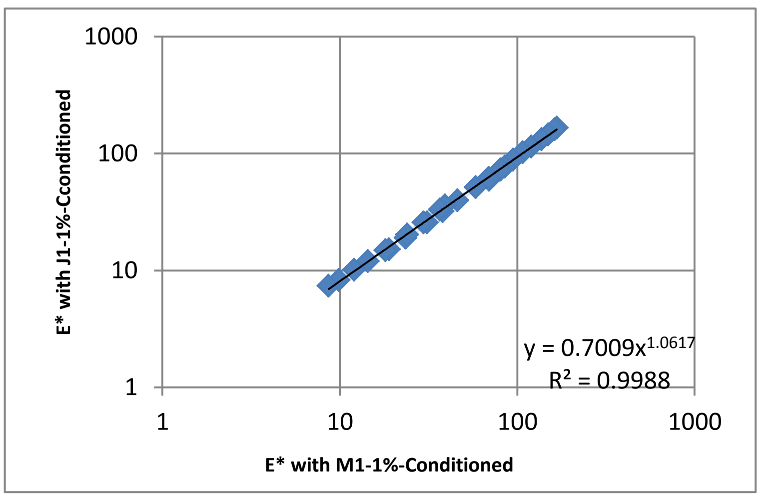


Figure 25. Comparison of Intercept Coefficients for the Conditioned J1-1% and M1-1%

Master Curve

Temperature and frequency significantly influence the physical response of asphalt materials and asphalt mixtures can be represented as linear viscoelastic materials with a dependency on temperature and loading time. Therefore modeling these materials using the time-temperature superposition principle to construct master curves is appropriate.

Figures 26 to 35 show master curves for the mixes with three contents of two additives tested at three temperatures. Developing master curves can also provide a direct visual approach to identifying the effect of moisture conditioning on specific mixes. The E* values is a parameter used in master curves, and in these illustrates 21°C is the reference temperature. In order to comprehensively reflect how different additive compositions influence a mixes' properties, five comparisons were considered as follows.

- Comparison of all J1/M1 samples.
  - Conditioned J1/M1 (0%, J1-0.5%, J1-1%) vs. Unconditioned J1/M1 (0%, J1-0.5%, J1-1%)
- Comparison of all J1/M1 conditioned samples.
  - Conditioned J1/M1 (0 % vs.0.5% vs.1%)
- Comparison of all J1/M1 unconditioned samples.
  - Unconditioned J1/M1 (0 % vs.0.5%, 0 vs.1.0%, 0.5vs.1%)
- Comparison of conditioned J1 samples and M1 samples.
  - Conditioned J1-0.5% / 1% vs. Conditioned M1-0.5% / 1%
- Comparison of unconditioned J1 samples and M1 samples.
  - Unconditioned J1-0.5% / 1% vs. Unconditioned M1-0.5% / 1%

The master curves contain a low frequency region located on the left side of the master curves, and a high frequency region located on the right side of the master curves. As described in Chapter 3, low frequency indicates high temperature behavior and high frequency indicates low temperature behavior. Practically, a larger E* value is desired at high temperatures to resist rutting with a higher stiffness, whereas, a comparable small E* value is preferred at low temperatures to prevent pavement low temperature cracking with a considerable lower stiffness. Therefore, a higher line towards the left side and a lower line toward right side are considered as an optimal master curve.

The fitted model which predicts the condition of a freeze-thaw cycle could increase the E* value and improve stiffness for both of J1 and M1 mixes. Comparing the J1 mixtures to the M1 mixtures, moisture conditioning improves the M1 mix stiffness at higher temperatures, but does not affect the stiffness at lower temperatures. Therefore, M1 mixes are more “optimal” and would perform better in terms of rutting resistance and low temperature cracking. Additionally, the additive does not affect the E* value for the unconditioned M1 samples but slightly influences the unconditioned J1 samples at the low frequency region. In addition to the above findings, under moisture conditioning, M1-0.5% mixes presents a more desirable master curve than the J1-0.5% mixes under moisture conditioning. There is no significant observable difference between conditioned J1-1% master curve and the conditioned M1-1% master curves.

