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THE EFFECT OF LOOSE MIX AGING ON THE PERFORMANCE PROPERTIES OF WARM ASPHALTS

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ABSTRACT OF THESIS

THE EFFECT OF LOOSE MIX AGING ON THE PERFORMANCE PROPERTIES OF WARM ASPHALTS

Recent improvements in warm mix asphalt technologies have spurred an aggressive adoption of these new practices within the asphalt paving industry. Concerns have arisen among federal and state agencies about the effects of this line of products on the performance of asphalt pavements. An investigation of the effects of lowering mixing, aging and compactions temperatures while varying the loose mix aging time was performed. Hamburg Wheel Tracking, Flow Number, Dynamic Modulus and Fracture Energy testing were used to evaluate mechanistic properties of the materials.

KEYWORDS: Asphalt, Pavements, Warm Mix Asphalt, Mechanistic Properties, Construction Materials

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May 4, 2011

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THESIS

Thomas Martin Clements

The Graduate School

University of Kentucky

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THE EFFECT OF LOOSE MIX AGING ON THE PERFORMANCE PROPERTIES OF WARM ASPHALTS

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in Civil Engineering in the College of Engineering at the University of Kentucky

By

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Lexington, Kentucky

Director: Dr. Kamyar Mahboub, University of Kentucky, Lexington, KY

2011

DISCLAIMER

The contents of this report reflect the views of the author, who is responsible for the facts and the accuracy of the data presented within. The contents do not necessarily reflect the official views and policies of the Federal Highway Administration (FHWA) of the Kentucky Department of Transportation (KYTC). The report does not constitute a standard, specification or regulation. Neither the authors nor the United States government endorse products or manufacturers. The names of companies or equipment manufacturers are included herein only because they are considered essential to the objectives of this report.

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Chapter 1: Introduction

Over the past several years concerns have arisen over emissions associated with hot mix asphalt production and placement and their role in climate change. In response to these concerns and rising energy cost, technologies which allow lower mixing and placement temperatures have garnered more attention. Hot Mix Asphalt (HMA) is typically produced at a mixing temperature between 280^{o}F (138^{o}C) and 320^{o}F (160^{o}C). This temperature is necessary to dry the aggregate, achieve adequate aggregate coating and to provide a sufficient amount of time for the mixed material to be transported and properly compacted. Warm Mix Asphalt (WMA) is the term used to describe the growing field of products and practices which lower the mixing/compaction temperatures of asphalt from 30^{o}F (16^{o}C) to as much as 100^{o}F (38^{o}C).

This reduction in mixing and compaction temperatures provides many benefits for both the contractor and the environment. Lower mixing temperatures at the plant will reduce energy consumption and plant emissions. In addition to this, the lower compaction temperature could potentially allow for longer haul distances, improvements in late season paving quality, increases in plant and labor productivity and the possibility of adding more recycled asphalt pavement (RAP) to the mix. These benefits have been the driving force in the adoption of these relatively new technologies by the construction community.

Although it is exciting to see the construction industry readily adopting new technologies, the knowledge base behind these products and processes is not sufficient considering the rapidly increasing rate at which they are being implemented.

There is reason to believe that lowering the mixing temperature of the asphalt mix could also improve pavement performance. Much of the aging of the asphalt binder occurs in the plant when it is exposed to elevated temperatures. Research has shown that the addition of additives which increase workability may also increase in-place density (Hurley and Prowell 2006). Increases in density have been shown to improve pavement performance (Rowe, et al. 2009) Additionally, lowering the mixing temperatures should cause the binder to experience less aging and undergo less oxidative hardening which should produce a more flexible pavement and could possibly extend the life of the pavement. The reduction of stiffness in the material although good for fatigue life, increases the materials susceptibility to rutting.

The goal of this research is to gain a greater understanding of the initial performance differences between regular HMA and WMA by conducting laboratory induced aging. This would allow a measured performance prediction for WMA.

In order to achieve this goal, hot and warm asphaltic concrete mixtures were tested in order to determine and compare their performance characteristics. Particular emphasis was placed on evaluating the stiffness, rutting potential and low-temperature fracture properties. Dynamic Modulus, Flow Number, Hamburg Wheel-Tracking, and Disk Shaped Compact Tension tests were selected. This suite of testing provides a good overall material characterization and met the approval of the Federal Highway Administration.

Chapter 2: Literature Review

The literature review conducted in this research revealed that implantation of warm mix technology is becoming quite widespread. States, producers and contractors have shown a willingness to adopt these new technologies because of the potential benefits. The three primary means by which warm and hot mix asphaltic concretes have been compared are the production and materials costs, the amount of emissions released, and the differences in performance in both the field and in the laboratory.

2.1 Economics of WMA

At this point, the primary cost comparisons between WMA and HMA which have been researched are based on two factors: cost of additives/plant modifications, and the cost savings from the reduction in fuel consumption.

The estimated fuel cost savings per ton from Kristjánsdóttir's operational cost comparisons based on energy consumption and price (Kristjánsdóttir, et al. 2007) are summarized in the following table.

Table 2.1: Estimated Fuel Cost Savings

Fuel	# 2 Oil	Diesel	Natural Gas
Reduction in Fuel Use			
20%	$1.00-$1.5	$0.88-$1.80	$0.38-$0.52
35%	$1.75-$2.63	$1.54-$3.15	$0.66-$0.92
50%	$2.50-$3.75	$2.20-$4.50	$0.94-$1.31

The actual fuel cost savings will vary heavily on the fuel being used in the plant and the reduction in mixing temperature which can be achieved.

Middleton provides approximations for the costs of various additives in their research and puts the cost of most WMA additives between $2.00 and $4.00 per ton (Middleton and Forfylow 2008). Looking at the potential fuel cost savings and the costs of current WMA technologies, the price of the WMA additives will be offset by or exceed the savings due to reductions in fuel consumption.

It should be noted that these studies do not account for possible but less quantifiable benefits of WMA such as: allowing for the addition of more recycled asphalt pavement in the mix, worker and plant productivity improvements, extended haul distances, possible reduction of compaction demand, and improved late season paving. It is possible that these additional benefits will outweigh the costs of the WMA additives for producers.

2.2 Emissions

The emissions data which have been collected suggest a consistent reduction in greenhouse gas emissions with the use of warm mix technologies. The extent, to which the emissions are reduced, like the fuel savings, is directly related to the temperature reductions in the plant (D'Angelo, et al. 2008).

The emissions reductions could also become a competitive advantage by allowing for the placement of asphalt plants in air quality non-attainment areas as declared by the Environmental Protection Agency, where they were previously prohibited. Furthermore, the plant would be more resilient to the effects of a carbon tax or cap and trade system if one were to be legislated.