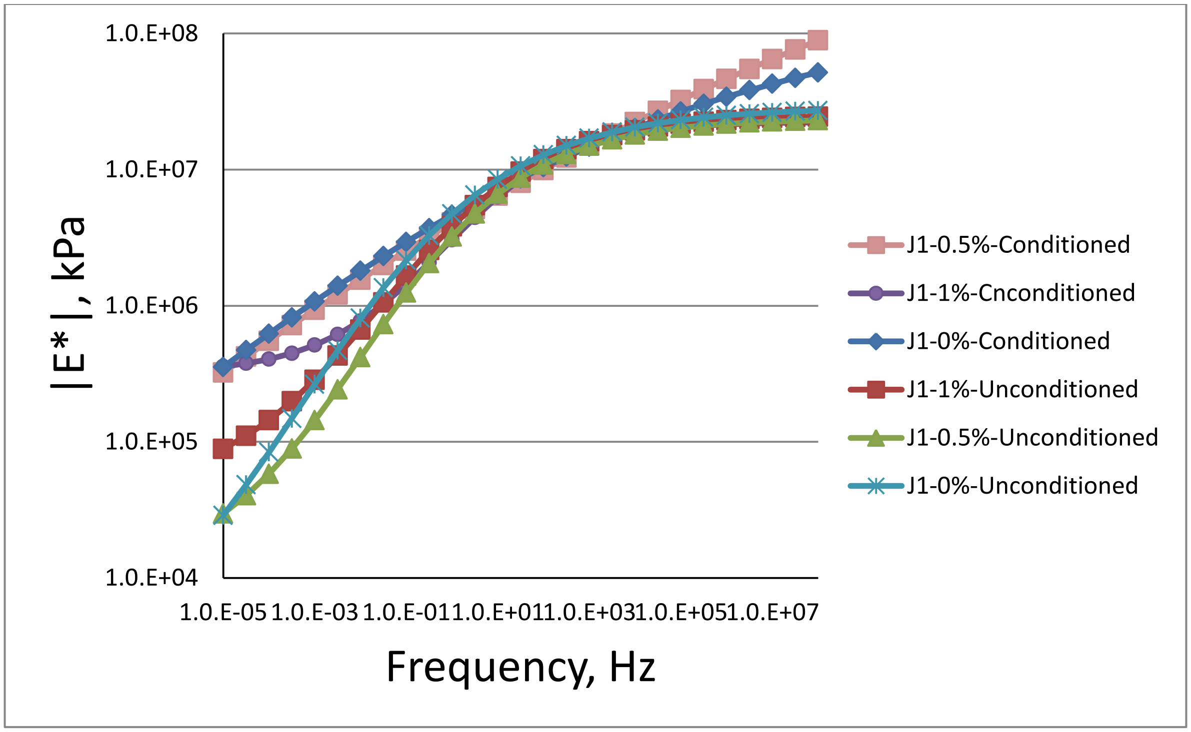


Figure 26. Master Curves for the J1 Mixes

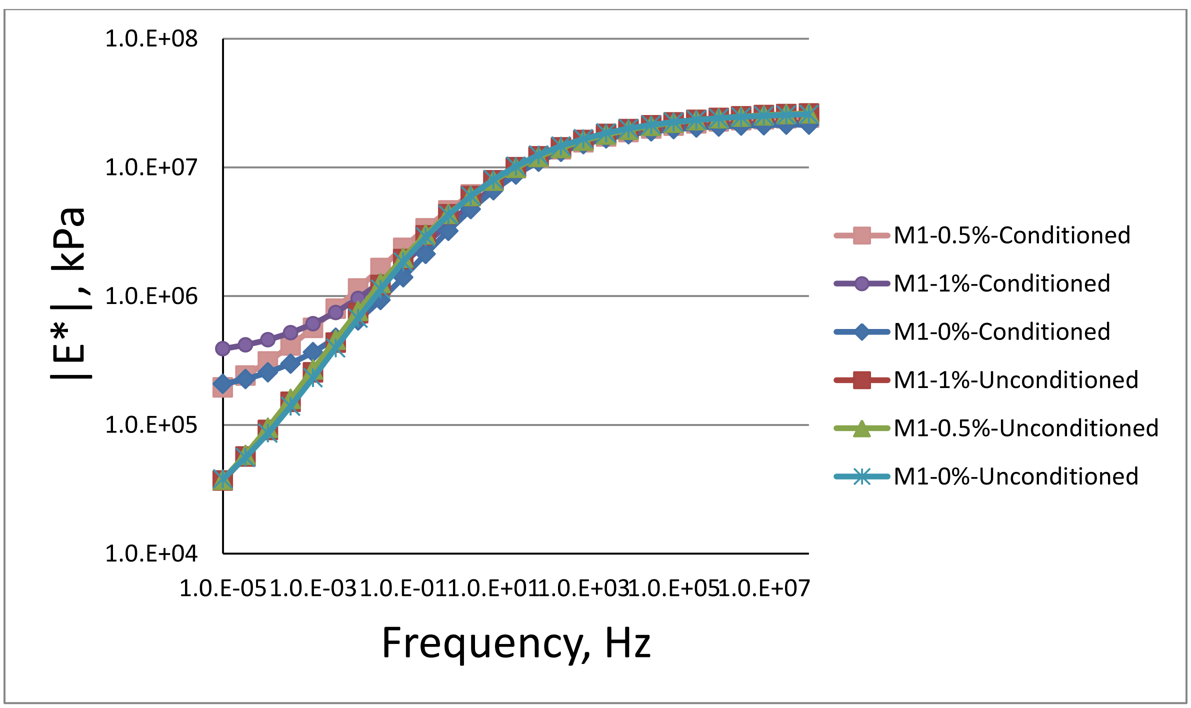


Figure 27. Master Curves for the M1 Mixes

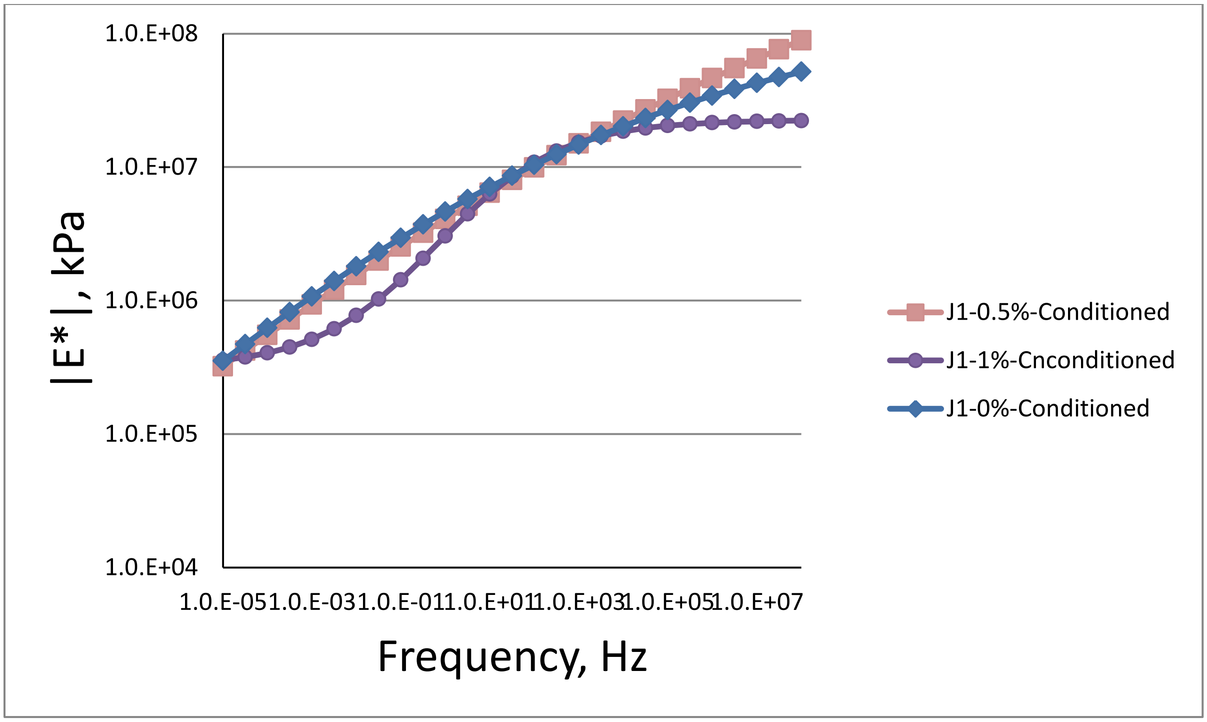


Figure 28. Master Curves for the J-1 Conditioned Mixes

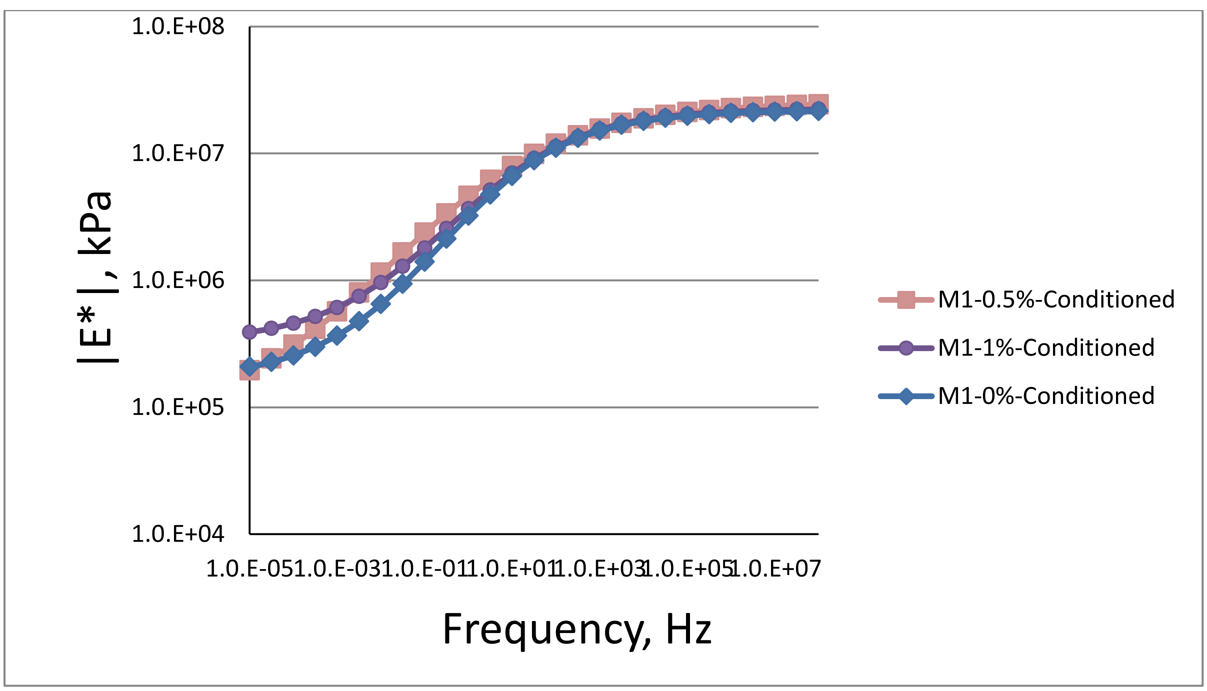


Figure 29. Master Curves for the M-1 Conditioned Mixes

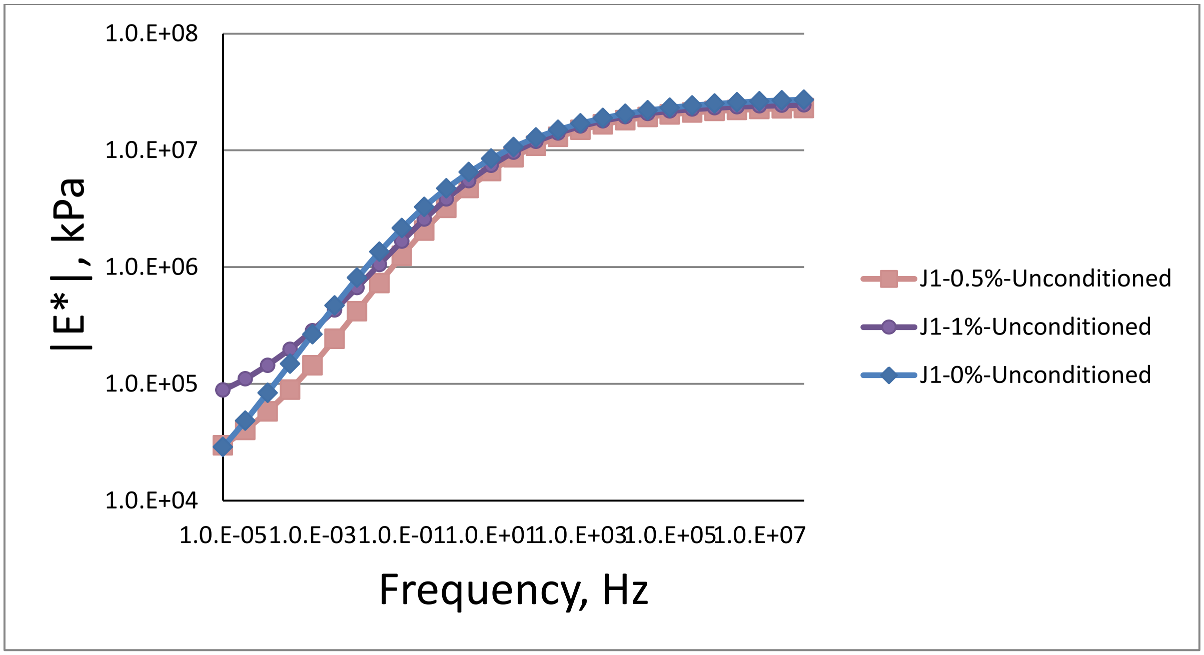


Figure 30. Master Curves for the J-1 Unconditioned Mixes

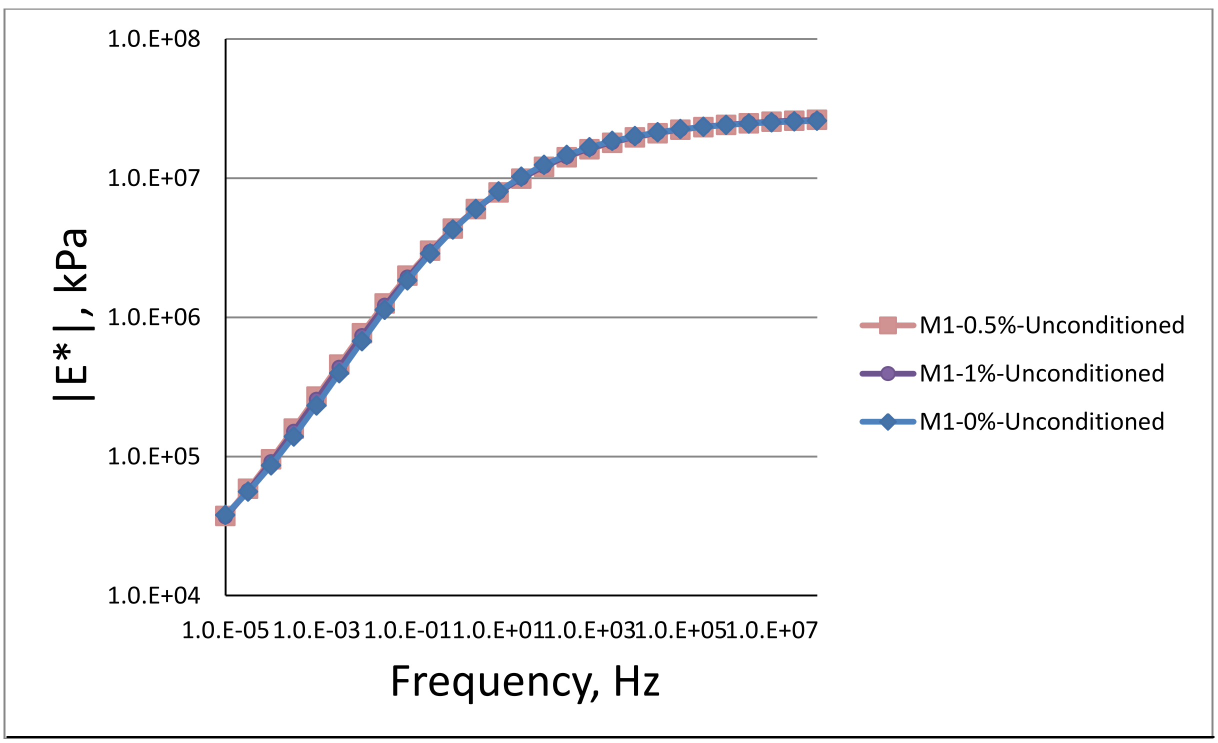


Figure 31. Master Curves for the M-1 Unconditioned Mixes

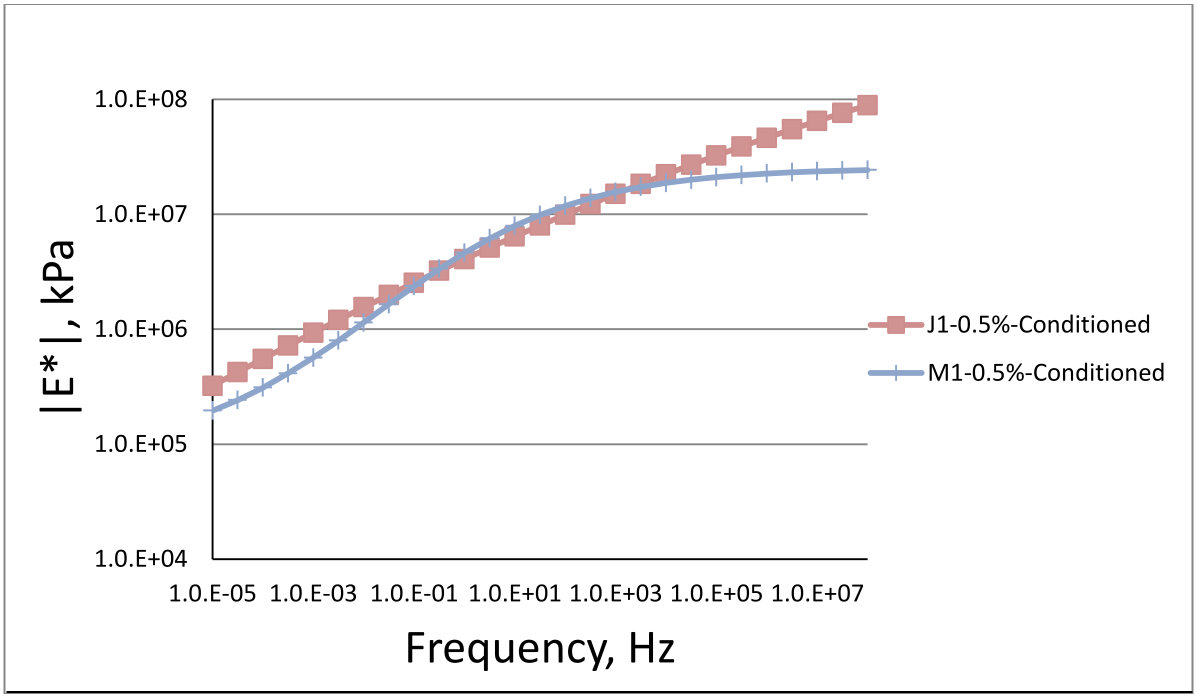


Figure 32. Master Curves for the Conditioned J1-0.5% and M1-0.5% Mixes

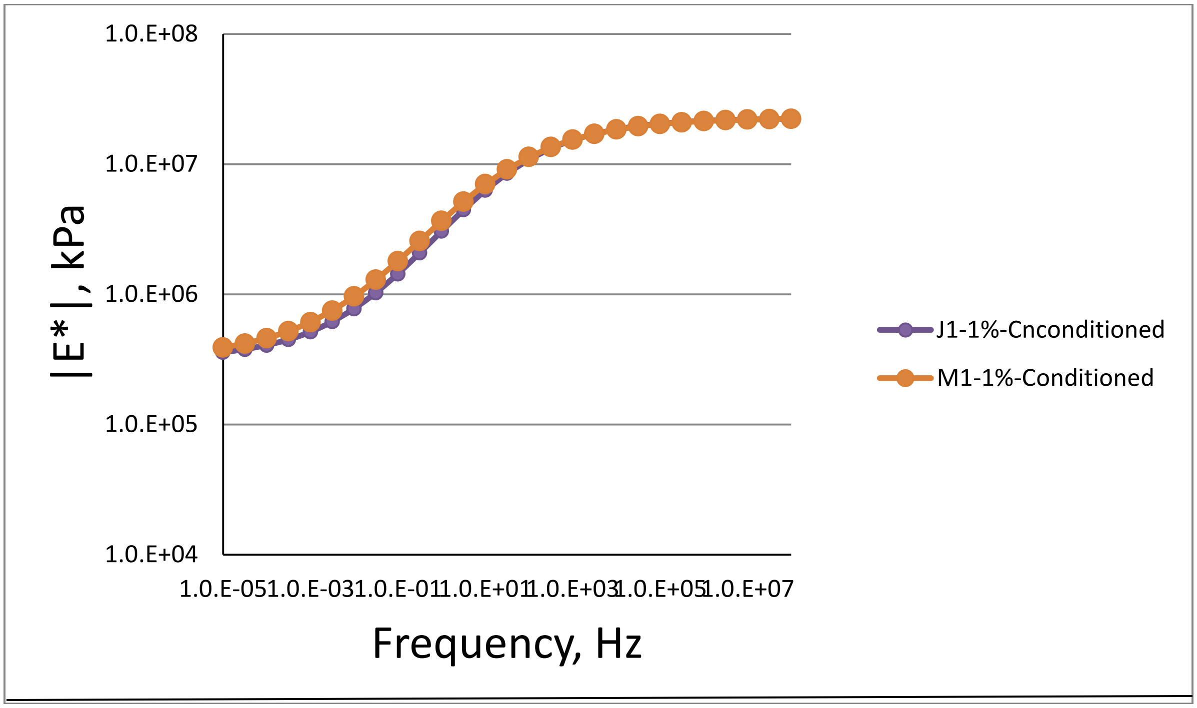


Figure 33. Master Curves for the Conditioned J1-1% and M1-1% Mixes

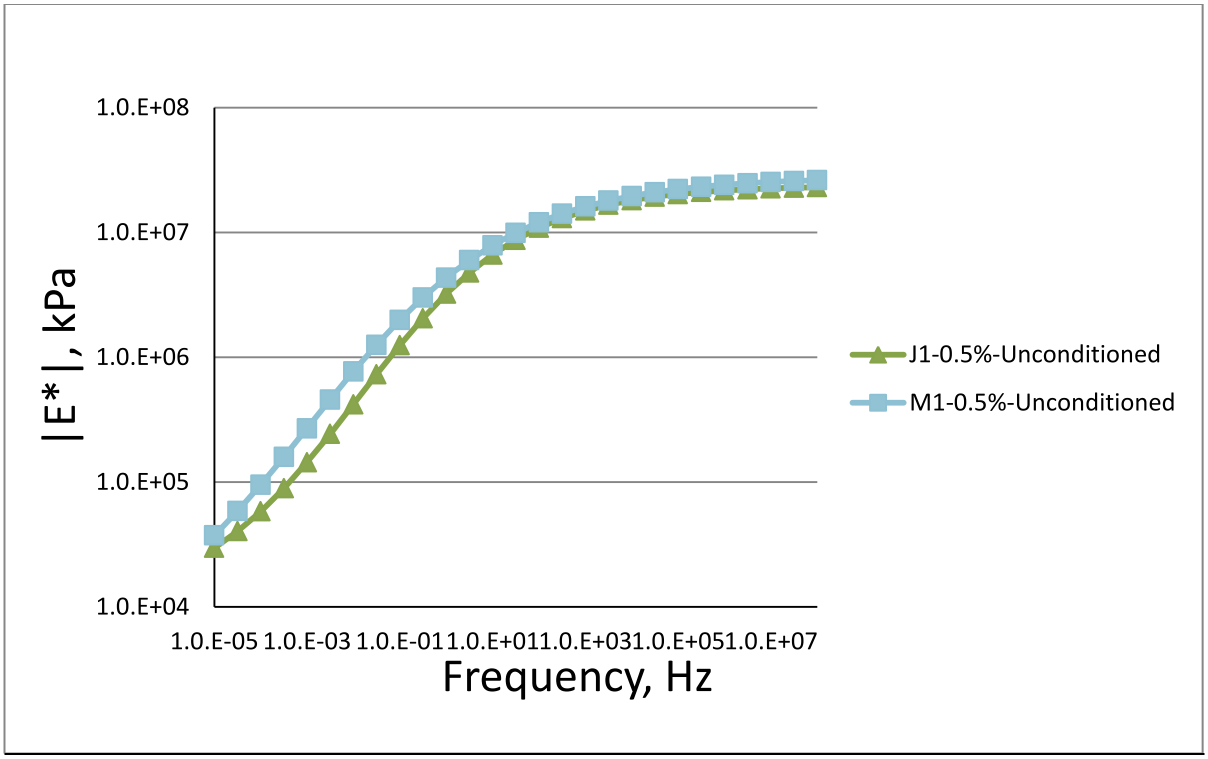


Figure 34. Master Curves for the Unconditioned J1-0.5% and M1-0.5% Mixes

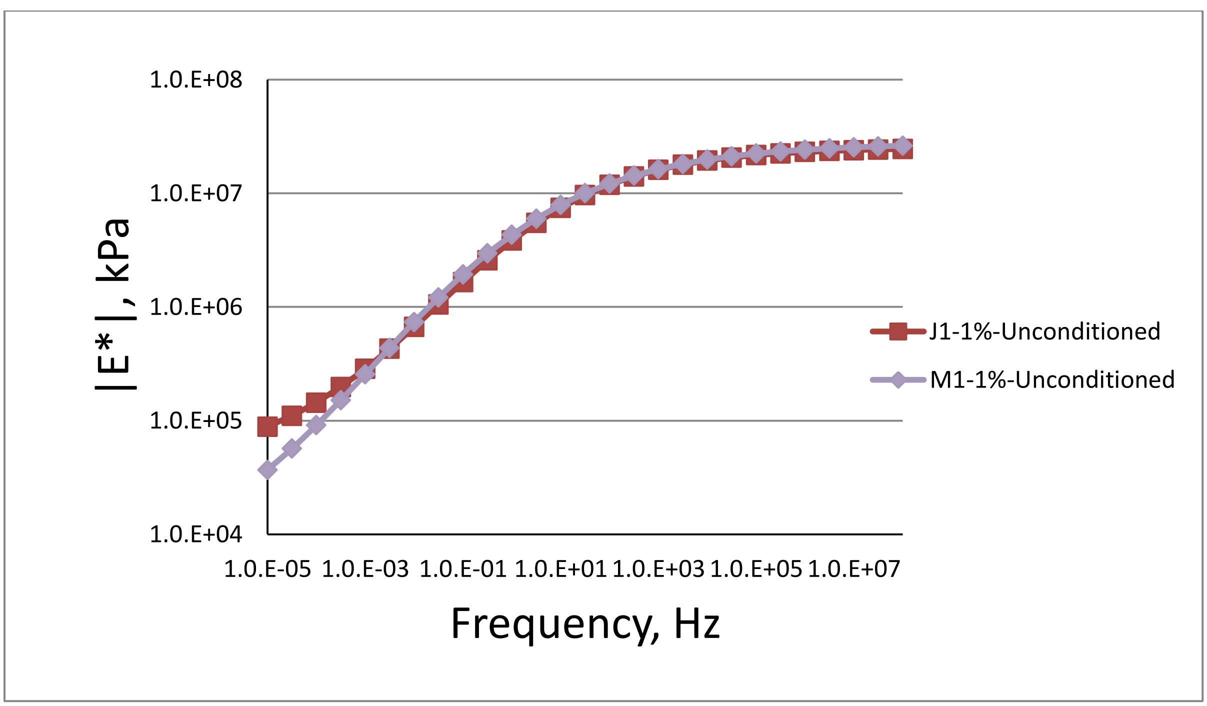


Figure 35. Master Curves for the Unconditioned J1-1% and M1-1% Mixes

Analysis of E* Ratio

For each type of mix, the E* ratio was calculated by dividing the average E* value that resulted from the moisture conditioned group by those from the non-moisture conditioned group. By comparing E* ratio, the relative moisture sensitivity could be compared between specific mixes. In order to better explain the E* for each mix, a tabulated summary is shown as follows in Table 28.

Table 28. E* Ratio

	Freq. Hz	J1-0%	J1-0.5%	J1-1%	M1-0%	M1-0.5%	M1-1%
4°C	25	0.89	0.96	0.89	0.87	0.92	0.89
	15	0.89	0.95	0.88	0.87	0.92	0.88
	10	0.89	0.94	0.86	0.87	0.92	0.87
	5	0.88	0.93	0.84	0.84	0.91	0.86
	3	0.88	0.91	0.81	0.82	0.91	0.84
	1	0.88	0.90	0.80	0.80	0.90	0.83
	0.5	0.87	0.88	0.76	0.78	0.91	0.82
	0.3	0.85	0.84	0.73	0.76	0.91	0.80
	0.1	0.85	0.80	0.67	0.73	0.89	0.79
21 °C	25	0.86	0.99	0.87	0.86	1.00	0.90
	15	0.86	0.99	0.86	0.86	1.00	0.90
	10	0.86	1.01	0.85	0.85	1.02	0.89
	5	0.87	1.03	0.84	0.83	1.02	0.88
	3	0.89	1.07	0.83	0.81	1.05	0.88
	1	0.91	1.14	0.81	0.78	1.08	0.88
	0.5	1.03	1.23	0.81	0.75	1.10	0.88
	0.3	1.24	1.49	0.81	0.71	1.13	0.89
	0.1	1.30	2.55	0.82	0.66	1.14	0.90
37 °C	25	0.97	1.18	0.94	1.10	1.02	0.91
	15	0.99	1.21	0.94	1.11	1.02	0.93
	10	1.06	1.31	0.95	1.13	1.05	0.96
	5	1.16	1.47	0.98	1.16	1.09	1.02
	3	1.36	1.78	1.04	1.20	1.16	1.13
	1	1.61	2.23	1.13	1.30	1.26	1.26
	0.5	1.89	2.69	1.24	1.39	1.36	1.42
	0.3	2.26	3.34	1.37	1.50	1.51	1.66
	0.1	3.14	4.10	1.53	1.64	1.68	1.92

As the above table illustrates, there is a tendency that the E ratios increase as the load frequency decreases and /or temperature increases. Generally, the E* ratios appear to vary with test frequency and temperature. The following split block statistical design analysis examined the E* ratios variability and show that how some major factors contributed to the test results.

The statistical response of the experiment is the E* ratio for each mix and it includes six mix types (J1-0%, J1-0.5%, J1-1%; M1-0%, M1-0.5%, M1-1%), All samples were randomly assigned to a moisture/non-moisture conditioned groups. According to the research objective, two statistical hypotheses are considered as follows:

- Comparison E* ratio for
  - J1-0% vs. J1-0.5% vs. J1-1%;
  - M1-0% vs. M1-0.5% vs. M1-1%.
- Comparison E* ratio for
  - J1-0.5% vs. M1-0.5%;
  - J1-1% vs. M1-1%.

Hypothesis Test 1 for E* Ratio

H_0:A_1=A_2=A_3, vs. H_a: At least one of the A_i is not equal (A_i means the E* ratio of one type additive J1/M1 with three different additive contents)

A three-way factorial analysis of variance (ANOVA) statistical technique was used to test whether there are statistically significant differences in the mean E* ratios for each specific mix among the different treatments. For each additive, there is an ANOVA table to match as shown in Table 29 and 30.

Table 29. Effect Test ANOVA Table for the J1 Mixes

Source	DF	Sum of Squares	F Ratio	Prob > F
Mix Type	2	3.6747	0.9470	0.4322
Freq.[Mix type]&random	24	7.7164	1.9693	0.0228
Temp.[Mix type]&random	6	10.6910	10.9139	<0.0001

Table 30. . Effect Test ANOVA Table for the M1Mixes

Source	DF	Sum of Squares	F Ratio	Prob > F
Mix Type	2	0.11674	0.0946	0.9111
Freq.[Mix type]&random	24	0.83676	0.8106	0.7064
Temp.[Mix type]&random	6	3.75061	14.5326	<0.0001

For both additives, the additive type did not affect E* ratio, however, after adding the temperature variable, there existed significant differences. At 37^{o}C, the J1-0.5% mix had the highest mean E* ratio and is significantly different than with J1-1% mixes. However, there are not statistically significant differences among all M1 mixes. At 4^{o}C, all mixes are not statistically different for J1 and M1. The detailed statistical analysis is located in Appendix C.

Hypothesis Test 2 for E* Ratio

This hypothesis includes two sub-hypothesis, one subset is: H_0:E_1=E_2, vs. Ha: At least one of E_i is not equal (E_i means the E* ratio of J1/M1 with 0.5% additive). Another one is H_0:E_1=E_2, vs. Ha: At least one of Ei is not equal (Ei means the E* ratio of J1/M1 with 1% additive). For each subset, a three-way factorial Analysis of Variance (ANOVA) statistical technique was used to test whether there are statistically significant differences in the mean dynamic modulus value ratio of each mix among the different treatments and their interactions. The summary of the analysis is contained in Tables 31 and 32.

Table 31. Effect Test ANOVA Table for the J1-0.5% vs. M1-0.5%

Source	DF	Sum of Squares	F Ratio	Prob > F
Mix Type	1	1.8667	0.8672	0.3961
Freq.[Mix Type]&Random	16	5.8323	2.1882	0.0290*
Temp.[Mix Type]&Random	4	7.81868	11.7339	<0.0001*

Table 32 Effect Test ANOVA Table for the J1-1% vs. M1-1%

Source	DF	Sum of Squares	F Ratio	Prob > F
Mix Type	1	0.06898	0.1998	0.6800
Freq.[Mix Type]&Random	16	1.44014	10.3292	<0.0001*
Temp.[Mix Type]&Random	4	0.32232	0.5779	0.8772

Similar to the hypothesis 1 conclusion, the mix type did not affect E* ratio. Besides, J1-0.5% is not significantly different from M1-0.5% at 37^{o}C, 21^{o}C and 4^{o}C, respectively. Meanwhile, the statistical analysis of J1-1% and M1-1% are same as the results of J1-0.5% and M1-0.5%. JMP output results for this hypothesis are attached in Appendix C.

Analysis of IDOT E* Ratio

For each type of mix, the IDOT E* ratio was calculated by dividing the average E* value that resulted from the moisture conditioned group by the E* from the non-moisture conditioned mixture without any additive. By keeping a consistent denominator, the data does not add a confounding factor and the value could effectively reflect the moisture damage effect and eliminate the additive effect in the asphalt mixture. A tabulated summary is shown as follows in Table 33.

Table 33. IDOT E* Ratio

	Freq. Hz	J1-0%	J1-0.5%	J1-1%	M1-0%	M1-0.5%	M1-1%
4°C	25	0.89	0.87	0.87	0.87	0.93	0.89
	15	0.89	0.87	0.86	0.87	0.93	0.89
	10	0.89	0.85	0.84	0.87	0.93	0.88
	5	0.88	0.83	0.82	0.84	0.93	0.87
	3	0.88	0.81	0.79	0.82	0.93	0.85
	1	0.88	0.79	0.78	0.80	0.92	0.84
	0.5	0.87	0.76	0.75	0.78	0.94	0.82
	0.3	0.85	0.73	0.71	0.76	0.95	0.81
	0.1	0.85	0.70	0.67	0.73	0.95	0.79
21 °C	25	0.86	0.80	0.78	0.86	0.99	0.91
	15	0.86	0.80	0.78	0.86	1.00	0.91
	10	0.86	0.79	0.75	0.85	1.01	0.90
	5	0.87	0.78	0.73	0.83	1.03	0.89
	3	0.89	0.78	0.70	0.81	1.06	0.88
	1	0.91	0.79	0.67	0.78	1.08	0.87
	0.5	1.03	0.80	0.65	0.75	1.11	0.87
	0.3	1.24	0.91	0.63	0.71	1.15	0.86
	0.1	1.30	1.46	0.61	0.66	1.16	0.85
37 °C	25	0.97	0.94	0.85	1.10	1.13	1.08
	15	0.99	0.95	0.85	1.11	1.15	1.10
	10	1.06	1.00	0.85	1.13	1.20	1.16
	5	1.16	1.09	0.88	1.16	1.27	1.24
	3	1.36	1.28	0.96	1.20	1.37	1.37
	1	1.61	1.54	1.08	1.30	1.51	1.54
	0.5	1.89	1.83	1.23	1.39	1.66	1.73
	0.3	2.26	2.27	1.44	1.50	1.83	1.99
	0.1	3.14	2.73	1.69	1.64	2.02	2.25

As the above table illustrates, there is a tendency that the IDOT E* ratios increase as the temperature increases. Generally, the IDOT E* ratios appear to vary with test frequency and temperature. The following split block statistical design analysis examined the IDOT E* ratios variability and show that how some major factors contributed to the test results.

The statistical response of the experiment is the IDOT E* ratio for each mix and it includes six mix types (J1-0%, J1-0.5%, J1-1%; M1-0%, M1-0.5%, M1-1%), All samples were randomly assigned to a moisture/non-moisture conditioned groups. According to the research objective, two statistical hypotheses are considered as follows:

- Comparison IDOT E* ratio for
  - J1-0% vs. J1-0.5% vs. J1-1%; and
  - M1-0% vs. M1-0.5% vs. M1-1%.
- Comparison IDOT E* ratio for
  - J1-0.5% vs. M1-0.5%; and
  - J1-1% vs. M1-1%.

Hypothesis Test 1 for E* Ratio

H_0:A_1=A_2=A_3, vs. H_a: At least one of the A_i is not equal (A_i means the IDOT E* ratio of one type additive J1/M1 with three different additive contents)

A three-way factorial analysis of variance (ANOVA) statistical technique was used to test whether there are statistically significant differences in the mean IDOT E* ratios for each specific mix among the different treatments. For each additive, there is an ANOVA table to match as shown in Table 34 and 35.

Table 34. Effect Test ANOVA Table for the J1 Mixes

Source	DF	Sum of Squares	F Ratio	Prob > F
Mix Type	2	1.22246	0.5563	0.5984
Freq.[Mix type]&random	24	0.15533	1.4219	0.1480
Temp.[Mix type]&random	6	1.05259	9.6359	<0.0001

Table 35. Effect Test ANOVA Table for the M1 Mixes

Source	DF	Sum of Squares	F Ratio	Prob > F
Mix Type	2	0.24938	0.2951	0.7548
Freq.[Mix type]&random	24	0.76553	0.8310	0.6825
Temp.[Mix type]&random	6	5.10911	22.1835	<0.0001

For both additives, the additive type did not affect E* ratio, however, after adding the temperature variable, there existed significant differences. The detailed statistical analysis is located in Appendix C.

Hypothesis Test 2 for E* Ratio

This hypothesis includes two sub-hypothesis, one subset is: H_0:E_1=E_2, vs. Ha: At least one of E_i is not equal (E_i means the IDOT E* ratio of J1/M1 with 0.5% additive). Another one is H_0:E_1=E_2, vs. Ha: At least one of Ei is not equal (Ei means the IDOT E* ratio of J1/M1 with 1% additive). For each subset, a three-way factorial Analysis of Variance (ANOVA) statistical technique was used to test whether there are statistically significant differences in the mean IDOT E* ratio of each mix among the different treatments and their interactions. The summary of the analysis is contained in Tables 36 and 37.

Table 36. Effect Test ANOVA Table for the J1-0.5% vs. M1-0.5%

Source	DF	Sum of Squares	F Ratio	Prob > F
Mix Type	1	0.10578	0.0989	0.7678
Freq.[Mix Type]&Random	16	1.99067	1.5479	0.1429
Temp.[Mix Type]&Random	4	4.10343	12.7625	<0.0001*

Table 37. Effect Test ANOVA Table for the J1-1% vs. M1-1%

Source	DF	Sum of Squares	F Ratio	Prob > F
Mix Type	1	0.62727	0.8263	0.4184
Freq.[Mix Type]&Random	16	0.4376	0.4928	0.9325
Temp.[Mix Type]&Random	4	3.14909	14.1853	<0.0001*

Similar to the hypothesis 1 conclusion, the mix type did not affect E* ratio. Besides, there are still no statistically significant differences among mix types after adding the factor of frequency, but the factor of temperature significant affect IDOT E* ratio. JMP output results for this hypothesis are attached in Appendix D.

Hamburg Wheel Track Testing Results and Analysis

In this section, the HWTD test was evaluated with laboratory compacted specimens which contain two types of additives (J1, M1) and three content level (0%, 0.5% and 1%). Therefore, a full factorial design for the two factors was used and three replicated were prepared at each combination of factor levels, which required a total of 36 specimens. As introduced in Chapter 3, the HWTD sample size (diameter × height) is 100 × 61±1 mm and the air voids for those samples are about 7%±0.5.

According to the literature review, it is not inevitable that HWTD result of a mixture shows all the three characteristic variables: creep slope, stripping slope and SIP. For the result of the HWTD test, no stripping deformation occurred. Therefore, only the creep slope and the maximum rut depth at 20,000 passes were used to analyze. Table 33 shows a summary of the test result and the detailed testing data are located in Appendix D.

The rut progression curves were developed to identify the rutting extent and visually reflect the creep slope. Figures 36 to 39 show the rut progression curves for the mixes with three contents of two additives. Based on figure comparison, it is clear that adding either, the Evotherm J1 or M1 can statistically reduce the rut depth. The mix types with the Evotherm additive (J1 or M1) present better rutting resistance with a reduced creep slope as compared to the HMA samples. The J1-0.5% and J1-1.0% performed almost same as the M1-0.5% and M1-1%, respectively.

Table 38. Summary of HWTD Testing Results

Additive Type	Specimen ID	Air Voids	Creep Slope (mm/pass)	Average	SIP	Stripping Slope (mm/pass)	Rut Depth at 20000 Passes (mm)	Average
Control	S1	7.2	-1.40E-04		N/A	N/A	-5.84	
Control	S5	7.5	x		N/A	N/A	x	
Control	S6	7.5	-1.73E-04		N/A	N/A	-5.73	
Control	S7	7.5	x		N/A	N/A	x	
Control	S8	6.9	-1.37E-04		N/A	N/A	-4.80	
Control	S9	7.0	-1.90E-04	-1.33E-04	N/A	N/A	-6.27	-4.96
Control	S10	7.1	-1.14E-04		N/A	N/A	-4.02	
Control	S11	7.2	x		N/A	N/A	-4.23	
Control	S12	6.7	-1.05E-04		N/A	N/A	-4.28	
Control	S13	7.1	-1.32E-04		N/A	N/A	-5.21	
Control	S14	7.5	-1.01E-04		N/A	N/A	x	
Control	S15	7.2	-1.03E-04		N/A	N/A	-4.21	
J1-0.5%	S16	7.0	-8.64E-05		N/A	N/A	x	
J1-0.5%	S17	7.0	-8.12E-05		N/A	N/A	-3.67	
J1-0.5%	S18	7.3	x	-7.99E-05	N/A	N/A	x	-3.43
J1-0.5%	S19	6.7	-8.60E-05		N/A	N/A	-3.63	
J1-0.5%	S20	6.5	-7.10E-05		N/A	N/A	-3.06	
J1-0.5%	S21	6.7	-7.50E-05		N/A	N/A	-3.36	
J1-1%	S22	6.7	-8.31E-05		N/A	N/A	-3.42	
J1-1%	S23	6.6	-8.62E-05		N/A	N/A	-3.59	
J1-1%	S24	6.7	-9.11E-05	-8.88E-05	N/A	N/A	-3.63	-3.52
J1-1%	S25	7.0	-9.46E-05		N/A	N/A	x	
J1-1%	S26	7.1	x		N/A	N/A	x	
J1-1%	S27	7.3	x		N/A	N/A	-3.44	
M1-0.5%	S28	7.5	-7.52E-05		N/A	N/A	-3.52	
M1-0.5%	S29	7.1	x		N/A	N/A	-3.45	
M1-0.5%	S30	6.9	x	-7.35E-05	N/A	N/A	x	-3.36
M1-0.5%	S31	7.1	-7.33E-05		N/A	N/A	-3.25	
M1-0.5%	S32	7.1	-7.40E-05		N/A	N/A	x	
M1-0.5%	S33	7.3	-7.15E-05		N/A	N/A	-3.23	
M1-1%	S34	7.0	x		N/A	N/A	-3.07	
M1-1%	S35	6.5	x		N/A	N/A	x	
M1-1%	S36	7.2	x	-7.92E-05	N/A	N/A	-3.44	-3.23
M1-1%	S37	7.4	-8.23E-05		N/A	N/A	x	
M1-1%	S38	6.8	-7.54E-05		N/A	N/A	-3.19	
M1-1%	S39	7.4	-8.00E-05		N/A	N/A	x	

[a] “x” indicates the data is outlier and is removed.

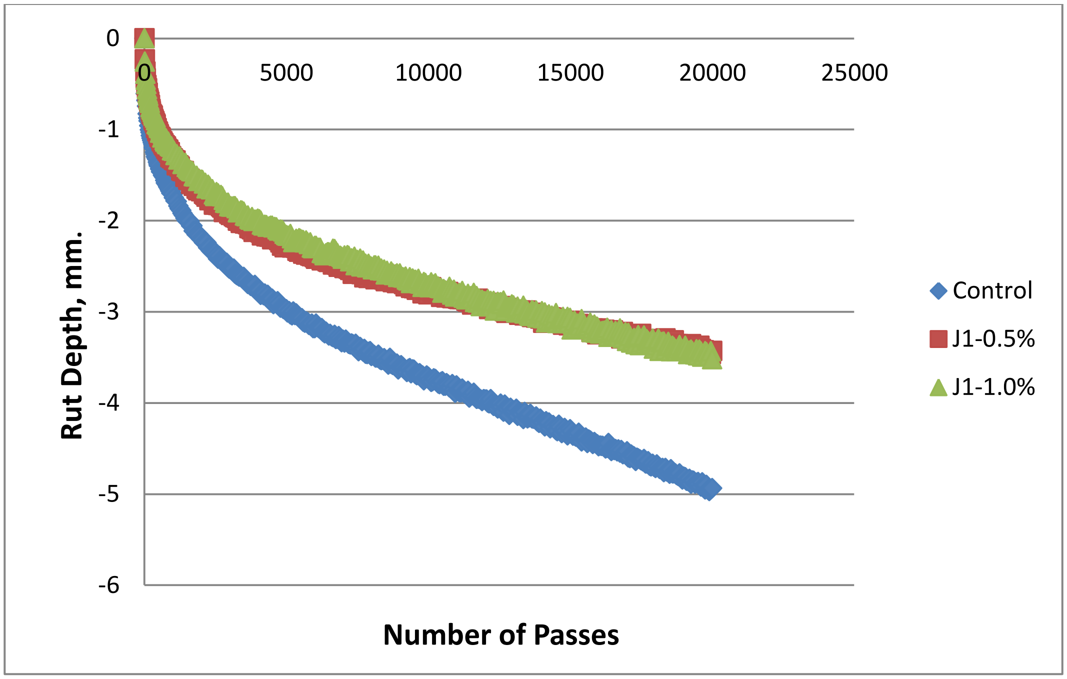


Figure 36. Rut Progression Curves for the J1-1 Mixes

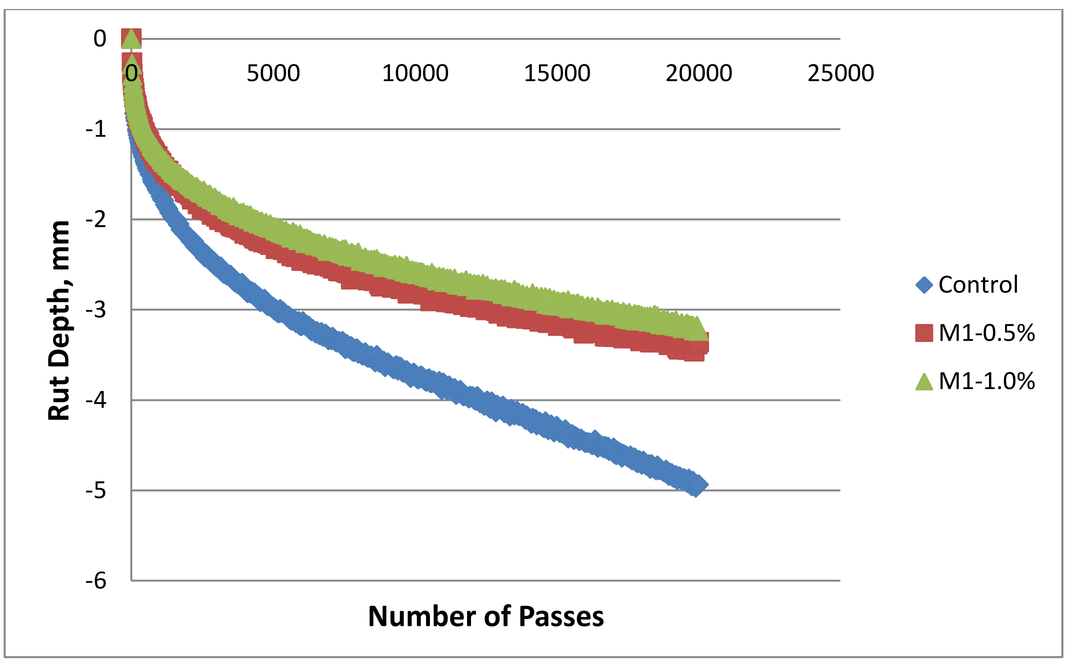


Figure 37. Rut Progression Curves for the M1-1 Mixes

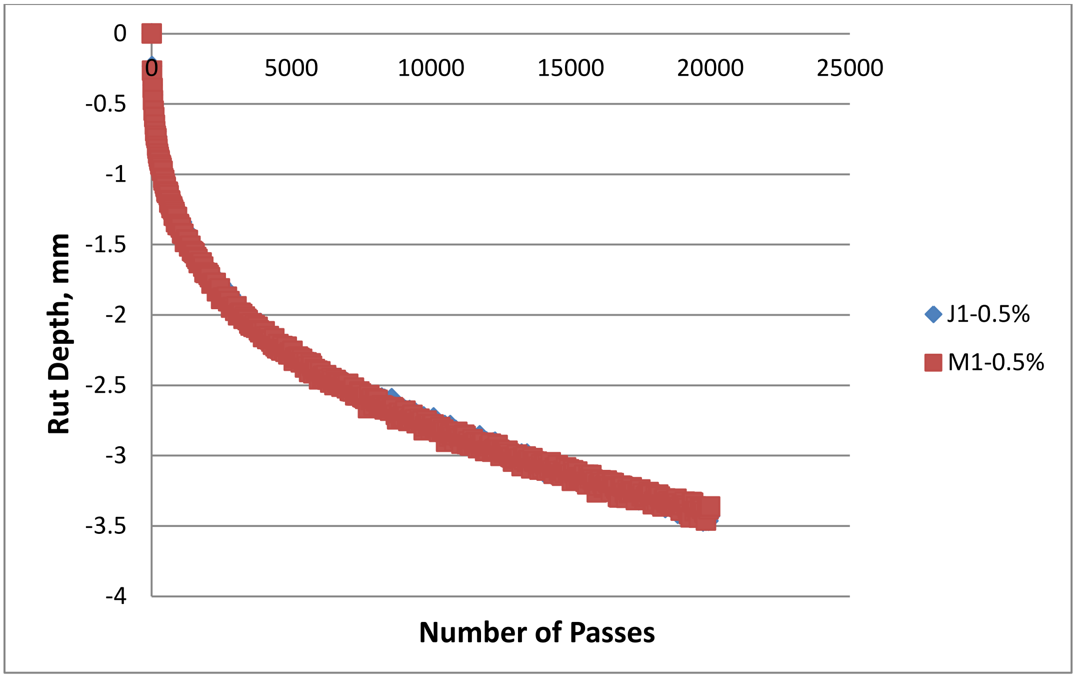


Figure 38. Rut Progression Curves for the J1-0.5% and M1-0.5% Mixes

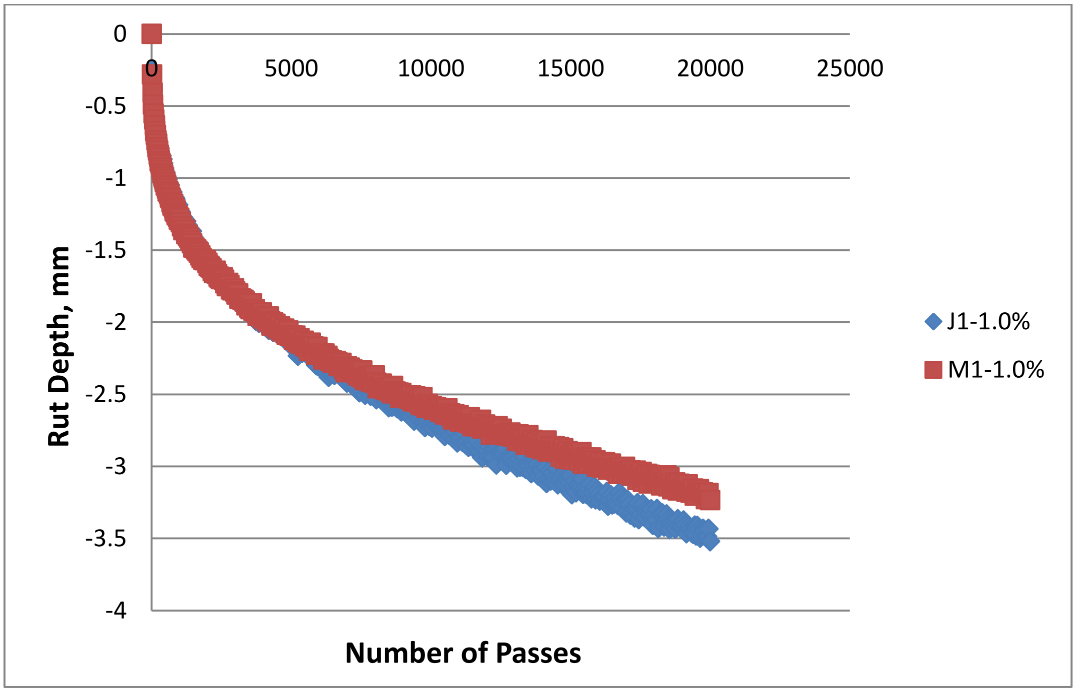


Figure 39. Rut Progression Curves for the J1-1.0% and M1-1.0% Mixes

Analysis of Creep Slope

Analysis of variance (ANOVA) was performed to evaluate the creep slope of the HWTD to distinguish the rutting effect from the different mix types. The creep slope was used as the response variable with two factor of interest: additive type (J1, M1), and additive content (0%, 0.5%, 1%). In order to evaluate how the factor effect creep slope, the following statistical hypothesis was considered at an α=0.05 level:

- Comparison of all J1/M1 samples: J1/M1 (0% vs. 0.5% vs. 1%).

The hypothesis for the creep slope is as follows: H_0:A_1=A_2=A_3=A_4=A_5=A_6, vs. H_a: At least one of the A_i is not equal (A_i means the creep slope of one of the five additive type mixes).