2.3 Performance

As the asphalt industry continues to adopt new warm mix technologies there will be a continued need for research to evaluate these new products and processes through both field and laboratory testing.

One of the primary concerns with WMA materials is that they will increase the rutting potential of mixtures due to their reduced stiffness. Lab test have consistently indicated an increased potential for rutting which is particularly evident in Hamburg Wheel Tracking testing. Differences in dynamic modulus of WMA and HMA have for the most part shown no significant statistical differences (Hurley and Prowell 2006). Another concern is increased stripping susceptibility due to the potential for the presence of residual moisture in the mixtures caused by lower mixture production temperature. Thus far, limited laboratory studies have been completed which would accurately model this issue, largely due in fact to the use of dried aggregate within laboratory settings. Although tests have indicated an increased susceptibility to rutting and stripping, field trials are yet to be conducted (Button, Estakhri and Wmsatt 2007).

Chapter 3: Materials Selection

The materials used in this study were chosen with the goal of providing an accurate representation of Kentucky asphalt highways with average annual traffic of less than 3 million Equivalent Single Axle Loads (ESAL). In order to accomplish this, a standard 9.5mm nominal maximum aggregate size mixture was selected as shown in Table 3.1. This mixture is commonly used as a surface layer by the Kentucky Transportation Cabinet and should produce a mix representative of many of Kentucky's pavements. A Performance Grade (PG) 64-22, which is the most common asphalt binder used in KY, was selected as the laboratory standard binder. By using the combination of 9.5mm nominal maximum aggregate size mixture and PG 64-22 asphalt binder, a representative Kentucky mixture was produced for initial laboratory testing.

The job mix formula chosen for the initial laboratory testing was a Kentucky Class 2 Asphalt Surface placed on non-primary routes with up to 3 million ESALS. The job mix formula was comprised of a combination of limestone from Harrod Stone in Frankfort and natural sand from Nugent Sand in Louisville. The aggregate combinations and job mix formula are presented in Table 3.1.

The Superpave type mixture was designed by Frankfort Testing Laboratory at 75 gyrations. The mixture design properties are provided in Table 3.2. The G_{mm} was verified using the PG 64-22 and determined to be 2.521. This G_{mm} was used for preparing the performance test specimens discussed later

Table 3.1: Aggregate Stockpile Percentages and JMF

Aggregate Type	G_{sb}	Percent of Total
Limestone #8's	2.700	25
Limestone Sand (Unwashed)	2.680	26
Limestone Sand (Washed)	2.690	34
Natural Sand	2.600	15

Sieve No.	Sieve Size, mm	Percent Passing
1/2”	12.5	100
3/8”	9.5	95
#4	4.75	73
#8	2.36	49
#16	1.18	32
#30	0.60	19
#50	0.30	10
#100	0.15	7
#200	0.075	6.0

Table 3.2: Mixture Design Properties

Mixture Property	Design Value
Coarse Aggregate Angularity (%)	100/100
Fine Aggregate Angularity, %	43
Flat & Elongated Particles, %	1
Clay Content (SE) , %	84
Voids Filled with Asphalt (VFA), %	73.0
Voids in the Mineral Aggregate	15.2
Dust to Asphalt Ratio (D/A)	1.3
G_{mm} @ $N_{initial}$, %	87.2
G_{mm} @ N_{max}, %	97.1
Air Voids, %	4.0
Unit Weight (lb/ft^3)	149.8
AC, %	5.4
Effective AC, %	4.8
Maximum Specific Gravity (Gmm)	2.521
Absorbed AC (Mix) , %	0.64
Gsb	2.68
Gse	2.724
Film Thickness, µm	8.5

The Kentucky Transportation Cabinet selected the type of WMA technology which was used in this study. The chemical additive which was selected reduces the temperatures generally required to overcome the difference in polarity between the aggregate and the asphalt (these temperatures are necessary to achieve adequate coating and allow for compaction), by the use of a surfactant. The surfactant achieves these results by reducing both the interfacial tension between the oil and aggregate and the surface tension of the oil. The chemical additive can be blended directly with the asphalt binder prior to mixing with the aggregate. This process required a very small change of procedure in the specimen production process. This product has similar advantages in HMA plants as it requires minimal modifications and currently offers one of the most significant temperature reductions on the market.

Chapter 4: A Brief Description of Laboratory Protocols

In order to assure accuracy of experimental results a series of laboratory protocols were followed for mixture, specimen and individual test preparation. The following provides a brief description of those processes and protocols.

4.1 Mixture Preparation

Prior to mixing with aggregate, the binder was heated to the point at which it would flow and then poured from the 1.89L (5gal) container it arrived in into 0.95L (1qt) cans and allowed to cool. This was done for safety and convenience in the mixing process. Asphalt binder which was going have the WMA chemical added to it was later reheated to 130^{o}C (266^{o}F) and the WMA chemical was added to the binder at 0.5% by weight of binder (in accordance with manufacturer specifications). The additive and binder were blended using the Ross Mixer. Asphalt and additive were blended at a speed of 1000 rpm for a period of 30 minutes to ensure complete blending of the additive. These specifications met the recommendations set forth by the manufacturer for preparing chemical treated binder.

Aggregate and asphalt were heated to 154^{o}C (310^{o}F) and 132^{o}C (270^{o}F) for the hot and warm mixes respectively. Blending was done at a speed of 40 rpm using the Binder-Aggregate mixer listed below, with the blending time ranging between 1-2 minutes depending on the time required to achieve adequate aggregate coating.

4.1.1 Mixture Preparation Equipment

Ross Mixer

The manufacturer's instruction for the blending of the WMA chemical additive required the use of an overhead mixer. The mixer used for blending the asphalt and additive in this study was a ROSS HSM-100LC Mixer/Emulsifier. The mixer was equipped with a metal impeller to be used as the stirrer and was capable of a rotational speed between 500 and 10,000 rpm. The capacity of the mixing vessel was 0.95L (1qt).

Binder-Aggregate Mixer

AASHTO T 312-09 "Preparing and Determining the Density of Hot Mix Asphalt Specimens by means of the Superpave Gyratory Compactor" allows the binder and aggregate to blended by hand or to be blended by a mechanical mixer. A Hobart A-120T Mixer was available for use at the Asphalt Institute and became the chosen method for mixing due to its ease of use and mixing consistency. The mixer had a maximum capacity of 11.36L (12qt) and was capable of a mixing speed between 30 and 200 rpm.