Table 39. Effect Test ANOVA Table for the Creep Slope Hypothesis

Source	DF	Sum of Squares	F Ratio	Prob. > F
Additive Type	1	1.48651e-9	5.7055	0.0281
Additive Content	2	6.91042 e-9	13.2617	0.0003
Additive Type * Additive Content	2	7.7575 e-10	1.4887	0.2522

Table 40. LS Means Differences Tukey HSD for the Creep Slope Hypothesis

Level			Least Sq Mean
M1-0.5%	A		-0.0000735
M1-1.0%	A		-0.0000792
J1-0.5%	A		-0.0000799
J1-1.0%	A		-0.0000888
M1-0%		B	-0.0001328
J1-0%		B	-0.0001363

[a] Levels not connected by same letter are significantly different.

Based on the above ANOVA table, the p values of the additive type and the additive content are smaller than 0.05, so the hypothesis of H_0 was rejected at α=0.05 and there are some significant differences existed in both factors. The M1 has the lowest mean creep slope and is statistically different with the J1. Moreover, the 0% additive content has the highest mean creep slope and is significantly different with the other additive contents (0.5%, 1.0%). Table 6 indicates the control group (J1-0 %, M1-0%) with the lowest mean creep slope is statistically different with the other mix types which are the interaction factors of the additive type and additive content.

Analysis of Rut Depth

The statistical analysis response of the experiment is the rut depth that called the maximum rut depth at 20,000 wheel passes for each mix type. There are two factors of interest: additive type (J1, M1) and additive content (0%, 0.5%, and 1.0%). Same as the creep slope hypothesis, a hypothesis for the rut depth is described as follows: H_0:A_1=A_2=A_3=A_4=A_5=A_6, vs. H_a: At least one of the A_i is not equal (A_i means the maximum rut depth of one of the five additive type mixes). The following is an ANOVA table.

Table 41. Effect Test ANOVA Table for the Rut Depth Hypothesis

Source	DF	Sum of Squares	F Ratio	Prob. > F
Additive Type	1	0.061935	0.1854	0.6719
Additive Content	2	13.706257	20.5093	<0.0001
Additive Type * Additive Content	2	0.108402	0.1622	0.8515

Table 42. LS Means Differences Tukey HSD for the Rut Depth Hypothesis

Level			Least Sq Mean
M1-1%	A		-3.233333
M1-0.5%	A		-3.362500
J1-0.5%	A		-3.430000
J1-1%	A		-3.520000
J1-0%		B	-4.934000
M1-0%		B	-4.980000

[a] Levels not connected by same letter are significantly different.

Based on the above ANOVA tables, p value indicates that there are some significantly statistical differences in the factor of additive content. The 0% additive content has the highest mean rut depth and is significantly different with the other additive contents (0.5%, 1.0%). Table 37 indicates the control group (J1-0%, M1-0%) with the highest mean rut depth is statistically different with the other mix types (additive type * additive content).

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

In this research, all laboratory experimental specimens had the same aggregate gradation and binder content but the two different types of Evotherm with three different blend contents were varied. The compaction Shear Capability test parameter was selected to address to the first object to evaluate performance of Evotherm J1 and M1 as a compaction technology additive. The Indirect Tensile Strength, Dynamic Modulus and Hamburg Wheel Tracking tests were executed to address the second purpose of the study the use as a moisture anti-strip of the two types Evotherm 3G additives. Based on the laboratory experiment and statistical analysis, the following conclusions are derived:

1. The compaction force index (CFI) and the traffic force index (TFI) will not be affected by the additive type (J1, M1) and additive content (0%, 0.5%, 1%). This means that the shear capability is not sensitive to the effect of Evotherm 3G products.

2. The mixtures have better shear capability at the temperature mixing/compaction combination of 145°C/130°C than at the combination of 130°C /115°C yet performed almost same as the HMA temperature combination 160°C /145°C.

3. Adding M1 does not affect the ITS without moisture conditioning. Inversely, J1 will significantly decrease the ITS for mixes without moisture conditioning.

4. Compared to the 0% and 1% Evotherm-J1, the 0.5% content of Evotherm-J1 is the optimum content for the asphalt mixtures studied. In addition, a mixture alternative of the M1-0.5% illustrates the same influence as the J1-0.5% in ITS, and it performed considerable well in moisture susceptibility testing.

5. The two types of additives affect the TSR differently with M1 better than J1 via the higher TSR values for the mixtures studied.

6. For the Tensile Strength Ratio (TSR), although 0.5% content is not significantly different than the 0% content, the 0.5% Evotherm mix had statistically significantly higher TSR values than 1% content and has lower moisture damage susceptibility.

7. The conditioning of samples via freeze-thaw cycling can increase the E* of all mixes. Besides, adding J1/M1 will slightly reduce the E* values, but the M1 mixtures performed the better than the J1 mixes after moisture conditioning, particularly for the M1-0.5%.

8. Temperature and frequency significantly influence E* ratio but the Evotherm type (J1and M1) does not. The E* ratio analytic result indicates that the J1-0.5% and M1-0.5% mixtures have the same effect on improving moisture anti-strip performance.

9. Hamburg WTD testing indicated that no moisture damage occurred for all the prepared samples.

10. Adding either additive, J1 or M1, can statistically reduce the rut depth. The mix types with Evotherm additive (J1 or M1) present better rutting resistance with a reduced creep slope as compared to the HMA samples. The J1-0.5% and J1-1.0% performed almost same as the M1-0.5% and M1-1%, respectively.

Recommendations

Based on the results of this research, the following recommendations are made:

1. As a WMA compaction technology additive, either additive type (J1-0.5%, J1-1.0%, M1-0.5% and M1-1.0%) can be selected, because the Evotherm type and content do not affect the Compaction Shear Capability.

2. The mixing and compaction temperature combination of 130°C /115°C is recommended for Evotherm 3G WMA products.

3. Integrating the conclusions of the three moisture susceptibility tests, all Evotherm 3G products (J1 and M1) demonstrated considerable moisture resistance ability, with the M1 performing slightly better than the J1. The M1-0.5% is the recommended dosage as the optimal amount for the mixtures studied due to a reduced compaction temperature described in the literature review, but also has the least moisture damage susceptibility. In addition, compared to the J1-1.0%, the J1-0.5% is recommended to use as a moisture anti-strip additive.

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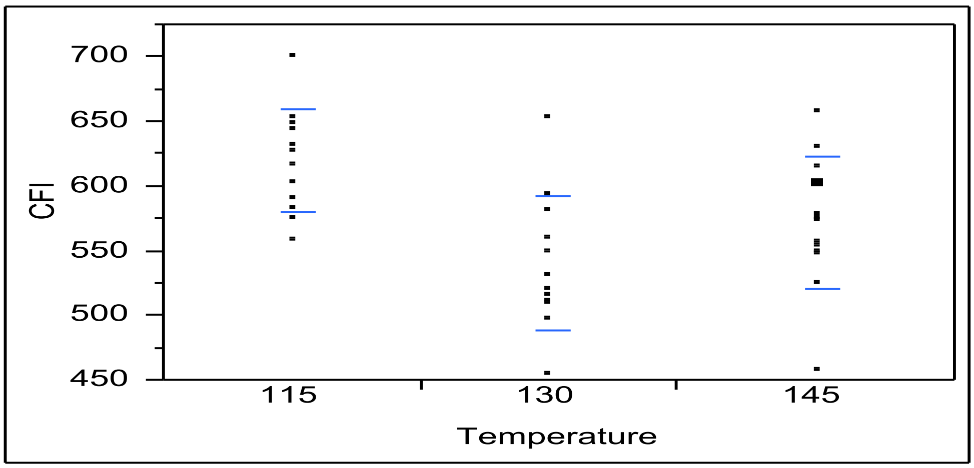
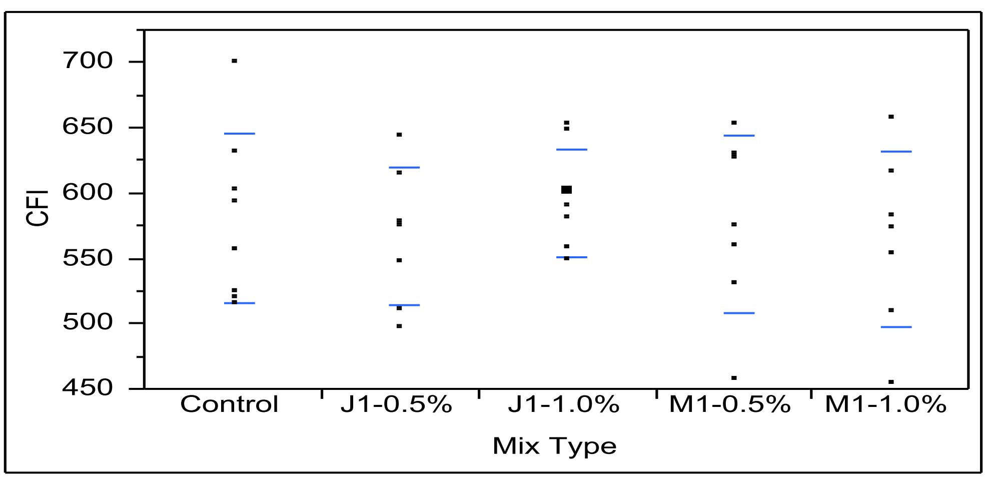
APPENDIX A. WMA COMPACTION TESTING RESULTS

One-way Analysis Plot for Outliers

One-way analysis of CFI by temperature



One-way Analysis of CFI by mix type



Note: the blue lines are the standard deviation line.

JMP Output Result for CFI Statistical Analysis

Hypothesis Test 1 for CFI of J1

Whole Model

Summary of Fit

RSquare	0.578494
RSquare Adj	0.337633
Root Mean Square Error	42.67348
Mean of Response	580.5522
Observations (or Sum Wgts)	23

Temperature

LSMeans Differences Tukey HSD

α=0.050 Q=2.61728 LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	115	130	145
115	0 0 0 0	70.7944 21.7283 13.9255 127.663	51.2833 22.4909 -7.5817 110.148
130	-70.794 21.7283 -127.66 -13.925	0 0 0 0	-19.511 22.4909 -78.376 39.3539
145	-51.283 22.4909 -110.15 7.58166	19.5111 22.4909 -39.354 78.3761	0 0 0 0

Level			Least Sq Mean
115	A		617.95556
145	A	B	566.67222
130		B	547.16111

Levels not connected by same letter are significantly different.

Mix Type

LSMeans Differences Tukey HSD

α=0.050 Q=2.61728 LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	Control	J1-0.5%	J1-1%
Control	0 0 0 0	11.6778 22.4909 -47.187 70.5428	-14.317 21.7283 -71.186 42.5523
J1-0.5%	-11.678 22.4909 -70.543 47.1872	0 0 0 0	-25.994 22.4909 -84.859 32.8705
J1-1%	14.3167 21.7283 -42.552 71.1857	25.9944 22.4909 -32.871 84.8594	0 0 0 0

Level		**Least Sq Mean**
J1-1%	A	590.70000
Control	A	576.38333
J1-0.5%	A	564.70556

Levels not connected by same letter are significantly different.

Temperature*Mix Type

LSMeans Differences Tukey HSD

α=0.050 Q=3.62744 LSMean[i] By LSMean[j]
LSMean[i] By LSMean[j]

Level		**Least Sq Mean**
115,Control	A	645.53333
115,J1-0.5%	A	609.40000
115,J1-1%	A	598.93333
130,J1-1%	A	594.46667
145,J1-0.5%	A	580.36667
145,J1-1%	A	578.70000
130,Control	A	542.66667
145,Control	A	540.95000
130,J1-0.5%	A	504.35000

Levels not connected by same letter are significantly different.

Hypothesis Test 1 for CFI of M1

Whole Model

Summary of Fit

RSquare	0.603248
RSquare Adj	0.359093
Root Mean Square Error	51.16469
Mean of Response	574.0182
Observations (or Sum Wgts)	22

Temperature

LSMeans Differences Tukey HSD

α=0.050 Q=2.64044 LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	115	130	145
115	0 0 0 0	105.256 27.8505 31.718 178.793	64.8833 26.9662 -6.3191 136.086
130	-105.26 27.8505 -178.79 -31.718	0 0 0 0	-40.372 26.9662 -111.57 30.8302
145	-64.883 26.9662 -136.09 6.31912	40.3722 26.9662 -30.83 111.575	0 0 0 0

Level			**Least Sq Mean**
115	A		628.41111
145	A	B	563.52778
130		B	523.15556

Levels not connected by same letter are significantly different.

Mix Type

LSMeans Differences Tukey HSD

α=0.050 Q=2.64044 LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	Control	M1-0.5%	M1-1%
Control	0 0 0 0	-3.5389 26.9662 -74.741 67.6636	17.5944 26.9662 -53.608 88.7969
M1-0.5%	3.53889 26.9662 -67.664 74.7413	0 0 0 0	21.1333 27.8505 -52.404 94.6709
M1-1%	-17.594 26.9662 -88.797 53.608	-21.133 27.8505 -94.671 52.4042	0 0 0 0

Level		**Least Sq Mean**
M1-0.5%	A	579.92222
Control	A	576.38333
M1-1%	A	558.78889

Levels not connected by same letter are significantly different.

Temperature*Mix Type

LSMeans Differences Tukey HSD

α=0.050 Q=3.6713 LSMean[i] By LSMean[j]

Level		**Least Sq Mean**
115,Control	A	645.53333
115,M1-0.5%	A	640.20000
115,M1-1%	A	599.50000
145,M1-1%	A	595.16667
145,M1-0.5%	A	554.46667
130,M1-0.5%	A	545.10000
130,Control	A	542.66667
145,Control	A	540.95000
130,M1-1%	A	481.70000

Levels not connected by same letter are significantly different.

Hypothesis Test 2 for CFI of the comparison between J1-0.5% and M1-0.5%

Whole Model

Summary of Fit

RSquare	0.530881
RSquare Adj	0.237682
Root Mean Square Error	51.3055
Mean of Response	571.6143
Observations (or Sum Wgts)	14

Temperature

LSMeans Differences Tukey HSD
α=0.050 Q=2.85742
LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	115	130	145
115	0 0 0 0	100.075 36.2785 -3.5879 203.738	57.3833 33.1176 -37.248 152.014
130	-100.07 36.2785 -203.74 3.58794	0 0 0 0	-42.692 33.1176 -137.32 51.9392
145	-57.383 33.1176 -152.01 37.2475	42.6917 33.1176 -51.939 137.323	0 0 0 0

Level		**Least Sq Mean**
115	A	624.80000
145	A	567.41667
130	A	524.72500

Levels not connected by same letter are significantly different.

Mix Type

LSMeans Differences Student's t
α=0.050 t=2.306
LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	J1-0.5%	M1-0.5%
J1-0.5%	0 0 0 0	-15.217 27.9272 -79.617 49.1835
M1-0.5%	15.2167 27.9272 -49.184 79.6169	0 0 0 0

Level		**Least Sq Mean**
M1-0.5%	A	579.92222
J1-0.5%	A	564.70556

Levels not connected by same letter are significantly different.

Temperature*Mix Type

LSMeans Differences Tukey HSD
α=0.050 Q=3.65378

Level		**Least Sq Mean**
115,M1-0.5%	A	640.20000
115,J1-0.5%	A	609.40000
145,J1-0.5%	A	580.36667
145,M1-0.5%	A	554.46667
130,M1-0.5%	A	545.10000
130,J1-0.5%	A	504.35000

Levels not connected by same letter are significantly different.

Hypothesis Test 2 for CFI of the comparison between J1-1% and M1-1%

Whole Model

Summary of Fit

RSquare	0.534137
RSquare Adj	0.275324
Root Mean Square Error	46.66307
Mean of Response	579.0333
Observations (or Sum Wgts)	15

Temperature

LSMeans Differences Tukey HSD

α=0.050 Q=2.79201

LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	115	130	145
115	0 0 0 0	61.1333 30.1209 -22.964 145.231	12.2833 30.1209 -71.814 96.3811
130	-61.133 30.1209 -145.23 22.9645	0 0 0 0	-48.85 30.1209 -132.95 35.2478
145	-12.283 30.1209 -96.381 71.8145	48.85 30.1209 -35.248 132.948	0 0 0 0

Level		**Least Sq Mean**
115	A	599.21667
145	A	586.93333
130	A	538.08333

Levels not connected by same letter are significantly different.

Mix Type

LSMeans Differences Student's t
α=0.050 t=2.26216
LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	J1-1%	M1-1%
J1-1%	0 0 0 0	31.9111 24.5936 -23.723 87.5457
M1-1%	-31.911 24.5936 -87.546 23.7235	0 0 0 0

Level		**Least Sq Mean**
J1-1%	A	590.70000
M1-1%	A	558.78889

Levels not connected by same letter are significantly different.

Temperature*Mix Type

LSMeans Differences Tukey HSD
α=0.050 Q=3.55216

Level		**Least Sq Mean**
115,M1-1%	A	599.50000
115,J1-1%	A	598.93333
145,M1-1%	A	595.16667
130,J1-1%	A	594.46667
145,J1-1%	A	578.70000
130,M1-1%	A	481.70000

Levels not connected by same letter are significantly different.

JMP Output Result for TFI Statistical Analysis

Hypothesis Test 1 for TFI for J1

Whole Model

Summary of Fit

RSquare	0.549201
RSquare Adj	0.291602
Root Mean Square Error	280.589
Mean of Response	3501.809
Observations (or Sum Wgts)	23

Temperature

LSMeans Differences Tukey HSD

α=0.050 Q=2.61728

LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	115	130	145
115	0	219.139	433.622
	0	142.869	147.883
	0	-154.79	46.5699
	0	593.067	820.675
130	-219.14	0	214.483
	142.869	0	147.883
	-593.07	0	-172.57
	154.789	0	601.536
145	-433.62	-214.48	0
	147.883	147.883	0
	-820.67	-601.54	0
	-46.57	172.569	0

Level			**Least Sq Mean**
115	A		3693.1333
130	A	B	3473.9944
145		B	3259.5111

Levels not connected by same letter are significantly different.

Mix Type

LSMeans Differences Tukey HSD

α=0.050 Q=2.61728

LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	Control	J1-0.5%	J1-1%
Control	0	222.728	175.7
	0	147.883	142.869
	0	-164.32	-198.23
	0	609.78	549.628
J1-0.5%	-222.73	0	-47.028
	147.883	0	147.883
	-609.78	0	-434.08
	164.325	0	340.025
J1-1%	-175.7	47.0278	0
	142.869	147.883	0
	-549.63	-340.02	0
	198.228	434.08	0

Level		**Least Sq Mean**
Control	A	3608.3556
J1-1%	A	3432.6556
J1-0.5%	A	3385.6278

Levels not connected by same letter are significantly different.

Temperature*Mix Type

LSMeans Differences Tukey HSD

α=0.050 Q=3.62744

Level		**Least Sq Mean**
115,Control	A	3966.3000
130,Control	A	3669.7667
115,J1-0.5%	A	3628.2000
130,J1-1%	A	3542.1667
115,J1-1%	A	3484.9000
145,J1-0.5%	A	3318.6333
145,J1-1%	A	3270.9000
130,J1-0.5%	A	3210.0500
145,Control	A	3189.0000

Levels not connected by same letter are significantly different.

Hypothesis Test 1 for TFI for M1

Whole Model

Summary of Fit

RSquare	0.710473
RSquare Adj	0.532303
Root Mean Square Error	225.3592
Mean of Response	3543.832
Observations (or Sum Wgts)	22

Temperature

LSMeans Differences Tukey HSD

α=0.050 Q=2.64044

LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	115	130	145
115	0 0 0 0	427.094 122.67 103.192 750.997	301.628 118.775 -11.989 615.245
130	-427.09 122.67 -751 -103.19	0 0 0 0	-125.47 118.775 -439.08 188.151
145	-301.63 118.775 -615.24 11.9894	125.467 118.775 -188.15 439.084	0 0 0 0

Level			**Least Sq Mean**
115	A		3752.1167
145	A	B	3450.4889
130		B	3325.0222

Levels not connected by same letter are significantly different.