4.2 Specimen Preparation

To fabricate the specimens the Superpave Gyratory Compactor (SGC) was used at a constant height. The mass of the mix was varied from 7160 (15.79) to 7280g (16.04lb) to account for the effects of aging on the compaction of the mixtures. All specimens were compacted to an Air Voids of (6.5%-7.5%) in accordance with FHWA requests. The aggregates and asphalt were mixed and aged according to AASHTO R30, Mixture Conditioning of Hot-Mix Asphalt.

An aging and compaction temperature of 135°C (275°F) was used for the control mix while an aging and compaction temperature of 114°C (240°F) was used for the mix containing the chemical additive.

All specimens were compacted into a cylindrical shape with a height of 180mm (7.09in) and diameter of 150mm (5.91in) using the SGC, except those to be used for Hamburg Wheel Tracking testing. Hamburg Wheel Tracking test specimens were compacted to 100mm (3.94in) in accordance with AASHTO T 324-04 "Hamburg Wheel-track Testing of Compacted Hot Mix Asphalt" and required 2443g (5.39lb) of loose mix asphaltic concrete to meet air voids requirements. The number of gyrations necessary to compact the specimens varied from 20 to 60.

After specimens were compacted they were removed from the SGC, labeled, and allowed to cool for 24 hours prior to undergoing final preparations for their respective test.

After specimens were cut and cored into their testing configurations the air voids were obtained though AASHTO T 209 "Theoretical Maximum Specific Gravity and Density of Hot Mix Asphalt" and AASHTO T 166 "Bulk Specific Gravity of Hot Mix Asphalt Using Surface Saturated-Dry Specimens."

4.2.1 Equipment Used in Specimen Preparation

Superpave Gyratory Compactor

For compaction of the asphaltic mixtures the SGC was used. ASM T 312-09 "Preparing and Determining the Density of Hot Mix Asphalt Specimens by means of the Superpave Gyratory Compactor" specifies the requirements for the SGC. For this study a Pine model AFG1 SGC which conforms to these specifications was used.

The molds used for the compaction process had an internal diameter of 150mm (5.91in) and internal height of 250mm (9.84in). The SGC compacts the specimen by applying pressure perpendicular to the cylindrical axis of the specimen while gyrating at an angle throughout the compaction process.

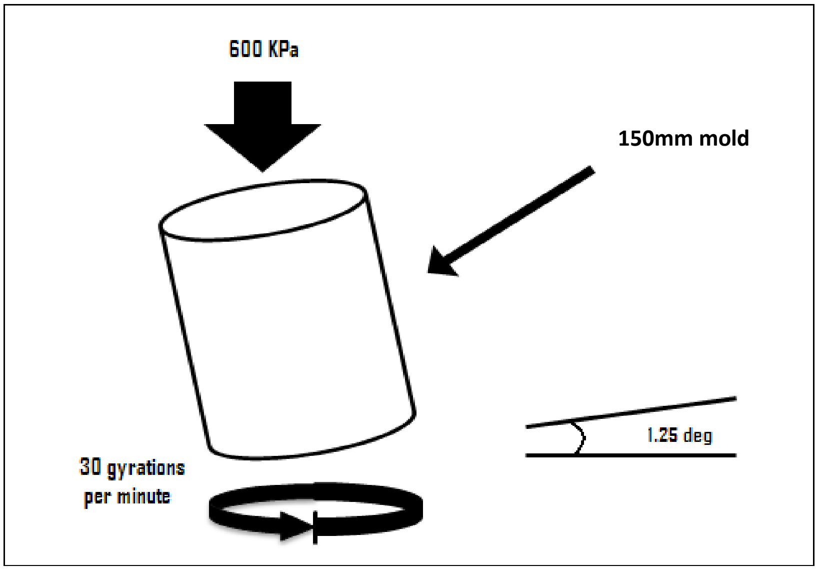

Figure 4.1: Superpave Gyratory Compactor

4.3 Dynamic Modulus and Flow Number Testing

Dynamic modulus is a performance property used for characterization of viscoelastic materials which represents the ratio of the stress to the strain. For HMA mixes it is a useful property for evaluating the stiffness of a material and can be used in pavement and mix designs. Generally speaking, a higher dynamic modulus is associated with a stiffer asphalt layer which will show greater resistance to rutting but will be more susceptible to low temperature cracking.

The Flow Number is a material property which characterizes the resistance of the material to permanent deformation. Flow Number can be used to design asphalt pavements and mixes with resistance to rutting. The higher the Flow Number, the more rut resistant a mixture should be.

4.3.1 Dynamic Modulus Testing

The Asphalt Mixture Performance Tester (AMPT) dynamic modulus test was performed at 0.5, 2, 4, and 8hr aging periods as suggested by FHWA staff in this study.

The AMPT was developed though NCHRP 9-19 and 9-29 specifically for the purpose of running dynamic modulus, Flow Number and static creep test. The dynamic modulus test was performed at 4°C (39^{o}F), 20°C (68^{o}F), and 40°C (104^{o}F) and at different frequencies of 25, 20, 10, 5, 2, 1, 0.5, 0.2, 0.1 Hz in accordance with AASHTO TP 62-03. Additional testing at 0.01 Hz was performed on specimens being tested at 40^{o}C (104^{o}F) in order to better define the tail of the dynamic modulus master-curves. Four replicate samples were used for each testing condition.

The dynamic modulus (E*) is defined as the ratio of the amplitude of the sinusoidal stress and the amplitude of the sinusoidal strain, as follows:

$$|E^*| = \frac{\sigma}{\varepsilon}$$

Where:

σ = the amplitude of stress
ε = the amplitude of strain

The dynamic modulus for each test condition is determined using the average amplitude of the haversine load from the load cell and the average deformation measured (strain) from each axial LVDT.

The procedure for dynamic modulus testing was as follows:

1. Cut and core the SGC compacted specimens to achieve the desired height of 150 +/- 2.5mm (5.91+/- 0.1in) and diameter of 100 +/- 0.5mm (3.94+/- 0.1in) required for AMPT dynamic modulus testing.
2. Determine the air voids in accordance with AASHTO T 166-07. Discard any specimen which does not meet the requirement of 7 +/- 0.5% air voids.

3. Attach the gauge points at equal intervals around the central axis of the specimen ensuring the gauge length is 70+/- 1mm (2.76 +/- 0.04in).
4. Attach end platens and place Teflon friction reducers between the specimen and the end platens.
5. Stretch the latex membrane over the specimens and loading platens and secure using O-rings.
6. Place specimen in environmental chamber and allow specimen temperature to equilibrate for a minimum of 2hrs.
7. Turn on AMPT, set temperature and allow to equilibrate for one hour.
8. When specimen and testing chamber reach target temperature, transfer specimen to testing chamber and install LVDTs.
9. Allow testing chamber to return to desired temperature while entering test information into AMPT.
10. Start the test.