Mix Type

LSMeans Differences Tukey HSD
α=0.050 Q=2.64044
LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	Control	M1-0.5%	M1-1%
Control	0 0 0 0	110.767 118.775 -202.85 424.384	186.672 118.775 -126.94 500.289
M1-0.5%	-110.77 118.775 -424.38 202.851	0 0 0 0	75.9056 122.67 -248 399.808
M1-1%	-186.67 118.775 -500.29 126.945	-75.906 122.67 -399.81 247.997	0 0 0 0

Level		**Least Sq Mean**
Control	A	3608.3556
M1-0.5%	A	3497.5889
M1-1%	A	3421.6833

Levels not connected by same letter are significantly different.

Temperature*Mix Type

LSMeans Differences Tukey HSD

α=0.050 Q3.6713

Level			**Least Sq Mean**
115,Control	A		3966.3000
115,M1-0.5%	A	B	3705.2500
130,Control	A	B	3669.7667
145,M1-1%	A	B	3661.0000
115,M1-1%	A	B	3584.8000
145,M1-0.5%	A	B	3501.4667
130,M1-0.5%	A	B	3286.0500
145,Control		B	3189.0000
130,M1-1%		B	3019.2500

Levels not connected by same letter are significantly different.

Hypothesis Test 2 for TFI of the comparison between J1-0.5% and M1-0.5%

Whole Model

Summary of Fit

RSquare	0.611032
RSquare Adj	0.367927
Root Mean Square Error	182.8371
Mean of Response	3437.1
Observations (or Sum Wgts)	14

Temperature

LSMeans Differences Tukey HSD

α=0.050 Q=2.85742

LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	115	130	145
115	0 0 0 0	418.675 129.285 49.252 788.098	256.675 118.021 -80.561 593.911
130	-418.68 129.285 -788.1 -49.252	0 0 0 0	-162 118.021 -499.24 175.236
145	-256.68 118.021 -593.91 80.5605	162 118.021 -175.24 499.236	0 0 0 0

Level			**Least Sq Mean**
115	A		3666.7250
145	A	B	3410.0500
130		B	3248.0500

Levels not connected by same letter are significantly different.

Mix Type

LSMeans Differences Student's t
α=0.050 t=2.306
LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	J1-0.5%	M1-0.5%
J1-0.5%	0 0 0 0	-111.96 99.5239 -341.46 117.541
M1-0.5%	111.961 99.5239 -117.54 341.464	0 0 0 0

Level		**Least Sq Mean**
M1-0.5%	A	3497.5889
J1-0.5%	A	3385.6278

Levels not connected by same letter are significantly different.

Temperature*Mix Type

LSMeans Differences Tukey HSD
α=0.050 Q=3.65378

Level		**Least Sq Mean**
115,M1-0.5%	A	3705.2500
115,J1-0.5%	A	3628.2000
145,M1-0.5%	A	3501.4667
145,J1-0.5%	A	3318.6333
130,M1-0.5%	A	3286.0500
130,J1-0.5%	A	3210.0500

Levels not connected by same letter are significantly different.

Hypothesis Test 2 for TFI of the comparison between J1-1% and M1-1%

Whole Model

Summary of Fit

RSquare	0.467721
RSquare Adj	0.17201
Root Mean Square Error	283.1421
Mean of Response	3454.273
Observations (or Sum Wgts)	15

Temperature

LSMeans Differences Tukey HSD
α=0.050 Q=2.79201
LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	115	130	145
115	0 0 0 0	254.142 182.767 -256.15 764.43	68.9 182.767 -441.39 579.188
130	-254.14 182.767 -764.43 256.147	0 0 0 0	-185.24 182.767 -695.53 325.047
145	-68.9 182.767 -579.19 441.388	185.242 182.767 -325.05 695.53	0 0 0 0

Level		**Least Sq Mean**
115	A	3534.8500
145	A	3465.9500
130	A	3280.7083

Levels not connected by same letter are significantly different.

Mix Type

LSMeans Differences Student's t
α=0.050 t=2.26216
LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	J1-1%	M1-1%
J1-1%	0 0 0 0	10.9722 149.229 -326.61 348.552
M1-1%	-10.972 149.229 -348.55 326.607	0 0 0 0

Level		Least Sq Mean
J1-1%	A	3432.6556
M1-1%	A	3421.6833

Levels not connected by same letter are significantly different.

Temperature*Mix Type

LSMeans Differences Tukey HSD
α=0.050 Q=3.55216

Level		Least Sq Mean
145,M1-1%	A	3661.0000
115,M1-1%	A	3584.8000
130,J1-1%	A	3542.1667
115,J1-1%	A	3484.9000
145,J1-1%	A	3270.9000
130,M1-1%	A	3019.2500

Levels not connected by same letter are significantly different.

WMA compaction shear capability test result summary

Additive	Mix Temperature	Sample ID	Va @ N_{des}	Average	Standard Deviation	95% CI	Va @ N_{max}	Average	Standard Deviation	95% CI	CFI	Average	Standard Deviation	95% CI	TFI	Average	Standard Deviation	95% CI	N_{92}	Average	Standard Deviation	95% CI
Control	160	1	2.6				1.4				524.5				3111.6				20			
		2	2.7	2.6	0.1	0.1	1.5	1.5	0.1	0.1	557.4	541.0	23.3	32.2	3266.4	3189.0	109.5	151.7	21	20.5	0.7	1.0
		3																				
	145	1	3.0				1.8				519.7				3601.4				22			
		2	3.1	3.0	0.1	0.1	1.9	1.8	0.1	0.1	592.9	542.7	43.6	60.4	3934.7	3669.8	238.2	330.2	22	21.7	0.6	0.8
		3	2.9				1.8				515.4				3473.2				21			
	130	1	2.8				1.6				602.9				3894.9				20			
		2	2.8	2.9	0.2	0.3	1.5	1.7	0.2	0.3	632.4	645.5	50.5	70.0	3645.9	3966.3	361.4	500.9	21	21.3	1.5	2.1
		3	3.1				1.9				701.3				4358.1				23			
0.5% M1	160	1	2.8				1.6				457.3				3195.3				20			
		2	3.2	3.0	0.2	0.3	1.9	1.7	0.2	0.2	575.4	554.5	88.6	122.8	3736.2	3501.5	277.4	384.5	23	22.0	1.7	2.4
		3	2.9				1.7				630.7				3572.9				23			
	145	1																				
		2	2.7	2.6	0.1	0.1	1.5	1.5	0.0	#NUM!	530.5	545.1	20.7	28.6	3301.7	3286.0	22.1	30.7	20	20.0	0.0	#NUM!
		3	2.6				1.5				559.7				3270.4				20			
	130	1	3.1				1.7				652.7				3667.5				24			
		2	3.1	3.1	0.0	0.0	1.8	1.7	0.1	0.1	627.7	640.2	17.7	24.5	3743.0	3705.3	53.4	74.1	23	23.5	0.7	1.0
		3																				
1.0% M1	160	1	3.2				2.0				657.9				3900.0				24			
		2	2.7	2.9	0.2	0.3	1.6	1.8	0.2	0.3	553.5	595.1	55.3	76.6	3491.4	3661.0	212.9	295.1	20	21.7	2.1	2.9
		3	2.9				1.7				574.1				3591.6				21			
	145	1	2.6				1.5				454.5				2943.9				20			
		2		2.5	0.1	0.2		1.4	0.1	0.2		481.7	38.5	53.3		3019.3	106.6	147.7		19.5	0.7	1.0
		3	2.4				1.3				508.9				3094.6				19			
	130	1																				
		2	2.7	2.8	0.1	0.2	1.6	1.6	0.1	0.1	582.6	599.5	23.9	33.1	3500.7	3584.8	118.9	164.8	21	21.5	0.7	1.0
		3	2.9				1.7				616.4				3668.9				22			
0.5% J1	160	1	2.7				1.5				578.0				3372.7				21			
		2	2.8	2.6	0.2	0.3	1.6	1.4	0.1	0.2	614.8	580.4	33.3	46.1	3470.2	3318.6	184.6	255.9	22	20.7	1.5	2.1
		3	2.4				1.3				548.3				3113.0				19			
	145	1	3.0				1.8				497.4				3318.1				22			
		2	2.7	2.8	0.2	0.3	1.5	1.6	0.3	0.4	511.3	504.4	9.8	13.6	3102.0	3210.0	152.8	211.7	20	21.0	1.4	2.0
		3																				
	130	1																				
		2	2.8	2.8	0.0	0.1	1.6	1.7	0.1	0.1	575.4	609.4	48.1	66.6	3531.7	3628.2	136.5	189.2	21	21.5	0.7	1.0
		3	2.9				1.7				643.4				3724.7				22			
1.0% J1	160	1	2.7				1.5				607.5				3426.6				20			
		2	2.4	2.5	0.2	0.3	1.1	1.3	0.2	0.3	549.9	578.7	40.7	56.4	3115.2	3270.9	220.2	305.1	19	19.5	0.7	1.0
		3																				
	145	1	2.6				1.4				549.4				3154.4				20			
		2	2.7	2.8	0.2	0.3	1.5	1.6	0.2	0.3	581.1	594.5	53.0	73.5	3426.6	3542.2	456.6	632.9	21	21.3	1.5	2.1
		3	3.0				1.8				652.9				4045.5				23			
	130	1	2.8				1.6				648.1				3722.8				22			
		2	2.4	2.6	0.2	0.3	1.3	1.5	0.2	0.2	558.2	598.9	45.5	63.1	3200.3	3484.9	264.4	366.4	19	20.3	1.5	2.1
		3	2.6				1.5				590.5				3531.6				20			

Note: Blank cell means the data is outlier and is moved.

APPENDIX B. INDIRECT TENSILE STRENGTH TESTING RESULTS

Evotherm-J1-0% indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples			Unconditioned Samples		
Sample Identification	S21-J1-0%	S23-J1-0%	S25-J1-0%	S56-J1-0%	S53-J1-0%	S59-J1-0%
Diameter (D), mm	99.49	99.48	99.28	99.06	99.01	99.48
Thickness (t), mm	61.66	62.60	62.23	62.54	62.69	62.80
Dry Mass in Air (A), g	1096.8	1097.7	1098.2	1099.6	1098.6	1099.2
SSD Mass (B), g	1101.6	1102.7	1102.1	1103.4	1103	1104.4
Submerged Mass (C), g	622.1	624.3	625.2	626.6	625.2	626.5
Volume(E=B-C), cm^3	479.08	486.31	481.50	481.72	482.45	487.87
Bulk Specific Gravity (G_{mb}=A/E)	2.287	2.295	2.303	2.306	2.299	2.300
Maximum Specific Gravity (G_{mm})	2.471	2.471	2.471	2.471	2.471	2.471
% Air Voids [Pa=100(G_{mm}-G_{mb})/G_{mm}])	7.4	7.1	6.8	6.7	6.9	6.9
Volume of Air Voids (Va=PaE/100), cm^3	35.60	34.73	32.78	32.13	33.53	33.75
Vacuum Saturation Condition						
SSD Mass, g	1123.4	1124.6	1122.2	Not Applicable		
Volume of Absorbed Water, cm^3	26.6	26.9	24			
% Saturation	74.7	77.5	73.2			
Tensile Strength Calculation						
Failure Load, N	11.823	11.542	11.616	14.045	12.609	12.599
Dry Strength [2000P/πtD], kpa				1444.0	1293.9	1284.5
Wet Strength [2000P'/πt'D], kpa	1229.19	1180.51	1197.55			
Average Dry Strength (S_1), kpa				1340.82		
Average Wet Strength (S_2), kpa	1202.42					
Average Standard TSR (S_2/S_1)	0.90					
Average Iowa DOT TSR (S_2/S_{1}-0%)	0.90					

Evotherm-J1-0.5% indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples			Unconditioned Samples		
Sample Identification	S6-J1-0.5%	S12-J1-0.5%	S11-J1-0.5%	S66-J1-0.5%	S67-J1-0.5%	S68-J1-0.5%
Diameter (D), mm	99.89	99.74	99.51	99.80	99.81	99.80
Thickness (t), mm	62.49	62.51	62.73	62.15	62.26	62.20
Dry Mass in Air (A), g	1099.6	1099.7	1098.1	1093.1	1096.7	1096.4
SSD Mass (B), g	1104	1105	1103.8	1095.2	1099.4	1100.4
Submerged Mass (C), g	627.9	628	628	620.3	624.9	624.8
Volume(E=B-C), cm^3	489.44	488.21	487.65	485.92	486.88	486.38
Bulk Specific Gravity (G_{mb}=A/E)	2.310	2.305	2.308	2.302	2.311	2.305
Maximum Specific Gravity (G_{mm})	2.471	2.471	2.471	2.471	2.471	2.471
% Air Voids [$Pa=100(G_{mm}-G_{mb})/G_{mm}$]	6.5	6.7	6.6	6.8	6.5	6.7
Volume of Air Voids (Va=PaE/100), cm^3	31.97	32.71	32.19	33.28	31.47	32.62
Vacuum Saturation Condition						
SSD Mass, g	1125.1	1124.3	1122.8	Not Applicable		
Volume of Absorbed Water, cm^3	25.5	24.6	24.7			
% Saturation	79.8	75.2	76.7			
Tensile Strength Calculation						
Failure Load, KN	12.971	13.414	13.02	7.823	8.855	9.080
Dry Strength [2000P/πtD], kpa				803.3	907.6	931.6
Wet Strength [2000P'/πt'D] kpa	1323.62	1370.26	1328.48			
Average Dry Strength (S_1), kpa				880.84		
Average Wet Strength (S_2), kpa	1340.79					
Average Standard TSR (S_2/S_1)	1.52					
Average Iowa DOT TSR (S_2/S_1-0%)	1.00					

Evotherm-J1-1% indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples			Unconditioned Samples		
Sample Identification	S15-J1-1%	S17-J1-1%	S19-J1-1%	S69-J1-1%	S70-J1-1%	S71-J1-1%
Diameter (D), mm	99.53	99.18	99.74	99.59	99.89	99.77
Thickness (t), mm	62.39	62.12	62.60	62.31	62.09	62.13
Dry Mass in Air (A), g	1097.7	1100.6	1098.7	1093.8	1097.8	1097
SSD Mass (B), g	1102.3	1104.3	1103.6	1096.4	1099.6	1099.5
Submerged Mass (C), g	623.5	626.7	626.5	619.5	623.1	623.9
Volume(E=B-C), cm^3	485.20	479.65	488.83	485.13	486.39	485.51
Bulk Specific Gravity (G_{mb}=A/E)	2.293	2.304	2.303	2.294	2.304	2.307
Maximum Specific Gravity (G_{mm})	2.471	2.471	2.471	2.471	2.471	2.471
% Air Voids [Pa=100(G_{mm}-G_{mb})/G_{mm}])	7.2	6.7	6.8	7.2	6.8	6.7
Volume of Air Voids (Va=PaE/100), cm^3	35.03	32.33	33.26	34.84	32.90	32.31
Vacuum Saturation Condition						
SSD Mass, g	1122.3	1123.7	1121.9	Not Applicable		
Volume of Absorbed Water, cm^3	24.6	23.1	23.2			
% Saturation	70.2	71.4	69.8			
Tensile Strength Calculation						
Failure Load, K N	10.1	11.365	11.778	8.001	8.625	10.441
Dry Strength [2000P/πtD]], kpa				821.2	885.7	1072.8
Wet Strength [2000P'/πt'D] ,kpa	1035.95	1175	1201.58			
Average Dry Strength (S_1), kpa				926.57		
Average Wet Strength (S_2), kpa	1137.51					
Average Standard TSR (S_2/S_1)	1.23					
Average Iowa DOT TSR ($S_2/S_{1-0\%}$)	0.85					

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Evotherm-M1-0% indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples			Unconditioned Samples		
Sample Identification	S31-M1-0%	S27-M1-0%	S29-M1-0%	S60-M1-0%	S58-M1-0%	S55-M1-0%
Diameter (D), mm	99.67	99.37	99.72	98.71	99.78	99.71
Thickness (t), mm	62.62	62.84	60.78	62.62	62.41	62.37
Dry Mass in Air (A), g	1098.9	1099.3	1099	1098.6	1099.3	1098.6
SSD Mass (B), g	1104.3	1104.4	1104	1103.1	1104.2	1103.1
Submerged Mass (C), g	624.7	625.1	627.2	626.4	626.6	625.3
Volume(E=B-C), cm^3	488.30	487.09	474.51	479.00	487.77	486.80
Bulk Specific Gravity (G_{mb}=A/E)	2.291	2.294	2.305	2.305	2.302	2.299
Maximum Specific Gravity (G_{mm})	2.471	2.471	2.471	2.471	2.471	2.471
% Air Voids [Pa=100(G_{mm}-G_{mb})/G_{mm}])	7.3	7.2	6.7	6.7	6.9	6.9
Volume of Air Voids (Va=PaE/100), cm^3	35.51	34.98	31.89	32.26	33.42	33.83
Vacuum Saturation Condition						
SSD Mass, g	1125.4	1123.8	1122.9	Not Applicable		
Volume of Absorbed Water, cm^3	26.5	24.5	23.9			
% Saturation	74.6	70.0	75.0			
Tensile Strength Calculation						
Failure Load, KN	10.497	11.849	12.291	12.508	10.534	12.774
Dry Strength [2000P/πtD]], kpa				1288.8	1077.4	1308.3
Wet Strength [2000P'/πt'D], kpa	1070.99	1208.6	1291.54			
Average Dry Strength (S_1), kpa				1224.85		
Average Wet Strength (S_2), kpa	1190.38					
Average Standard TSR (S_2/S_1)	0.97					
Average Iowa DOT TSR (S_2/$S_{1-0\%}$)	0.97					

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Evotherm-M1-0.5% indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples			Unconditioned Samples		
Sample Identification	S35-M1-0.5%	S38-M1-0.5%	S50-M1-0.5%	S49-M1-0.5%	S52-M1-0.5%	S39-M1-0.5%
Diameter (D), mm	99.66	99.55	98.75	99.60	98.42	99.44
Thickness (t), mm	62.58	62.51	62.66	62.31	62.43	61.17
Dry Mass in Air (A), g	1097.6	1098.4	1098.1	1096.4	1098.6	1097.4
SSD Mass (B), g	1102.1	1102.4	1101.9	1100.1	1102.6	1100.6
Submerged Mass (C), g	622.1	626.7	623	622.8	625.3	625.8
Volume(E=B-C), cm^3	487.95	486.30	479.64	485.20	474.72	474.79
Bulk Specific Gravity (G_{mb}=A/E)	2.287	2.309	2.293	2.297	2.302	2.311
Maximum Specific Gravity (G_{mm})	2.471	2.471	2.471	2.471	2.471	2.471
% Air Voids [$Pa=100(G_{mm}-G_{mb})/G_{mm}$]	7.5	6.6	7.2	7.0	6.9	6.5
Volume of Air Voids (Va=PaE/100), cm^3	36.40	31.88	34.56	34.15	32.53	30.69
Vacuum Saturation Condition						
SSD Mass, g	1123.2	1120.8	1123.2	Not Applicable		
Volume of Absorbed Water, cm^3	25.6	22.4	25.1			
% Saturation	70.3	70.3	72.6			
Tensile Strength Calculation						
Failure Load, K N	13.044	13.129	10.994	10.545	12.271	12.860
Dry Strength [2000P/πtD]], kpa				1082.3	1272.1	1346.7
Wet Strength [2000P'/πt'D], kpa	1332.11	1343.82	1131.75			
Average Dry Strength (S_1), kpa				1233.67		
Average Wet Strength (S_2), kpa	1269.23					
Average Standard TSR (S_2/S_1)	1.03					
Average Iowa DOT TSR ($S_2/S_{1-0\%}$)	1.04					

Evotherm-M1-1% indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples			Unconditioned Samples		
Sample Identification	S46-M1-1%	S42-M1-1%	S45-M1-1%	S72-M1-1%	S73-M1-1%	S74-M1-1%
Diameter (D), mm	99.59	99.87	99.64	99.82	99.80	99.57
Thickness (t), mm	62.59	62.75	62.19	62.22	62.43	62.35
Dry Mass in Air (A), g	1098.9	1098.1	1098	1096.4	1095.5	1097.7
SSD Mass (B), g	1104	1102.7	1102.5	1098.8	1098.2	1101.3
Submerged Mass (C), g	627.6	624	625.2	623	622.3	625
Volume(E=B-C), cm^3	487.31	491.25	484.66	486.64	488.12	485.27
Bulk Specific Gravity (G_{mb}=A/E)	2.307	2.294	2.300	2.304	2.302	2.305
Maximum Specific Gravity (G_{mm})	2.471	2.471	2.471	2.471	2.471	2.471
% Air Voids [$Pa=100(G_{mm}-G_{mb})/G_{mm}$]	6.7	7.2	6.9	6.7	6.8	6.7
Volume of Air Voids (Va=PaE/100), cm^3	32.41	35.20	33.45	32.82	33.39	32.67
Vacuum Saturation Condition						
SSD Mass, g	1122	1120.8	1122.1	Not Applicable		
Volume of Absorbed Water, cm^3	23.1	22.4	24.1			
% Saturation	71.3	71.6	72.0			
Tensile Strength Calculation						
Failure Load, KN	11.9	11.189	11.488	10.104	9.512	9.640
Dry Strength [2000P/πtD], kpa				1036.2	972.4	989.0
Wet Strength [2000P'/πt'D] (psi), kpa	1215.98	1137.31	1180.9			
Average Dry Strength (S_1), kpa				999.22		
Average Wet Strength (S_2), kpa	1178.07					
Average Standard TSR (S_2/S_1)	1.18					
Average Iowa DOT TSR ($S_2/S_{1-0\%}$)	0.96					

JMP Output Result for Hypothesis 1

Whole Model

Summary of Fit

RSquare	0.151839
RSquare Adj	0.100436
Root Mean Square Error	156.4775
Mean of Response	1160.361
Observations (or Sum Wgts)	36

Conditioning

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
Conditioned	1219.7328	36.882103	1219.73
Unconditioned	1100.9889	36.882103	1100.99

LSMeans Differences Student's t

α=0.050 t=2.03452

LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	Conditioned	Unconditioned
Conditioned	0 0 0 0	118.744 52.1592 12.6253 224.863
Unconditioned	-118.74 52.1592 -224.86 -12.625	0 0 0 0

Level			Least Sq Mean
Conditioned	A		1219.7328
Unconditioned		B	1100.9889

Levels not connected by same letter are significantly different.

Additive Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
J1	1138.1556	36.882103	1138.16
M1	1182.5661	36.882103	1182.57

LSMeans Differences Student's t

α=0.050 t=2.03452

LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	J1	M1
J1	0 0 0 0	-44.411 52.1592 -150.53 61.7081
M1	44.4106 52.1592 -61.708 150.529	0 0 0 0

Level		Least Sq Mean
M1	A	1182.5661
J1	A	1138.1556

Levels not connected by same letter are significantly different.

JMP Output Result for Hypothesis 2

- **J1-Unconditioned**

Whole Model
Summary of Fit

RSquare	0.866254
RSquare Adj	0.821672
Root Mean Square Error	99.56662
Mean of Response	1049.4
Observations (or Sum Wgts)	9

Evotherm Type & Content

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
J1 -0%	1340.8000	57.484816	1340.80
J1-0.5%	880.8333	57.484816	880.83
J1-1%	926.5667	57.484816	926.57

LSMeans Differences Tukey HSD
α=0.050 Q=3.06815
LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	J1 -0%	J1-0.5%	J1-1%
J1 -0%	0	459.967	414.233
	0	81.2958	81.2958
	0	210.539	164.806
	0	709.394	663.661
J1-0.5%	-459.97	0	-45.733
	81.2958	0	81.2958
	-709.39	0	-295.16
	-210.54	0	203.694
J1-1%	-414.23	45.7333	0
	81.2958	81.2958	0
	-663.66	-203.69	0
	-164.81	295.161	0

Level			Least Sq Mean
J1 -0%	A		1340.8000
J1-1%		B	926.5667
J1-0.5%		B	880.8333

Levels not connected by same letter are significantly different.

- **M1-Unconditioned**

Whole Model

Summary of Fit

RSquare	0.594951
RSquare Adj	0.459935
Root Mean Square Error	109.6599
Mean of Response	1152.578
Observations (or Sum Wgts)	9

Evotherm Type & Content

Least Squares Means Table

Level	**Least Sq Mean**	**Std Error**	**Mean**
M1-0%	1224.8333	63.312192	1224.83
M1-0.5%	1233.7000	63.312192	1233.70
M1-1%	999.2000	63.312192	999.20

LSMeans Differences Tukey HSD

α=0.050 Q=3.06815

LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	M1-0%	M1-0.5%	M1-1%
M1-0%	0 0 0 0	-8.8667 89.537 -283.58 265.846	225.633 89.537 -49.079 500.346
M1-0.5%	8.86667 89.537 -265.85 283.579	0 0 0 0	234.5 89.537 -40.213 509.213
M1-1%	-225.63 89.537 -500.35 49.0794	-234.5 89.537 -509.21 40.2128	0 0 0 0

Level		**Least Sq Mean**
M1-0.5%	A	1233.7000
M1-0%	A	1224.8333
M1-1%	A	999.2000

Levels not connected by same letter are significantly different.

JMP Output Result for Hypothesis 3

- **J1 conditioned**

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
J1-0%	1202.4333	31.951253	1202.43
J1-0.5%	1340.8000	31.951253	1340.80
J1-1%	1137.5000	31.951253	1137.50

LSMeans Differences Tukey HSD

α=0.050 Q=3.06815

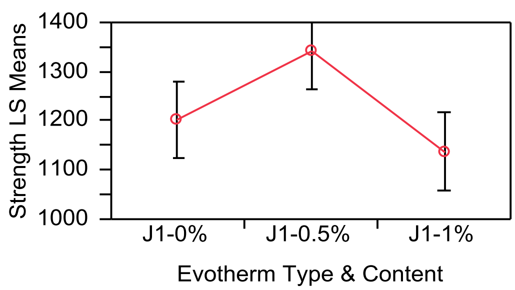
LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	J1-0%	J1-0.5%	J1-1%
J1-0%	0 0 0 0	-138.37 45.1859 -277 0.27041	64.9333 45.1859 -73.704 203.57
J1-0.5%	138.367 45.1859 -0.2704 277.004	0 0 0 0	203.3 45.1859 64.6629 341.937
J1-1%	-64.933 45.1859 -203.57 73.7037	-203.3 45.1859 -341.94 -64.663	0 0 0 0

Level			Least Sq Mean
J1-0.5%	A		1340.8000
J1-0%	A	B	1202.4333
J1-1%		B	1137.5000

Levels not connected by same letter are significantly different.

LS Means Plot



- **M1 conditioned**

Least Squares Means Table

Level	**Least Sq Mean**	**Std Error**	**Mean**
M1-0%	1190.3667	55.934330	1190.37
M1-0.5%	1269.2333	55.934330	1269.23
M1-1%	1178.0633	55.934330	1178.06

LSMeans Differences Tukey HSD

α=0.050 Q=3.06815

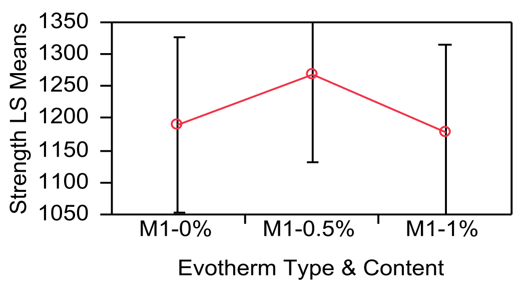
LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	M1-0%	M1-0.5%	M1-1%
M1-0%	0 0 0 0	-78.867 79.1031 -321.57 163.833	12.3033 79.1031 -230.4 255.003
M1-0.5%	78.8667 79.1031 -163.83 321.567	0 0 0 0	91.17 79.1031 -151.53 333.87
M1-1%	-12.303 79.1031 -255 230.397	-91.17 79.1031 -333.87 151.53	0 0 0 0

Level		**Least Sq Mean**
M1-0.5%	A	1269.2333
M1-0%	A	1190.3667
M1-1%	A	1178.0633

Levels not connected by same letter are significantly different.

LS Means Plot



JMP Output Result for Hypothesis 4

- **J1-0.5% vs. M1-0.5%**

Whole Model

Summary of Fit

RSquare	0.800763
RSquare Adj	0.750954
Root Mean Square Error	107.7853
Mean of Response	1057.267
Observations (or Sum Wgts)	6

Additive Type & Content

LSMeans Differences Student's t

α=0.050 t=2.77645

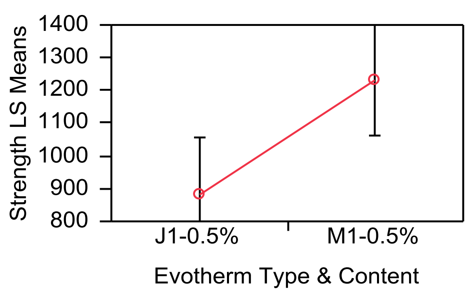
LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	J1-0.5%	M1-0.5%
J1-0.5%	0 0 0 0	-352.87 88.0063 -597.21 -108.52
M1-0.5%	352.867 88.0063 108.522 597.211	0 0 0 0

Level			**Least Sq Mean**
M1-0.5%	A		1233.7000
J1-0.5%		B	880.8333

Levels not connected by same letter are significantly different.

LS Means Plot



- **J1-1% vs. M1-1%**

Whole Model

Summary of Fit

RSquare	0.178789
RSquare Adj	-0.02651
Root Mean Square Error	95.32535
Mean of Response	962.8833
Observations (or Sum Wgts)	6

Additive Type & Content

Least Squares Means Table

Level	**Least Sq Mean**	**Std Error**	**Mean**
J1-1%	926.56667	55.036114	926.567
M1-1%	999.20000	55.036114	999.200

LSMeans Differences Student's t
α=0.050 t=2.77645
LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	J1-1%	M1-1%
J1-1%	0 0 0 0	-72.633 77.8328 -288.73 143.465
M1-1%	72.6333 77.8328 -143.47 288.732	0 0 0 0

Level		**Least Sq Mean**
M1-1%	A	999.20000
J1-1%	A	926.56667

Levels not connected by same letter are significantly different.

JMP Output Result for Hypothesis 5

- **J1-0.5% vs. M1-0.5%**

Whole Model

Summary of Fit

RSquare	0.205417
RSquare Adj	0.006771
Root Mean Square Error	86.19412
Mean of Response	1305.017
Observations (or Sum Wgts)	6

AdditiveType & Content

Least Squares Means Table

Level	**Least Sq Mean**	**Std Error**	**Mean**
J1-0.5%	1340.8000	49.764200	1340.80
M1-0.5%	1269.2333	49.764200	1269.23

LSMeans Differences Student's t

α=0.050 t=2.77645

LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	J1-0.5%	M1-0.5%
J1-0.5%	0 0 0 0	71.5667 70.3772 -123.83 266.965
M1-0.5%	-71.567 70.3772 -266.97 123.832	0 0 0 0

Level		**Least Sq Mean**
J1-0.5%	A	1340.8000
M1-0.5%	A	1269.2333

Levels not connected by same letter are significantly different.

- **J1-1% vs. M1-1%**

Whole Model

Summary of Fit

RSquare	0.115265
RSquare Adj	-0.10592
Root Mean Square Error	68.81892
Mean of Response	1157.782
Observations (or Sum Wgts)	6

Additive Type & Content

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
J1-1%	1137.5000	39.732621	1137.50
M1-1%	1178.0633	39.732621	1178.06

LSMeans Differences Student's t

α=0.050 t=2.77645

LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	J1-1%	M1-1%
J1-1%	0 0 0 0	-40.563 56.1904 -196.57 115.446
M1-1%	40.5633 56.1904 -115.45 196.573	0 0 0 0

Level		Least Sq Mean
M1-1%	A	1178.0633
J1-1%	A	1137.5000

Levels not connected by same letter are significantly different.

APPENDIX C. DYNAMIC MODULUS TESTING RESULTS

J-1 conditioned mixtures dynamic modulus values (Kpa)

		J1-0%			J1-0.5%		J1-1%		
	Freq. Hz	S14	S8	S19	S20	S25	S30	S27	S29
4 °C	25	1.72E+07	1.74E+07	1.63E+07	1.39E+07	1.66E+07	1.79E+07	1.57E+07	1.62E+07
	15	1.67E+07	1.70E+07	1.62E+07	1.37E+07	1.61E+07	1.72E+07	1.53E+07	1.57E+07
	10	1.55E+07	1.60E+07	1.49E+07	1.27E+07	1.48E+07	1.54E+07	1.41E+07	1.44E+07
	5	1.41E+07	1.51E+07	1.36E+07	1.16E+07	1.35E+07	1.40E+07	1.28E+07	1.31E+07
	3	1.24E+07	1.38E+07	1.20E+07	1.01E+07	1.17E+07	1.20E+07	1.11E+07	1.13E+07
	1	1.11E+07	1.28E+07	1.08E+07	8.96E+06	1.04E+07	1.10E+07	9.88E+06	9.92E+06
	0.5	9.75E+06	1.18E+07	9.34E+06	7.80E+06	9.04E+06	9.29E+06	8.63E+06	8.62E+06
	0.3	8.09E+06	1.00E+07	7.71E+06	6.45E+06	7.39E+06	7.66E+06	7.03E+06	6.98E+06
	0.1	6.88E+06	9.35E+06	6.49E+06	5.37E+06	6.22E+06	6.06E+06	5.97E+06	5.80E+06
21 °C	25	8.60E+06	8.21E+06	8.59E+06	7.44E+06	7.91E+06	7.54E+06	7.49E+06	8.08E+06
	15	8.15E+06	7.96E+06	8.25E+06	7.13E+06	7.52E+06	7.18E+06	7.11E+06	7.65E+06
	10	6.92E+06	7.14E+06	7.17E+06	6.15E+06	6.45E+06	6.14E+06	5.96E+06	6.45E+06
	5	5.81E+06	6.40E+06	6.21E+06	5.29E+06	5.51E+06	5.22E+06	4.92E+06	5.38E+06
	3	4.52E+06	5.50E+06	5.08E+06	4.29E+06	4.43E+06	4.16E+06	3.67E+06	4.12E+06
	1	3.69E+06	4.91E+06	4.36E+06	3.66E+06	3.75E+06	3.50E+06	2.87E+06	3.27E+06
	0.5	2.95E+06	4.40E+06	4.83E+06	3.14E+06	3.17E+06	2.94E+06	2.20E+06	2.58E+06
	0.3	2.16E+06	3.77E+06	5.37E+06	2.55E+06	2.76E+06	2.34E+06	1.54E+06	1.84E+06
	0.1	1.69E+06	3.40E+06	4.64E+06	2.20E+06	3.65E+06	1.99E+06	1.16E+06	1.39E+06
37 °C	25	5.28E+06	3.19E+06	3.79E+06	3.25E+06	3.94E+06	3.87E+06	3.95E+06	2.95E+06
	15	5.01E+06	3.00E+06	3.56E+06	3.05E+06	3.71E+06	3.59E+06	3.67E+06	2.70E+06
	10	4.29E+06	2.48E+06	2.81E+06	2.49E+06	3.02E+06	2.84E+06	2.88E+06	2.01E+06
	5	3.71E+06	2.04E+06	2.26E+06	2.09E+06	2.51E+06	2.25E+06	2.26E+06	1.58E+06
	3	3.09E+06	1.55E+06	1.70E+06	1.69E+06	1.99E+06	1.67E+06	1.64E+06	1.15E+06
	1	2.72E+06	1.26E+06	1.40E+06	1.48E+06	1.71E+06	1.36E+06	1.32E+06	9.25E+05
	0.5	2.41E+06	1.05E+06	1.19E+06	1.32E+06	1.51E+06	1.15E+06	1.09E+06	7.98E+05
	0.3	2.05E+06	8.43E+05	9.98E+05	1.15E+06	1.30E+06	9.42E+05	8.76E+05	6.60E+05
	0.1	2.47E+06	7.38E+05	8.99E+05	1.06E+06	1.19E+06	8.37E+05	7.74E+05	6.04E+05

M-1 conditioned mixtures dynamic modulus values (Kpa)

		M1-0%			M1-0.5%			M1-1%		
	Freq. Hz	S11	S12	S13	S33	S34	S37	S38	S42	S43
4 C	25	1.68E+07	1.52E+07	1.68E+07	1.70E+07	1.75E+07	1.75E+07	1.65E+07	1.71E+07	1.65E+07
	15	1.64E+07	1.48E+07	1.64E+07	1.66E+07	1.71E+07	1.72E+07	1.60E+07	1.67E+07	1.61E+07
	10	1.50E+07	1.36E+07	1.58E+07	1.54E+07	1.59E+07	1.60E+07	1.47E+07	1.54E+07	1.48E+07
	5	1.36E+07	1.24E+07	1.37E+07	1.43E+07	1.47E+07	1.52E+07	1.34E+07	1.41E+07	1.36E+07
	3	1.21E+07	1.08E+07	1.18E+07	1.25E+07	1.31E+07	1.38E+07	1.17E+07	1.25E+07	1.18E+07
	1	1.06E+07	9.69E+06	1.06E+07	1.13E+07	1.19E+07	1.23E+07	1.05E+07	1.12E+07	1.05E+07
	0.5	9.26E+06	8.61E+06	9.23E+06	1.01E+07	1.07E+07	1.18E+07	9.30E+06	9.97E+06	9.21E+06
	0.3	7.59E+06	7.30E+06	7.62E+06	8.54E+06	9.18E+06	1.04E+07	7.83E+06	8.50E+06	7.60E+06
	0.1	6.40E+06	6.42E+06	6.25E+06	7.46E+06	7.83E+06	9.56E+06	6.89E+06	7.55E+06	6.38E+06
21 °C	25	8.92E+06	6.86E+06	8.24E+06	8.97E+06	9.29E+06	9.45E+06	7.56E+06	9.08E+06	8.85E+06
	15	8.51E+06	6.47E+06	7.85E+06	8.62E+06	8.84E+06	9.13E+06	7.16E+06	8.66E+06	8.44E+06
	10	7.28E+06	5.41E+06	6.69E+06	7.49E+06	7.61E+06	8.17E+06	6.00E+06	7.45E+06	7.25E+06
	5	6.17E+06	4.49E+06	5.62E+06	6.43E+06	6.48E+06	7.30E+06	5.00E+06	6.33E+06	6.18E+06
	3	4.86E+06	3.45E+06	4.35E+06	5.14E+06	5.16E+06	6.27E+06	3.89E+06	5.02E+06	4.93E+06
	1	3.98E+06	2.76E+06	3.49E+06	4.28E+06	4.29E+06	5.57E+06	3.17E+06	4.15E+06	4.10E+06
	0.5	3.19E+06	2.18E+06	2.75E+06	3.50E+06	3.52E+06	4.94E+06	2.57E+06	3.37E+06	3.37E+06
	0.3	2.34E+06	1.57E+06	1.94E+06	2.63E+06	2.65E+06	4.16E+06	1.96E+06	2.52E+06	2.57E+06
	0.1	1.80E+06	1.12E+06	1.45E+06	2.08E+06	2.08E+06	3.60E+06	1.61E+06	1.99E+06	2.07E+06
37 °C	25	3.75E+06	3.85E+06	4.33E+06	2.45E+06	5.62E+06	4.22E+06	3.42E+06	4.59E+06	3.71E+06
	15	3.47E+06	3.58E+06	4.03E+06	2.11E+06	5.34E+06	3.99E+06	3.18E+06	4.32E+06	3.51E+06
	10	2.70E+06	2.82E+06	3.16E+06	1.55E+06	4.46E+06	3.17E+06	2.45E+06	3.48E+06	2.95E+06
	5	2.08E+06	2.21E+06	2.46E+06	1.14E+06	3.72E+06	2.49E+06	1.88E+06	2.78E+06	2.52E+06
	3	1.45E+06	1.57E+06	1.74E+06	7.58E+05	2.91E+06	1.77E+06	1.29E+06	2.05E+06	2.08E+06
	1	1.10E+06	1.22E+06	1.33E+06	4.95E+05	2.42E+06	1.34E+06	8.90E+05	1.61E+06	1.83E+06
	0.5	8.72E+05	9.69E+05	1.06E+06	3.91E+05	2.04E+06	1.05E+06	6.88E+05	1.29E+06	1.64E+06
	0.3	6.65E+05	7.57E+05	8.05E+05	2.90E+05	1.64E+06	7.90E+05	5.07E+05	1.00E+06	1.45E+06
	0.1	5.62E+05	6.43E+05	6.81E+05	2.39E+05	1.43E+06	6.58E+05	4.04E+05	8.44E+05	1.35E+06