4.3.2 Flow Number Testing

The AMPT Flow Number tests were performed at 0.5, 2, 4, and 8hr aging periods as requested by FHWA. It should be noted that theses sample underwent no previous testing as it was found in (Rowe, et al. 2009) that sufficient strain was developed in dynamic modulus testing to invalidate Flow Number testing. For this study, a deviator stress of 600kPa (87Psi) and a five percent initial contact stress of 30kPa (4.4Psi) were used with no confining stress. These test conditions were selected because they are the same which were used in the NCHRP 9-29 interlaboratory study which evaluated the AMPT. All specimens were run to five percent total strain. A test temperature of

55°C (131°F) was selected using LTPPBind 98 percent reliable pavement temperature at 20mm (.79in) depth (LTTPBIND 2005). Four replicate samples were used for each testing condition. During testing the specimen is subjected to a repeated axial compressive load at a rate of 0.1 seconds every one second. The permanent axial deformation resulting from the loading is recorded with number of load cycles. The Flow Number is the number of cycles which correspond to the minimum rate of change in permanent axial deformation and is found by differentiating the axial strain as a function of loading cycles.

The procedure for Flow Number Testing was as follows:

1. Cut and core the SGC compacted specimens to achieve the desired height of 150 +/- 2.5mm (5.91+/- 0.1in) and diameter of 100 +/- 0.5mm (3.94+/- 0.1in) required for flow number testing.
2. Determine the air voids in accordance with AASHTO T 166-07. Discard any specimen which does not meet the air void requirement of 7 +/- 0.5%.
3. Attach end platens and place double greased Teflon friction reducers between the specimen and the end platens.
4. Place specimen in environmental chamber and allow specimen temperature to equilibrate for a minimum of 2hrs.
5. Turn on AMPT, set temperature and allow to equilibrate for one hour.
6. Allow testing chamber to return to desired temperature while entering test information into AMPT.
7. Start the test.

4.3.3 Equipment Used in Dynamic Modulus and Flow Number Testing

Asphalt Mixture Performance Tester

Dynamic modulus and Flow Number tests were performed using the Asphalt Mixture Performance Tester (AMPT). The AMPT was developed though NCHRP 9-19 and 9-29 specifically for the purpose of running dynamic modulus, Flow Number and static creep test. The AMPT is an integrated hydraulic testing machine which combines an environmental chamber, hydraulic actuator and power pack, triaxial cell, and a control and data acquisition system in order to perform these tests (IPC Global 2010). The system performs these tests by applying a specific load at predetermined intervals and recording the reaction of the material.

The user inputs the desired loading rate, load, confining pressure, specimen dimensions, and temperature. The equipment measures the strain through three LVDTs attached to the specimen and can calculate dynamic modulus and Flow Number using this information.

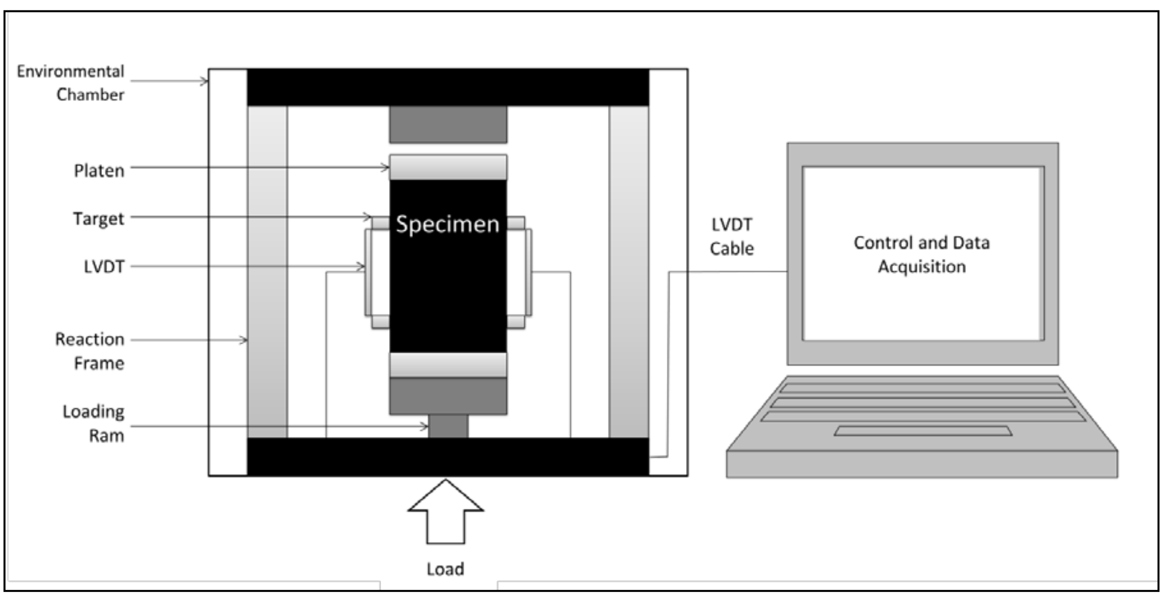

Figure 4.2: Diagram of AMPT

4.4 Disk Shaped Compact Tension Testing

The disk-shaped compact tension test is a practical means by which to determine the low-temperature cracking properties of asphaltic concrete. The higher the fracture energy, the less likely the asphalt pavement is to have its service life reduced by cracking.

Disk-shaped compact tension test were performed at 0.5, 2, 4, and 8hr aging periods as suggested by the FHWA staff on this project. The testing temperatures were selected as -2^{o}C (28^{o}F), -12^{o}C (10^{o}F), and -22^{o}C (-7^{o}F) in accordance with ASTM D 7313-07. Tests were performed with a constant crack mouth opening displacement of 0.01667 mm/s (0.00066in/s) the load necessary to maintain this displacement rate was recorded. The test lasts until the load necessary to maintain this rate is reduced to 0.1KN (22.5lbf). Three replicate samples were used for each testing condition.

The fracture energy is determined by first plotting the load vs. the crack mouth opening displacement, and calculating the area under this curve which represents the total energy required to fail the specimen. By dividing the area under the curve by the surface area of the portion of the specimen which was under loading we are able to determine the fracture energy.

The Procedure for DC(t) testing was as follows.

1. Cut the SGC compacted specimen into two separate specimens with a thickness of 50+/- 5mm (2 +/- 0.2in).
2. Determine the air voids in accordance with AASHTO T 166-07. Discard any specimen which does not meet the air void requirement of 7 +/- 0.5%.
3. Notch and core the specimen in accordance with Figure 4.4.

4. Instrument the specimen then place in the environmental chamber and allow specimen temperature to equilibrate for a minimum of 2hrs.
5. Turn on environmental chamber and allow test apparatus and chamber to reach testing temperature.
6. Insert specimen into loading fixtures and begin test.

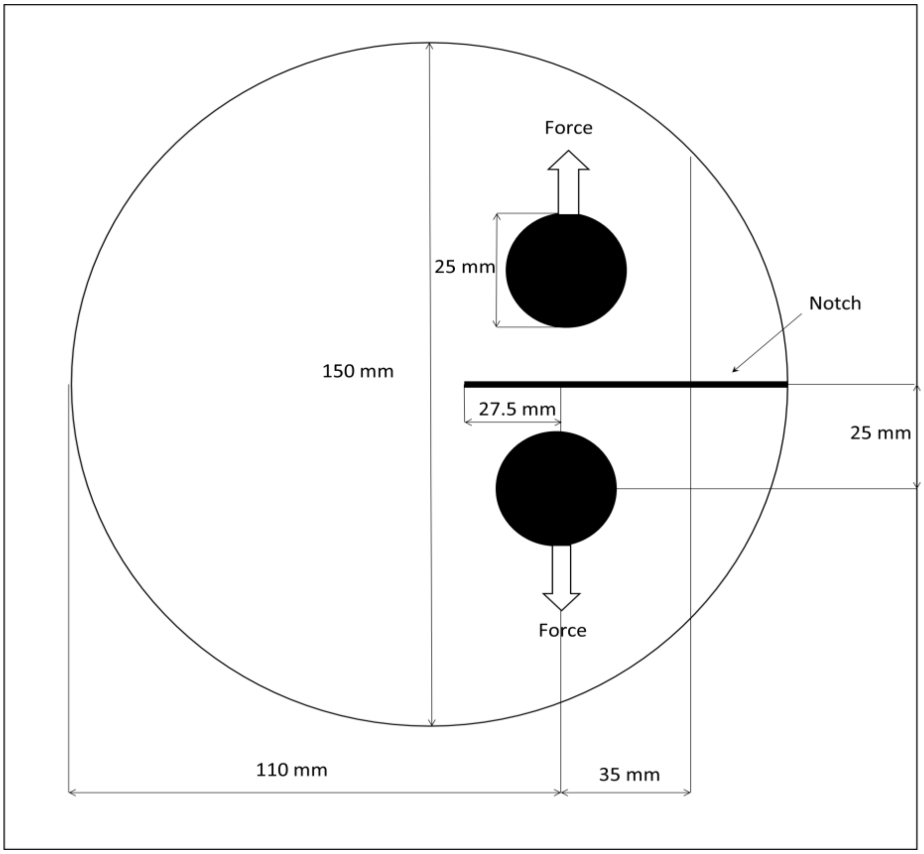

Figure 4.3: DC(t) Test Specimen

4.4.1 Equipment Used in DC(t) Testing

Disk Shaped Compact Tension Loading Frame and Fixture

ASTM D 7313-07a “Standard Test Method for Determining Fracture Energy of Asphalt-Aggregate Mixtures Using the Disk-Shaped Compact Tension Geometry” specifies the requirements for the loading frame and fixture required to perform Disk

Shaped Compact Tension (DC(t)) testing. A Cox and Sons closed loop servo-hydraulic unit integrated with an environmental chamber and data acquisition and control system was used in correlation with Cox and Sons DC(t) testing fixture to perform the testing. This equipment met the requirements set forth by ASTM D 7313-07a for DC(t) testing. The system performs the test by straining the material at a set rate and recording the force necessary to maintain that rate. The user inputs the desired crack mouth opening displacement and the minimum load at which the test will stop. The machine outputs the force necessary to maintain the given displacement rate and the length of the test.

Figure 4.4: *Cox and Sons* DC(t) Loading Frame and Fixture

4.5 Hamburg Wheel Tracking Testing

Hamburg Wheel Tracking (HWT) testing is used to evaluate the mixtures susceptibility to premature failure as a result of inadequate binder stiffness, aggregate structure or moisture susceptibility.

HWT testing was performed at 0.5, 2, 4, and 8hr aging periods on WMA mixtures and at 0.5, 2, and 4hr aging periods on HMA mixtures as requested by FHWA. As suggested by KYTC staff on this project two replicate specimens were used to establish each data point. All tests were in accordance with AASHTO T 324-04 and performed at 64^{o}C (147^{o}F) as suggested by KYTC.

The test is run by applying a reciprocating loaded steel wheel to a submerged specimen and recording the number of passes and the rut depth. Evaluating the rate at which the pavement ruts can reveal a pavements susceptibility to moisture damage and rutting.

The procedure for Hamburg Wheel Tracking testing was as follows.

1. Use plaster to rigidly mount the specimen into the mounting tray, then allow at least one hour to set.
2. Fill the wheel tracking device with water and adjust temperature as is necessary.
3. After the water temperature has been allowed to equilibrate for 30 minutes, lower the wheels onto the specimen.
4. Check that the average LVDT displacement is between 10 (0.4) and 18mm (0.7in), then begin test.

4.5.1 Equipment Used for Hamburg Wheel Tracking Testing

Hamburg Wheel Tracking Machine

HWTT was performed using a Hamburg Wheel Tracking machine. This equipment meets the requirements set for by AASHTO T 324-08 "Hamburg Wheel Track Testing for Hot Mix Asphalt" which specifies the requirements for a Hamburg Wheel Tracking machine. The Hamburg Wheel Tracking machine performs the test by continually rolling a loaded steel wheel over the specimen at a predetermined rate and measuring the rut depth using an LVDT while recording the number of passes. During the tests the samples are submerged in a temperature controlled bath. An overhead view of one side of a HWTT machine can be seen in Figure 4.5.

The user controls the testing temperature and the machine outputs the number of passes, time, and rut depths measured every 20 passes by LVDTs.