C3

J-1 unconditioned mixtures dynamic modulus values (Kpa)

		J1-0%			J1-0.5%			J1-1%		
	Freq. Hz	S10	S16	S18	S21	S23	S24	S26	S28	S31
4 °C	25	1.91E+07	1.78E+07	1.90E+07	1.78E+07	1.73E+07	1.71E+07	1.84E+07	1.94E+07	1.84E+07
	15	1.86E+07	1.75E+07	1.85E+07	1.73E+07	1.69E+07	1.67E+07	1.80E+07	1.89E+07	1.79E+07
	10	1.74E+07	1.63E+07	1.72E+07	1.62E+07	1.56E+07	1.55E+07	1.68E+07	1.76E+07	1.69E+07
	5	1.61E+07	1.50E+07	1.59E+07	1.49E+07	1.42E+07	1.43E+07	1.55E+07	1.63E+07	1.57E+07
	3	1.45E+07	1.33E+07	1.42E+07	1.33E+07	1.25E+07	1.26E+07	1.37E+07	1.46E+07	1.42E+07
	1	1.32E+07	1.20E+07	1.29E+07	1.20E+07	1.13E+07	1.14E+07	1.24E+07	1.32E+07	1.30E+07
	0.5	1.18E+07	1.07E+07	1.16E+07	1.08E+07	1.00E+07	1.01E+07	1.11E+07	1.19E+07	1.19E+07
	0.3	1.01E+07	9.07E+06	9.93E+06	9.31E+06	8.44E+06	8.66E+06	9.12E+06	1.02E+07	1.05E+07
	0.1	8.87E+06	7.84E+06	8.78E+06	8.33E+06	7.28E+06	7.76E+06	7.71E+06	8.98E+06	9.76E+06
21 °C	25	9.86E+06	9.25E+06	7.61E+06	7.92E+06	8.44E+06	7.71E+06	9.53E+06	8.77E+06	8.35E+06
	15	9.42E+06	8.81E+06	7.29E+06	7.52E+06	8.00E+06	7.31E+06	9.12E+06	8.34E+06	7.95E+06
	10	8.19E+06	7.57E+06	6.13E+06	6.31E+06	6.78E+06	6.16E+06	7.86E+06	7.09E+06	6.81E+06
	5	7.05E+06	6.43E+06	5.03E+06	5.25E+06	5.69E+06	5.13E+06	6.69E+06	5.96E+06	5.77E+06
	3	5.68E+06	5.06E+06	3.73E+06	4.03E+06	4.41E+06	3.93E+06	5.29E+06	4.64E+06	4.55E+06
	1	4.76E+06	4.13E+06	2.88E+06	3.19E+06	3.56E+06	3.13E+06	4.32E+06	3.75E+06	3.76E+06
	0.5	3.95E+06	3.31E+06	2.22E+06	2.49E+06	2.82E+06	2.45E+06	3.47E+06	3.00E+06	3.06E+06
	0.3	3.04E+06	2.40E+06	1.57E+06	1.78E+06	2.03E+06	1.76E+06	2.53E+06	2.21E+06	2.31E+06
	0.1	2.49E+06	1.83E+06	1.22E+06	1.36E+06	1.57E+06	1.36E+06	1.93E+06	1.76E+06	1.86E+06
37 °C	25	4.21E+06	2.93E+06	2.80E+06	3.39E+06	3.41E+06	3.23E+06	3.53E+06	4.07E+06	3.85E+06
	15	3.90E+06	2.65E+06	2.48E+06	3.08E+06	3.13E+06	2.95E+06	3.24E+06	3.76E+06	3.58E+06
	10	3.02E+06	1.98E+06	1.81E+06	2.32E+06	2.38E+06	2.22E+06	2.45E+06	2.93E+06	2.80E+06
	5	2.29E+06	1.46E+06	1.30E+06	1.71E+06	1.77E+06	1.63E+06	1.82E+06	2.26E+06	2.16E+06
	3	1.55E+06	9.71E+05	8.33E+05	1.12E+06	1.16E+06	1.07E+06	1.20E+06	1.61E+06	1.49E+06
	1	1.11E+06	6.56E+05	5.37E+05	7.71E+05	8.12E+05	7.26E+05	8.32E+05	1.26E+06	1.09E+06
	0.5	8.22E+05	4.95E+05	3.96E+05	5.59E+05	5.90E+05	5.30E+05	6.16E+05	1.02E+06	8.19E+05
	0.3	5.74E+05	3.59E+05	2.79E+05	3.90E+05	4.08E+05	3.71E+05	4.32E+05	7.90E+05	5.82E+05
	0.1	4.36E+05	2.92E+05	2.17E+05	2.97E+05	3.07E+05	2.68E+05	3.28E+05	6.74E+05	4.47E+05

M-1 unconditioned mixtures dynamic modulus values (Kpa)

		M1-0%			M1-0.5%			M1-1%		
	Freq. Hz	S9	S15	S17	S32	S35	S36	S39	S40	S41
4 °C	25	2.08E+07	1.89E+07	1.89E+07	1.84E+07	1.90E+07	1.93E+07	1.91E+07	1.88E+07	1.82E+07
	15	2.04E+07	1.84E+07	1.84E+07	1.79E+07	1.86E+07	1.88E+07	1.87E+07	1.83E+07	1.78E+07
	10	1.94E+07	1.72E+07	1.72E+07	1.69E+07	1.75E+07	1.73E+07	1.75E+07	1.70E+07	1.66E+07
	5	1.84E+07	1.59E+07	1.59E+07	1.57E+07	1.63E+07	1.63E+07	1.62E+07	1.57E+07	1.54E+07
	3	1.71E+07	1.43E+07	1.42E+07	1.42E+07	1.46E+07	1.44E+07	1.45E+07	1.40E+07	1.38E+07
	1	1.61E+07	1.30E+07	1.29E+07	1.30E+07	1.34E+07	1.30E+07	1.31E+07	1.27E+07	1.25E+07
	0.5	1.50E+07	1.17E+07	1.15E+07	1.19E+07	1.22E+07	1.17E+07	1.18E+07	1.14E+07	1.13E+07
	0.3	1.36E+07	1.00E+07	9.89E+06	1.05E+07	1.06E+07	9.91E+06	1.01E+07	9.77E+06	9.85E+06
	0.1	1.25E+07	8.83E+06	8.71E+06	9.76E+06	9.46E+06	8.58E+06	8.82E+06	8.51E+06	8.91E+06
21 °C	25	1.25E+07	9.40E+06	9.53E+06	8.35E+06	9.31E+06	1.01E+07	9.29E+06	9.25E+06	9.34E+06
	15	1.21E+07	8.99E+06	9.05E+06	7.95E+06	8.88E+06	9.65E+06	8.85E+06	8.81E+06	8.93E+06
	10	1.09E+07	7.74E+06	7.78E+06	6.81E+06	7.69E+06	8.39E+06	7.67E+06	7.60E+06	7.66E+06
	5	9.85E+06	6.60E+06	6.63E+06	5.77E+06	6.63E+06	7.41E+06	6.61E+06	6.49E+06	6.51E+06
	3	8.49E+06	5.23E+06	5.28E+06	4.55E+06	5.36E+06	5.82E+06	5.36E+06	5.16E+06	5.16E+06
	1	7.54E+06	4.31E+06	4.38E+06	3.76E+06	4.52E+06	4.86E+06	4.53E+06	4.26E+06	4.27E+06
	0.5	6.64E+06	3.48E+06	3.56E+06	3.06E+06	3.80E+06	4.00E+06	3.81E+06	3.47E+06	3.47E+06
	0.3	5.58E+06	2.59E+06	2.67E+06	2.31E+06	3.00E+06	3.03E+06	3.01E+06	2.59E+06	2.63E+06
	0.1	4.89E+06	2.05E+06	2.14E+06	1.86E+06	2.52E+06	2.39E+06	2.51E+06	2.04E+06	2.12E+06
37 °C	25	6.38E+06	4.21E+06	4.36E+06	3.85E+06	3.66E+06	4.51E+06	3.65E+06	3.13E+06	4.08E+06
	15	6.11E+06	3.86E+06	4.05E+06	3.58E+06	3.38E+06	4.25E+06	3.36E+06	2.82E+06	3.81E+06
	10	5.22E+06	2.97E+06	3.18E+06	2.80E+06	2.59E+06	3.39E+06	2.58E+06	2.12E+06	2.97E+06
	5	4.43E+06	2.25E+06	2.45E+06	2.16E+06	1.95E+06	2.65E+06	1.94E+06	1.57E+06	2.28E+06
	3	3.54E+06	1.51E+06	1.68E+06	1.49E+06	1.32E+06	1.86E+06	1.31E+06	1.07E+06	1.57E+06
	1	2.94E+06	1.08E+06	1.22E+06	1.09E+06	9.31E+05	1.36E+06	9.34E+05	7.44E+05	1.13E+06
	0.5	2.44E+06	7.87E+05	9.08E+05	8.19E+05	6.97E+05	1.03E+06	7.01E+05	5.48E+05	8.42E+05
	0.3	1.90E+06	5.54E+05	6.35E+05	5.82E+05	4.92E+05	7.22E+05	4.95E+05	3.95E+05	5.93E+05
	0.1	1.59E+06	4.24E+05	4.75E+05	4.47E+05	3.85E+05	5.53E+05	3.83E+05	3.14E+05	4.55E+05

Specimens information for dynamic modulus test

J1-0% Mixtures	Moisture-Conditioned Samples			Unconditioned Samples		
Sample Identification	S14	S8	S19	S10	S16	S18
Diameter (D), mm	99.82	99.67	99.81	99.81	99.72	99.74
Thickness (t), mm	148.39	148.52	148.53	148.46	148.35	148.35
Dry Mass in Air (A), g	2622.5	2623.6	2626.1	2620.5	2622.7	2626.8
SSD Mass (B), g	2636	2646.1	2640	2632.2	2633.6	2640.3
Submerged Mass (C), g	1491.4	1504.5	1495.6	1487.6	1494	1497.2
Bulk Specific Gravity (G_{mb}=A/E)	2.291	2.298	2.295	2.289	2.301	2.298
Maximum Specific Gravity (G_{mm})	2.471	2.471	2.471	2.471	2.471	2.471
% Air Voids [$Pa=100(G_{mm}-G_{mb})/G_{mm}$]	7.3	7.0	7.1	7.3	6.9	7.0
Volume of Air Voids (Va=PaE/100), cm^3	84.46	81.24	82.86	85.30	79.47	81.13
Vacuum Saturation Condition						
SSD Mass, g	2683.8	2686.7	2688.1	Not Applicable		
Volume of Absorbed Water, cm^3	61.3	63.1	62			
% Saturation	73	78	75			

J1-0.5% Mixtures	Moisture-Conditioned Samples			Unconditioned Samples		
Sample Identification	S20	S22	S25	S21	S23	S24
Diameter (D), mm	99.25	99.65	99.69	99.68	99.65	99.71
Thickness (t), mm	148.71	148.43	148.14	148.33	148.27	148.38
Dry Mass in Air (A), g	2621.2	2626.7	2624.3	2625.4	2619.2	2625.3
SSD Mass (B), g	2633.5	2638.7	2638.4	2639.6	2630	2636.9
Submerged Mass (C), g	1487.4	1492.8	1493.4	1492.8	1484	1494.1
Bulk Specific Gravity (G_{mb}=A/E)	2.2287	2.292	2.292	2.289	2.286	2.297
Maximum Specific Gravity (G_{mm})	2.471	2.471	2.471	2.471	2.471	2.471
% Air Voids [$Pa=100(G_{mm}-G_{mb})/G_{mm}$]	7.4	7.2	7.2	7.4	7.5	7.0
Volume of Air Voids (Va=PaE/100), cm^3	85.61	83.69	83.74	85.05	86.76	81.43
Vacuum Saturation Condition						
SSD Mass, g	2680.9	2688.9	2682.5	Not Applicable		
Volume of Absorbed Water, cm^3	59.7	62.2	58.2			
% Saturation	70	74	70			

J1-1% Mixtures	Moisture-Conditioned Samples			Unconditioned Samples		
Sample Identification	S30	S27	S29	S26	S28	S31
Diameter (D), mm	99.79	99.68	99.62	99.87	99.88	99.81
Thickness (t), mm	148.40	148.39	148.64	148.11	148.37	148.31
Dry Mass in Air (A), g	2622.4	2624.5	2627.2	2625.6	2624.8	2626.9
SSD Mass (B), g	2635.5	2634.8	2638.2	2637.4	2640.8	2639.3
Submerged Mass (C), g	1491.6	1489.7	1494.7	1493.1	1494.6	1494.1
Bulk Specific Gravity (G_{mb}=A/E)	2.293	2.292	2.298	2.295	2.290	2.294
Maximum Specific Gravity (G_{mm})	2.471	2.471	2.471	2.471	2.471	2.471
% Air Voids [$Pa=100(G_{mm}-G_{mb})/G_{mm}$])	7.2	7.2	7.0	7.1	7.3	7.2
Volume of Air Voids (Va=PaE/100), cm^3	83.80	83.87	81.20	82.83	85.12	83.15
Vacuum Saturation Condition						
SSD Mass, g	2681	2686.3	2688.8	Not Applicable		
Volume of Absorbed Water, cm^3	58.6	61.8	61.6			
% Saturation	70	74	76			

M1-0% Mixtures	Moisture-Conditioned Samples			Unconditioned Samples		
Sample Identification	S11	S12	S13	S9	S15	S17
Diameter (D), mm	99.61	99.69	99.78	99.69	99.68	99.94
Thickness (t), mm	148.49	148.31	148.47	148.61	148.48	148.26
Dry Mass in Air (A), g	2620.8	2619.2	2621.7	2620.9	2624.8	2621.9
SSD Mass (B), g	2635.2	2634.2	2634	2642.9	2638.5	2635.1
Submerged Mass (C), g	1493.3	1493.6	1491.5	1499.1	1494.4	1492.8
Bulk Specific Gravity (G_{mb}=A/E)	2.295	2.296	2.295	2.291	2.294	2.295
Maximum Specific Gravity (G_{mm})	2.471	2.471	2.471	2.471	2.471	2.471
% Air Voids [$Pa=100(G_{mm}-G_{mb})/G_{mm}$])	7.1	7.1	7.1	7.3	7.2	7.1
Volume of Air Voids (Va=PaE/100), cm^3	82.33	81.79	82.79	84.26	82.87	82.67
Vacuum Saturation Condition						
SSD Mass, g	2678.2	2681.2	2679.8	Not Applicable		
Volume of Absorbed Water, cm^3	57.4	62	58.1			
% Saturation	70	76	70			

M1-0.5% Mixtures	Moisture-Conditioned Samples			Unconditioned Samples		
Sample Identification	S33	S34	S37	S32	S35	S36
Diameter (D), mm	99.76	99.88	99.74	99.92	99.89	99.78
Thickness (t), mm	148.28	148.31	148.56	148.49	148.54	148.55
Dry Mass in Air (A), g	2626.1	2628.3	2623.8	2624.2	2627.6	2627
SSD Mass (B), g	2637.6	2643.2	2640.3	2637	2642.6	2641.7
Submerged Mass (C), g	1488.6	1498.6	1496.2	1488.6	1496.8	1496.7
Bulk Specific Gravity (G_{mb}=A/E)	2.286	2.296	2.293	2.285	2.293	2.294
Maximum Specific Gravity (G_{mm})	2.471	2.471	2.471	2.471	2.471	2.471
% Air Voids [$Pa=100(G_{mm}-G_{mb})/G_{mm}$])	7.5	7.1	7.2	7.5	7.2	7.2
Volume of Air Voids (Va=PaE/100), cm^3	86.94	82.13	83.42	87.56	83.70	83.01
Vacuum Saturation Condition						
SSD Mass, g	2689.5	2689.9	2690.2	Not Applicable		
Volume of Absorbed Water, cm^3	63.4	61.6	64.4			
% Saturation	73	75	80			

M1-1% Mixtures	Moisture-Conditioned Samples			Unconditioned Samples		
Sample Identification	S38	S42	S43	S39	S40	S41
Diameter (D), mm	99.83	99.82	99.86	99.55	99.66	99.72
Thickness (t), mm	148.53	148.42	148.32	148.60	148.46	148.44
Dry Mass in Air (A), g	2624.5	2622	2627.4	2625	2624.8	2628.2
SSD Mass (B), g	2639.7	2632.1	2640.5	2637.8	2641.2	2641
Submerged Mass (C), g	1496.1	1488	1496.2	1498	1496.4	1495.4
Bulk Specific Gravity (G_{mb}=A/E)	2.295	2.292	2.296	2.303	2.293	2.294
Maximum Specific Gravity (G_{mm})	2.471	2.471	2.471	2.471	2.471	2.471
% Air Voids [$Pa=100(G_{mm}-G_{mb})/G_{mm}$])	7.1	7.3	7.1	6.8	7.2	7.2
Volume of Air Voids (Va=PaE/100), cm^3	82.79	84.21	82.19	78.58	83.47	82.92
Vacuum Saturation Condition						
SSD Mass, g	2687.9	2682	2691.6	Not Applicable		
Volume of Absorbed Water, cm^3	63.4	60	64.2			
% Saturation	77	71	78			

JMP Output Result for E* Ratio Hypothesis 1

- **J1**

Effect Details
Temp.[Mix Type]&Random
Effect Test

Sum of Squares	F Ratio	DF	Prob > F
10.690970	10.9139	6	<.0001*

Denominator MS Synthesis:
Residual

LSMeans Differences Tukey HSD

Level				Least Sq Mean
[J1-0.5%]37 °C	A			2.1455556
[J1-0%]37 °C	A	B		1.6044444
[J1-0.5%]21 °C		B	C	1.2777778
[J1-1%]37 °C		B	C	1.1244444
[J1-0%]21 °C			C	0.9800000
[J1-0.5%]4°C			C	0.9011111
[J1-0%]4°C			C	0.8755556
[J1-1%]21 °C			C	0.8333333
[J1-1%]4°C			C	0.8044444

Levels not connected by same letter are significantly different.

Mix Type Effect Test

Sum of Squares	F Ratio	DF	Prob > F
3.6746963	0.9470	2	0.4322

Denominator MS Synthesis:
Temp.[Mix Type]&Random+Freq.[Mix Type]&Random-1*Residual

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
J1-0%	1.1533333	0.26805769	1.15333
J1-0.5%	1.4414815	0.26805769	1.44148
J1-1%	0.9207407	0.26805769	0.92074

LSMeans Differences Tukey HSD
α=0.050 Q=2.94007
LSMean[i] By LSMean[j]

Level		Least Sq Mean
J1-0.5%	A	1.4414815
J1-0%	A	1.1533333
J1-1%	A	0.9207407

Levels not connected by same letter are significantly different.

- **M1**

Effect Details

Mix Type

Effect Test

Sum of Squares	F Ratio	DF	Prob > F
0.11674321	0.0946	2	0.9111

Denominator MS Synthesis:
Temp.[Mix Type]&Random+Freq.[Mix Type]&Random-1*Residual

LSMeans Differences Tukey HSD

α=0.050 Q=3.09319

LSMean[i] By LSMean[j]

Level		Least Sq Mean
M1-0%	A	1.0755556
M1-0.5%	A	1.0696296
M1-1%	A	0.9922222

Levels not connected by same letter are significantly different.