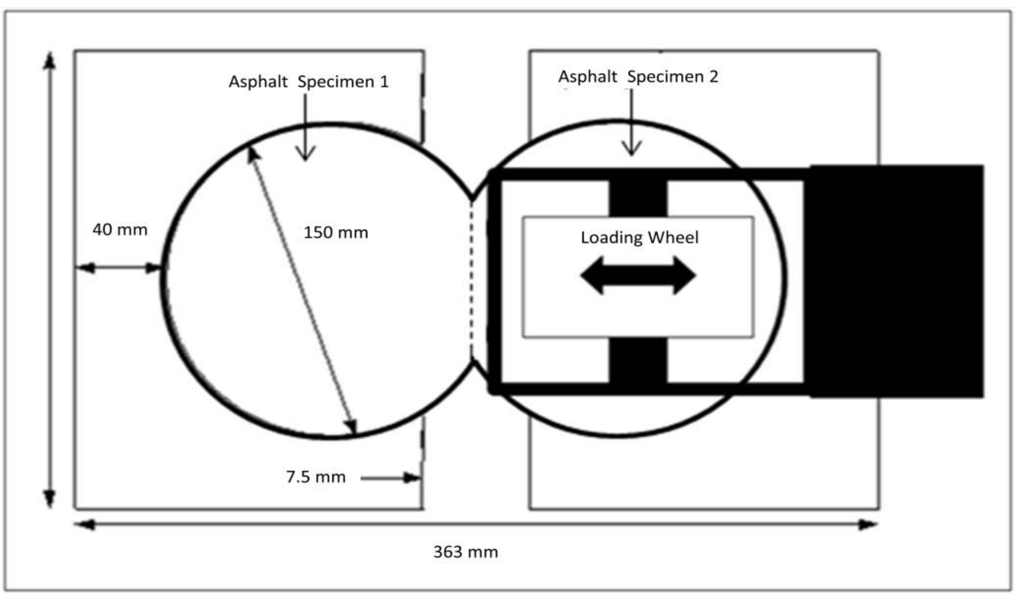

Figure 4.5: Overhead Diagram of One Side of Hamburg Wheel Tracking Machine

Chapter 5: Analysis of Laboratory Data

5.1 Dynamic Modulus

The AMPT dynamic modulus test was performed on all specimens identified previously. This test was the result of the NCHRP 9-29 research (Bonaquist 2003). The dynamic modulus was determined at 4°C (39°F), 20°C (68°F), and 40°C (104°F) at different frequencies of 25, 20, 10, 5, 2, 1, 0.5, 0.2, 0.1 Hz in accordance with AASHTO TP 62-03. The dynamic modulus was also determined at 0.01 Hz on specimens which were tested at 40°C (104°F) in order to better define the tail end of the dynamic modulus master-curves. The results of the dynamic modulus testing can be seen in Table 5.1. In addition, the percent differences were calculated between the dynamic modulus values at each give temperature and frequency and are displayed in Table 5.1.

Table 5.1(a): Dynamic Modulus Data obtained from AMPT

4° C(39°F) Test Temperature		Frequency								
	Aging Period (Hr)	25 Hz	20 Hz	10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz
HMA	0.5	16350	15989	14881	13761	12266	11121	9967	8444	7343
WMA	0.5	15039	14708	13629	12545	11075	9940	8814	7356	6369
% Diff	0.5	8.35	8.35	8.78	9.25	10.21	11.22	12.28	13.77	14.21
HMA	2	15752	15379	14232	13097	11591	10463	9360	7919	6942
WMA	2	15364	15047	13950	12832	11338	10174	9047	7597	6618
% Diff	2	2.49	2.18	2.00	2.04	2.21	2.80	3.40	4.15	4.78
HMA	4	16682	16320	15200	14079	12591	11464	10333	8887	7866
WMA	4	14592	14322	13314	12279	10876	9803	8739	7401	6516
% Diff	4	13.37	13.04	13.23	13.66	14.62	15.62	16.72	18.25	18.77
HMA	8	17013	16662	15479	14298	12750	11586	10464	9044	8109
WMA	8	15506	15230	14259	13270	11934	10933	9912	8587	7650
% Diff	8	9.27	8.98	8.20	7.46	6.61	5.80	5.42	5.18	5.83

(Positive percent difference values indicate a higher HMA value.)

Table 5.1(b): Dynamic Modulus Data obtained from AMPT

20^o C (68^{o}F) Test Temperature										
	Aging Period (Hr)	25 Hz	20 Hz	10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz
HMA	0.5	7852	7493	6350	5305	4056	3232	2518	1774	1373
WMA	0.5	7936	7566	6436	5380	4136	3304	2566	1812	1400
% Diff	0.5	-1.06	-0.97	-1.35	-1.39	-1.97	-2.22	-1.89	-2.12	-1.95
HMA	2	8719	8327	7186	6120	4819	3925	3131	2264	1754
WMA	2	8055	7672	6534	5484	4232	3394	2663	1892	1460
% Diff	2	7.92	8.19	9.49	10.96	12.96	14.50	16.16	17.91	18.28
HMA	4	9442	9063	7931	6838	5499	4594	3761	2805	2203
WMA	4	8351	7994	6868	5812	4552	3711	2954	2125	1647
% Diff	4	12.27	12.53	14.36	16.23	18.85	21.28	24.04	27.60	28.88
HMA	8	9035	8623	7504	6442	5177	4325	3570	2718	2208
WMA	8	9034	8678	7561	6512	5231	4358	3548	2634	2063
% Diff	8	0.00	-0.64	-0.76	-1.07	-1.05	-0.77	0.63	3.14	6.77

(Positive percent difference values indicate a higher HMA value.)

Table 5.1(c): Dynamic Modulus Output from AMPT

40^o C(104^{o}F) Test Temperature						
	Aging Period (Hr)	25 Hz	20 Hz	10 Hz	5 Hz	2 Hz
HMA	0.5	1836	1696	1281	986	718
WMA	0.5	1734	1607	1232	964	729
% Diff	0.5	5.74	5.40	3.90	2.29	-1.41
HMA	2	2311	2137	1635	1266	927
WMA	2	1882	1744	1334	1035	773
% Diff	2	20.44	20.26	20.29	20.07	18.18
HMA	4	2758	2559	1976	1521	1089
WMA	4	2031	1883	1430	1100	804
% Diff	4	30.37	30.45	32.08	32.12	30.02
HMA	8	2706	2539	1988	1538	1097
WMA	8	2276	2130	1649	1284	948
% Diff	8	17.27	17.52	18.60	18.01	14.65

(Positive percent difference values indicate a higher HMA value.)

Table 5.1(d): Dynamic Modulus Output from AMPT

40° C(104°F) Test Temperature						
	Aging Period (Hr)	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.01 Hz
HMA	0.5	1836	1696	1281	986	718
WMA	0.5	1734	1607	1232	964	729
% Diff	0.5	5.74	5.40	3.90	2.29	-1.41
HMA	2	2311	2137	1635	1266	927
WMA	2	1882	1744	1334	1035	773
% Diff	2	20.44	20.26	20.29	20.07	18.18
HMA	4	2758	2559	1976	1521	1089
WMA	4	2031	1883	1430	1100	804
% Diff	4	30.37	30.45	32.08	32.12	30.02
HMA	8	2706	2539	1988	1538	1097
WMA	8	2276	2130	1649	1284	948
% Diff	8	17.27	17.52	18.60	18.01	14.65

(Positive percent difference values indicate a higher HMA value.)

As expected, the dynamic modulus values tended to increase as the aging period increaces. Additionally, the values for dynamic modulus are there highest at low temperatures/fast loading rates and lowest at the high temperature/slow loading rates, which is a typical trend of dynamic modulus values for asphalt in in these temperature and frequencies ranges. The values for dynamic modulus in the HMA and WMA mixes diverge from one another most significantly between 1 Hz at 20°C (68°F) and 0.2 Hz at 40°C (104°F) in the 2 and 4hr aging periods, with the HMA mix being much stiffer. This trend deserves attention because it is occuring at a range of temperatures and loading rates which a pavement would commonly experience.

The reduced dynamic modulus master curves are shown in Figure 5.1. The general form of the dynamic modulus master curve is a modified version of the dynamic modulus master curve equation included in the Mechanistic Empirical Design guide (AASHTO TP 62-03).

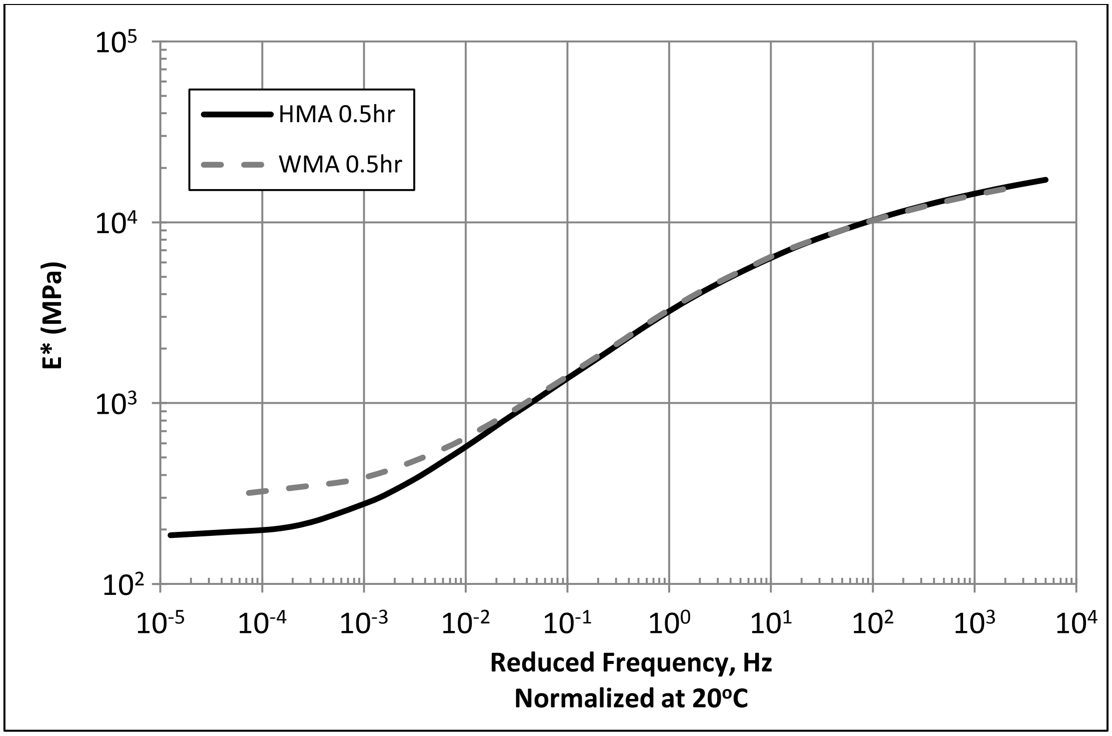

Figure 5.1(a): Comparison of the Shifted Dynamic Modulus Master Curves at the 0.5hr Aging Period

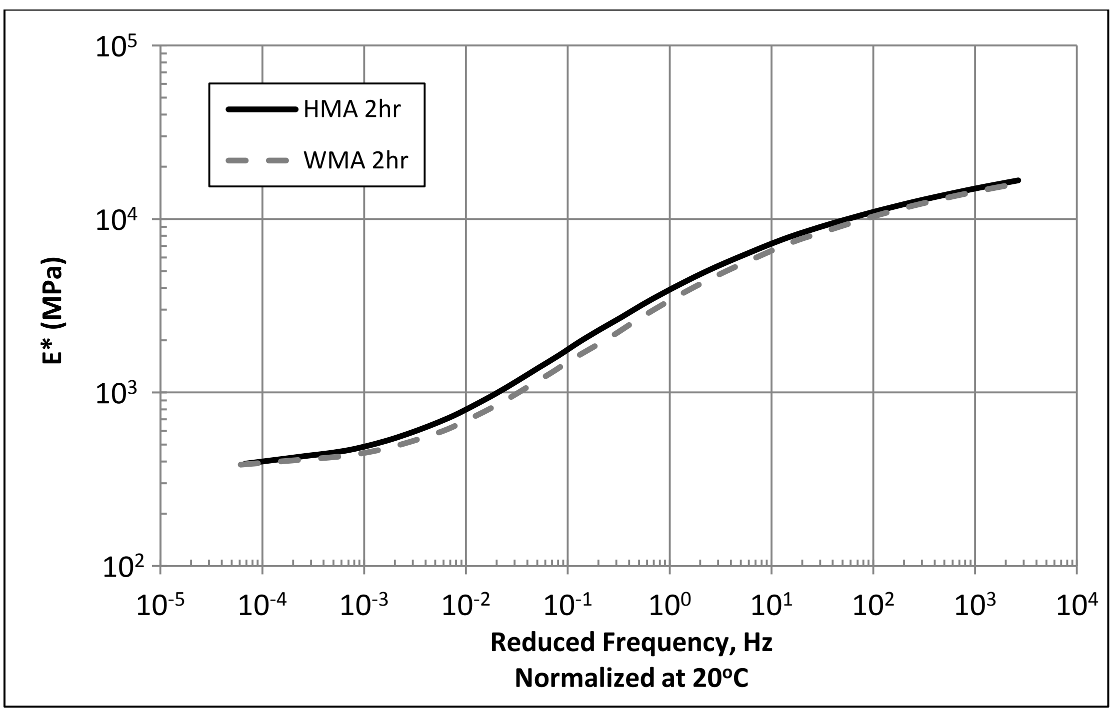

Figure 5.1(b): Comparison of the Shifted Dynamic Modulus Master Curves at the 2hr Aging Period