Temp.[Mix Type]&Random

Effect Test

Sum of Squares	F Ratio	DF	Prob > F
3.7506074	14.5326	6	<.0001*

Denominator MS Synthesis: Residual

LSMeans Differences Tukey HSD

α=0.050 Q=3.24723

LSMean[i] By LSMean[j]

Level				Least Sq Mean
[M1-0%]37 °C	A			1.4955556
[M1-1%]37 °C	A	B		1.2455556
[M1-0.5%]37 °C	A	B		1.2388889
[M1-0.5%]21 °C		B	C	1.0600000
[M1-0.5%]4°C			C	0.9100000
[M1-1%]21 °C			C	0.8888889
[M1-0%]21 °C			C	0.8822222
[M1-0%]4°C			C	0.8488889
[M1-1%]4°C			C	0.8422222

Levels not connected by same letter are significantly different.

JMP Output Result for E* Ratio Hypothesis 2

- **J1-0.5% vs. M1-0.5%**

Effect Details

Mix Type

Effect Test

Sum of Squares	F Ratio	DF	Prob > F
1.8666963	0.8672	1	0.3961

Denominator MS Synthesis:
Freq.[Mix Type]&Random+Temp.[Mix Type]&Random-1*Residual

LSMeans Differences Student's t

α=0.050 t=2.60228

LSMean[i] By LSMean[j]

Mean[i]-Mean[j] Std Err Dif Lower CL Dif Upper CL Dif	J1-0.5%	M1-0.5%
J1-0.5%	0 0 0 0	0.37185 0.39931 -0.6673 1.41098
M1-0.5%	-0.3719 0.39931 -1.411 0.66728	0 0 0 0

Level		Least Sq Mean
J1-0.5%	A	1.4414815
M1-0.5%	A	1.0696296

Levels not connected by same letter are significantly different.

Temp. [Mix Type]&Random

Effect Test

Least Squares Means Table

LSMeans Differences Tukey HSD

α=0.050 Q=3.02917

LSMean[i] By LSMean[j]

Level			Least Sq Mean
[J1-0.5%]37 °C	A		2.1455556
[J1-0.5%]21 °C		B	1.2777778
[M1-0.5%]37 °C		B	1.2388889
[M1-0.5%]21 °C		B	1.0600000
[M1-0.5%]4°C		B	0.9100000
[J1-0.5%]4°C		B	0.9011111

Levels not connected by same letter are significantly different.

- **J1-1% vs. M1-1%**

Effect Details

Mix Type

Effect Test

Sum of Squares	F Ratio	DF	Prob > F
0.06897963	0.1998	1	0.6800

Denominator MS Synthesis:
Temp.[Mix Type]&Random+Freq.[Mix Type]&Random-1*Residual

Least Squares Means Table

LSMeans Differences Student's t

α=0.050 t=2.87683

LSMean[i] By LSMean[j]

Level		Least Sq Mean
M1-1%	A	0.99222222
J1-1%	A	0.92074074

Levels not connected by same letter are significantly different.

Temp.[Mix Type]&Random

Effect Test

Sum of Squares	F Ratio	DF	Prob > F
1.4401407	10.3292	4	<.0001*

Denominator MS Synthesis:
Residual

LSMeans Differences Tukey HSD

α=0.050 Q=3.02917

LSMean[i] By LSMean[j]

Level				Least Sq Mean
[M1-1%]37 °C	A			1.2455556
[J1-1%]37 °C	A	B		1.1244444
[M1-1%]21 °C		B	C	0.8888889
[M1-1%]4°C			C	0.8422222
[J1-1%]21 °C			C	0.8333333
[J1-1%]4°C			C	0.8044444

Levels not connected by same letter are significantly different.

JMP Output Result for IDOT E* Ratio Hypothesis 1

- **J1**

Whole Model

Summary of Fit

RSquare	0.682397
RSquare Adj	0.470662
Root Mean Square Error	0.330509
Mean of Response	1.026049
Observations (or Sum Wgts)	81

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	32	11.265788	0.352056	3.2229
Error	48	5.243348	0.109236	**Prob > F**
C. Total	80	16.509136		0.0001*

Tests wrt Random Effects

Source	SS	DF Num	F Ratio	Prob > F
Temperature[Mix Type]&Random	6.31552	6	9.6359	<.0001*
Frequency[Mix Type]&Random	3.72781	24	1.4219	0.1480
Mix Type	1.22246	2	0.5563	0.5984

Temperature [Mix Type] &Random
Effect Test

Sum of Squares	F Ratio	DF	Prob > F
6.3155185	9.6359	6	<.0001*

Denominator MS Synthesis:
Residual

Level				Least Sq Mean
[J1-0%]37 °C	A			1.6044444
[J1-0.5%]37 °C	A	B		1.5144444
[J1-1%]37 °C		B	C	1.0922222
[J1-0%]21 °C			C	0.9800000
[J1-0.5%]21 °C			C	0.8788889
[J1-0%]4°C			C	0.8755556
[J1-0.5%]4°C			C	0.8011111
[J1-1%]4°C			C	0.7877778
[J1-1%]21 °C			C	0.7000000

Levels not connected by same letter are significantly different.

Frequency [Mix Type] &Random

Effect Test

Sum of Squares	F Ratio	DF	Prob > F
3.7278074	1.4219	24	0.1480

LSMeans Differences Tukey HSD

α=0.050   Q=3.9227

LSMean[i] By LSMean[j]

Level		Least Sq Mean
[J1-0%]0.1	A	1.7633333
[J1-0.5%]0.1	A	1.6300000
[J1-0%]0.3	A	1.4500000
[J1-0.5%]0.3	A	1.3033333
[J1-0%]0.5	A	1.2633333
[J1-0%]1	A	1.1333333
[J1-0.5%]0.5	A	1.1300000
[J1-0%]3	A	1.0433333
[J1-0.5%]1	A	1.0400000
[J1-1%]0.1	A	0.9900000
[J1-0%]5	A	0.9700000
[J1-0.5%]3	A	0.9566667
[J1-0%]10	A	0.9366667
[J1-1%]0.3	A	0.9266667
[J1-0%]15	A	0.9133333
[J1-0%]25	A	0.9066667
[J1-0.5%]5	A	0.9000000
[J1-0.5%]10	A	0.8800000
[J1-1%]0.5	A	0.8766667
[J1-0.5%]15	A	0.8733333
[J1-0.5%]25	A	0.8700000
[J1-1%]1	A	0.8433333
[J1-1%]25	A	0.8333333
[J1-1%]15	A	0.8300000
[J1-1%]3	A	0.8166667
[J1-1%]10	A	0.8133333
[J1-1%]5	A	0.8100000

Levels not connected by same letter are significantly different.

Mix Type

Effect Test

Sum of Squares	F Ratio	DF	Prob > F
1.2224617	0.5563	2	0.5984

LSMeans Differences Tukey HSD

α=0.050   Q=3.00176

Level		Least Sq Mean
J1-0%	A	1.1533333
J1-0.5%	A	1.0648148
J1-1%	A	0.8600000

Levels not connected by same letter are significantly different.

- **M1**

Whole Model

Summary of Fit

RSquare	0.775741
RSquare Adj	0.626235
Root Mean Square Error	0.195921
Mean of Response	1.063704
Observations (or Sum Wgts)	81

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	32	6.3734000	0.199169	5.1887
Error	48	1.8424889	0.038385	**Prob > F**
C. Total	80	8.2158889		<.0001*

Tests wrt Random Effects

Source	SS	DF Num	F Ratio	Prob > F
Temperature[Mix Type]&Random	5.10911	6	22.1835	<.0001*
Frequency[Mix Type]&Random	0.76553	24	0.8310	0.6825
Mix Type	0.49876	2	0.2951	0.7548

Temperature [Mix Type] &Random
Effect Test

Sum of Squares	F Ratio	DF	Prob > F
5.1091111	22.1835	6	<.0001*

LSMeans Differences Tukey HSD

α=0.050 Q=3.24723

Level				Least Sq Mean
[M1-1%]37 °C	A			1.4955556
[M1-0.5%]37 °C	A			1.4600000
[M1-0%]37 °C	A	B		1.2811111
[M1-0.5%]21 °C		B	C	1.0655556
[M1-0.5%]4°C			C	0.9344444
[M1-1%]21 °C			C	0.8822222
[M1-1%]4°C			C	0.8488889
[M1-0%]4°C			C	0.8155556
[M1-0%]21 °C			C	0.7900000

Levels not connected by same letter are significantly different.

Frequency [Mix Type] &Random

Effect Test

Sum of Squares	F Ratio	DF	Prob > F
0.76553333	0.8310	24	0.6825

LSMeans Differences Tukey HSD

Level		Least Sq Mean
[M1-0.5%]0.1	A	1.3766667
[M1-0.5%]0.3	A	1.3100000
[M1-1%]0.1	A	1.2966667
[M1-0.5%]0.5	A	1.2366667
[M1-1%]0.3	A	1.2200000
[M1-0.5%]1	A	1.1700000
[M1-1%]0.5	A	1.1400000
[M1-0.5%]3	A	1.1200000
[M1-1%]1	A	1.0833333
[M1-0.5%]5	A	1.0766667
[M1-0.5%]10	A	1.0466667
[M1-1%]3	A	1.0333333
[M1-0.5%]15	A	1.0266667
[M1-0.5%]25	A	1.0166667
[M1-0%]0.1	A	1.0100000
[M1-1%]5	A	1.0000000
[M1-0%]0.3	A	0.9900000
[M1-1%]10	A	0.9800000
[M1-0%]0.5	A	0.9733333
[M1-1%]15	A	0.9666667
[M1-0%]1	A	0.9600000
[M1-1%]25	A	0.9600000
[M1-0%]10	A	0.9500000
[M1-0%]15	A	0.9466667
[M1-0%]25	A	0.9433333
[M1-0%]3	A	0.9433333
[M1-0%]5	A	0.9433333

Levels not connected by same letter are significantly different.

Mix Type

Effect Test

Sum of Squares	F Ratio	DF	Prob > F
0.49875556	0.2951	2	0.7548

LSMeans Differences Tukey HSD

α=0.050   Q=3.08245
LSMean[i] By LSMean[j]

Level		Least Sq Mean
M1-0.5%	A	1.1533333
M1-1%	A	1.0755556
M1-0%	A	0.9622222

Levels not connected by same letter are significantly different.

JMP Output Result for IDOT E* Ratio Hypothesis 2

- **J1-0.5% vs. M1-0.5%**

Whole Model
Summary of Fit

RSquare	0.706777
RSquare Adj	0.514349
Root Mean Square Error	0.283514
Mean of Response	1.109074
Observations (or Sum Wgts)	54

Tests wrt Random Effects

Source	SS	DF Num	F Ratio	Prob > F
Temperature[Mix Type]&Random	4.10343	4	12.7625	<.0001*
Frequency[Mix Type]&Random	1.99067	16	1.5479	0.1429
Mix Type	0.10578	1	0.0989	0.7678

Temperature [Mix Type] & Random
Effect Test

Sum of Squares	F Ratio	DF	Prob > F
4.1034296	12.7625	4	<.0001*

LSMeans Differences Tukey HSD

α=
0.050 Q=
3.02917
LSMean[i] By LSMean[j]

Level				Least Sq Mean
[J1-0.5%]37 °C	A			1.5144444
[M1-0.5%]37 °C	A	B		1.4600000
[M1-0.5%]21 °C		B	C	1.0655556
[M1-0.5%]4°C			C	0.9344444
[J1-0.5%]21 °C			C	0.8788889
[J1-0.5%]4°C			C	0.8011111

Levels not connected by same letter are significantly different.

Frequency [Mix Type] &Random

Effect Test

Sum of Squares	F Ratio	DF	Prob > F
1.9906741	1.5479	16	0.1429

LSMeans Differences Tukey HSD

α=0.050 Q=3.78372

Level		Least Sq Mean
[J1-0.5%]0.1	A	1.6300000
[M1-0.5%]0.1	A	1.3766667
[M1-0.5%]0.3	A	1.3100000
[J1-0.5%]0.3	A	1.3033333
[M1-0.5%]0.5	A	1.2366667
[M1-0.5%]1	A	1.1700000
[J1-0.5%]0.5	A	1.1300000
[M1-0.5%]3	A	1.1200000
[M1-0.5%]5	A	1.0766667
[M1-0.5%]10	A	1.0466667
[J1-0.5%]1	A	1.0400000
[M1-0.5%]15	A	1.0266667
[M1-0.5%]25	A	1.0166667
[J1-0.5%]3	A	0.9566667
[J1-0.5%]5	A	0.9000000
[J1-0.5%]10	A	0.8800000
[J1-0.5%]15	A	0.8733333
[J1-0.5%]25	A	0.8700000

Levels not connected by same letter are significantly different.

Mix Type

Effect Test

Sum of Squares	F Ratio	DF	Prob > F
0.10577963	0.0989	1	0.7678

Denominator MS Synthesis:
Temperature [Mix Type] &Random Frequency [Mix Type]&Random-1*Residual

LSMeans Differences Student's t

α=0.050 t=2.69461

Level		Least Sq Mean
M1-0.5%	A	1.1533333
J1-0.5%	A	1.0648148

Levels not connected by same letter are significantly different.

- **J1-1% vs. M1-1%**

Whole Model
Summary of Fit

RSquare	0.703506
RSquare Adj	0.508932
Root Mean Square Error	0.235583
Mean of Response	0.967778
Observations (or Sum Wgts)	54

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	21	4.2139556	0.200665	3.6156
Error	32	1.7759778	0.055499	**Prob > F**
C. Total	53	5.9899333		0.0005*

Tests wrt Random Effects

Source	SS	DF Num	F Ratio	Prob > F
Temperature[Mix Type]&Random	3.14909	4	14.1853	<.0001*
Frequency[Mix Type]&Random	0.4376	16	0.4928	0.9325
Mix Type	0.62727	1	0.8263	0.4184

Temperature [Mix Type] &Random
Effect Test

Sum of Squares	F Ratio	DF	Prob > F
3.1490889	14.1853	4	<.0001*

LSMeans Differences Tukey HSD

α=0.050 Q=3.02917
LSMean[i] By LSMean[j]

Level				Least Sq Mean
[M1-1%]37 °C	A			1.4955556
[J1-1%]37 °C		B		1.0922222
[M1-1%]21 °C		B	C	0.8822222
[M1-1%]4°C		B	C	0.8488889
[J1-1%]4°C		B	C	0.7877778
[J1-1%]21 °C			C	0.7000000

Levels not connected by same letter are significantly different.

Frequency [Mix Type] &Random

Effect Test

Sum of Squares	F Ratio	DF	Prob > F
0.43760000	0.4928	16	0.9325

LSMeans Differences Tukey HSD

α=0.050 Q=3.78372

Level		Least Sq Mean
[M1-1%]0.1	A	1.2966667
[M1-1%]0.3	A	1.2200000
[M1-1%]0.5	A	1.1400000
[M1-1%]1	A	1.0833333
[M1-1%]3	A	1.0333333
[M1-1%]5	A	1.0000000
[J1-1%]0.1	A	0.9900000
[M1-1%]10	A	0.9800000
[M1-1%]15	A	0.9666667
[M1-1%]25	A	0.9600000
[J1-1%]0.3	A	0.9266667
[J1-1%]0.5	A	0.8766667
[J1-1%]1	A	0.8433333
[J1-1%]25	A	0.8333333
[J1-1%]15	A	0.8300000
[J1-1%]3	A	0.8166667
[J1-1%]10	A	0.8133333
[J1-1%]5	A	0.8100000

Levels not connected by same letter are significantly different.

Mix Type

Effect Test

Sum of Squares	F Ratio	DF	Prob > F
0.62726667	0.8263	1	0.4184

LSMeans Differences Student's t

α=0.050 t=2.86229

LSMean[i] By LSMean[j]

Level		Least Sq Mean
M1-1%	A	1.0755556
J1-1%	A	0.8600000

Levels not connected by same letter are significantly different.

APPENDIX D. HAMBURG WHEEL TRACK TESTING RESULTS

Hamburg wheel track test result summary

Additive Type	Specimen ID	Air Voids	Creep Slope	Average	Stdev.	95% CI	SIP	Stripping Slope	Rut Depth at 20000 Passes	Average	Stdev.	95% CI
Control	S1	7.2	-1.40E-04	-1.55E-04	7.06E-05	4.17E-05	N/A	N/A	-5.84	-5.38	1.49713	0.884734
Control	S5	7.5	**-2.92E-04**				N/A	N/A	**-8.64**			
Control	S6	7.5	-1.73E-04				N/A	N/A	-5.73			
Control	S7	7.5	-2.93E-04				N/A	N/A	**-7.48**			
Control	S8	6.9	-1.37E-04				N/A	N/A	-4.80			
Control	S9	7.0	-1.90E-04				N/A	N/A	-6.27			
Control	S10	7.1	-1.14E-04				N/A	N/A	-4.02			
Control	S11	7.2	**-8.61E-05**				N/A	N/A	-4.23			
Control	S12	6.7	-1.05E-04				N/A	N/A	-4.28			
Control	S13	7.1	-1.32E-04				N/A	N/A	-5.21			
Control	S14	7.5	-1.01E-04				N/A	N/A	**-3.85**			
Control	S15	7.2	-1.03E-04				N/A	N/A	-4.21			
J1-0.5%	S16	7.0	-8.64E-05	-7.67E-05	9.96E-06	8.73E-06	N/A	N/A	**-3.75**	-3.40	0.34157	0.299395
J1-0.5%	S17	7.0	-8.12E-05				N/A	N/A	-3.67			
J1-0.5%	S18	7.3	**-6.06E-05**				N/A	N/A	**-2.93**			
J1-0.5%	S19	6.7	-8.60E-05				N/A	N/A	-3.63			
J1-0.5%	S20	6.5	-7.10E-05				N/A	N/A	-3.06			
J1-0.5%	S21	6.7	-7.50E-05				N/A	N/A	-3.36			
J1-1%	S22	6.7	-8.31E-05	-8.92E-05	8.65E-06	7.58E-06	N/A	N/A	-3.42	-3.41	0.56771	0.497614
J1-1%	S23	6.6	-8.62E-05				N/A	N/A	-3.59			
J1-1%	S24	6.7	-9.11E-05				N/A	N/A	-3.63			
J1-1%	S25	7.0	-9.46E-05				N/A	N/A	**-4.04**			
J1-1%	S26	7.1	**-7.79E-05**				N/A	N/A	**-2.35**			
J1-1%	S27	7.3	**-1.02E-04**				N/A	N/A	-3.44			
M1-0.5%	S28	7.5	-7.52E-05	-7.37E-05	3.67E-06	3.22E-06	N/A	N/A	-3.52	-3.35	0.18854	0.165263
M1-0.5%	S29	7.1	**-6.85E-05**				N/A	N/A	-3.45			
M1-0.5%	S30	6.9	**-7.95E-05**				N/A	N/A	**-3.09**			
M1-0.5%	S31	7.1	-7.33E-05				N/A	N/A	-3.25			
M1-0.5%	S32	7.1	-7.40E-05				N/A	N/A	**-3.56**			
M1-0.5%	S33	7.3	-7.15E-05				N/A	N/A	-3.23			
M1-1%	S34	7.0	**-6.89E-05**	-7.66E-05	6.79E-06	5.95E-06	N/A	N/A	-3.07	-3.30	0.23855	0.209093
M1-1%	S35	6.5	**-6.85E-05**				N/A	N/A	**-3.02**			
M1-1%	S36	7.2	**-8.43E-05**				N/A	N/A	-3.44			
M1-1%	S37	7.4	-8.23E-05				N/A	N/A	**-3.55**			
M1-1%	S38	6.8	-7.54E-05				N/A	N/A	-3.19			
M1-1%	S39	7.4	-8.00E-05				N/A	N/A	**-3.55**			

[a] The bold numbers are outliers.