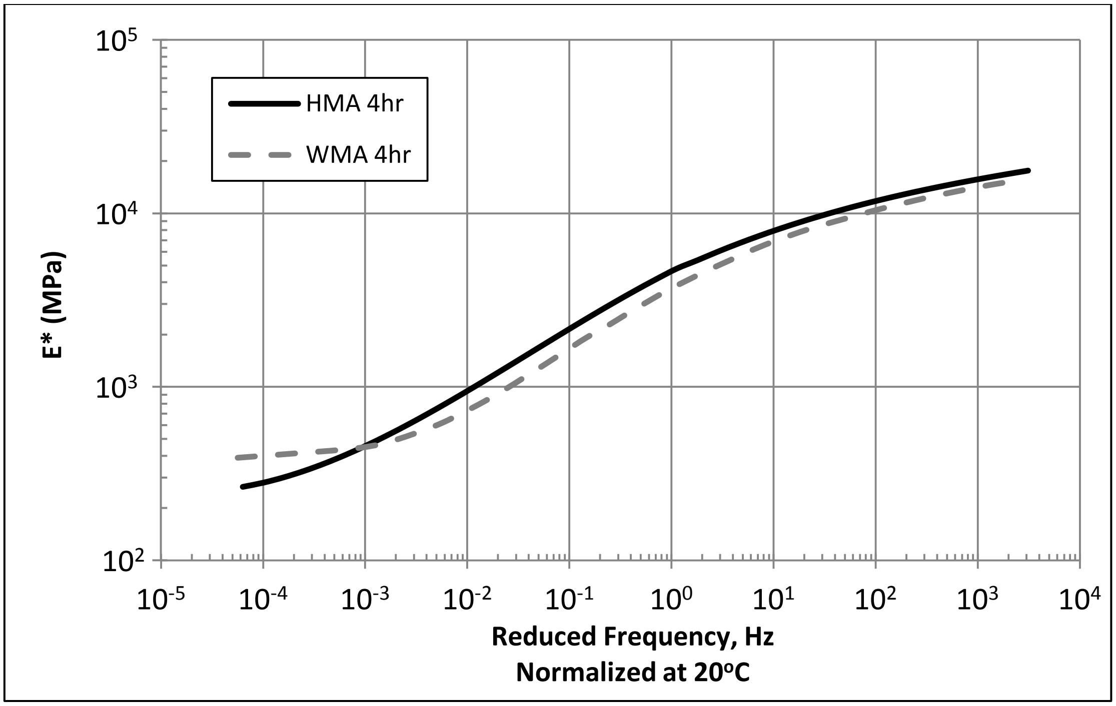

Figure 5.1(c): Comparison of the Shifted Dynamic Modulus Master Curves at the 4hr Aging Period

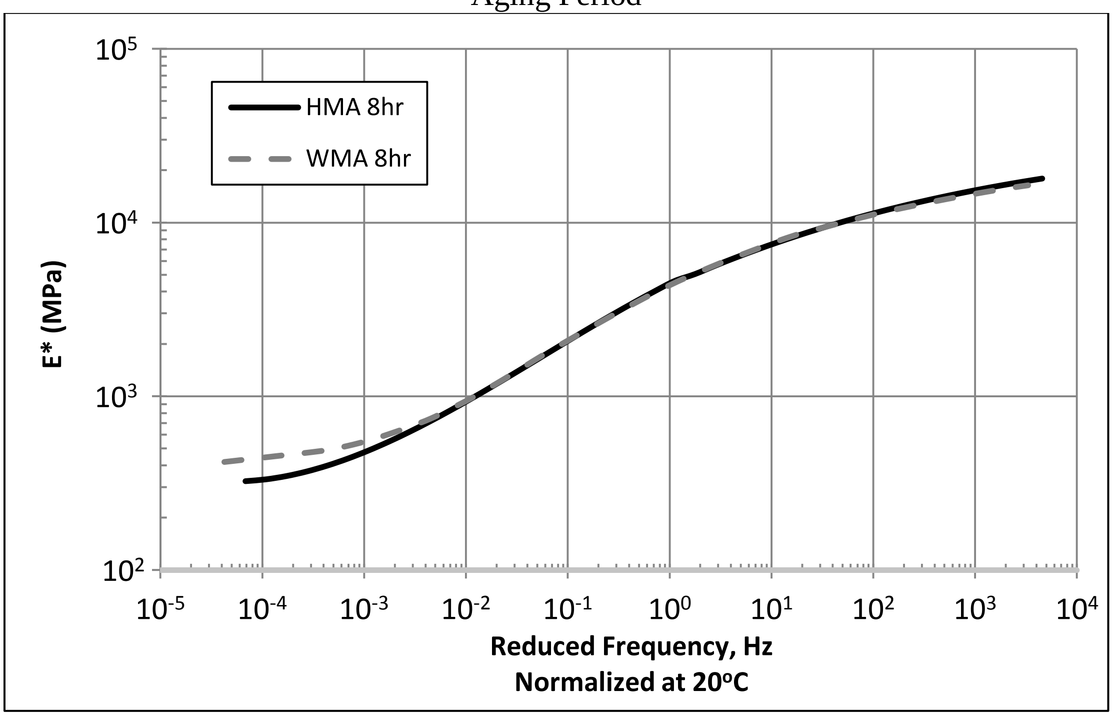

Figure 5.1(d): Comparison of the Shifted Dynamic Modulus Master Curves at the 8hr Aging Period

At the 0.5, 4, and 8hr loose mix aging periods the tail of the dynamic modulus master curves begins to diverge with the WMA mix maintaining a higher dynamic modulus as compared to the HMA mix. This portion of the graph should represent very slow loading or high temperature levels at which the mix should be aggregate controlled. The data would be expected to converge at this point while in fact the opposite appears to be happening.

Statistical analysis of the data set shown in Table 5.2 reveals that neither the aging time nor the reduction of mixing and compaction temperatures is a significant factor. This confirms the hypothesis that the HMA mechanical response is in fact controlled by the aggregate.

Table 5.2: P-values from General Linear Modeling of Dynamic Modulus Data

4^{o}C Test Temperature	Frequency				
Factor	25 Hz	20 Hz	10 Hz	5 Hz	2 Hz
Aging Time	0.2771	0.2289	0.1717	0.1219	0.0689
Additive/Temp Reduction	0.0003	0.0003	0.0004	0.0004	0.0004
Interaction	0.2816	0.2677	0.2480	0.2291	0.1935
20^{o}C Test Temperature					
Aging Time	0.0009	0.0005	0.0002	<0.0001	<0.0001
Additive/Temp Reduction	0.0282	0.0273	0.0192	0.0134	0.0087
Interaction	0.1030	0.0817	0.0514	0.0348	0.0209
40^{o}C Test Temperatures					
Aging Time	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Additive/Temp Reduction	<0.0001	<0.0001	<0.0001	<0.0001	0.0006
Interaction	0.0381	0.0340	0.0257	0.0306	0.0586

(Testing at 0.01 Hz was only performed at 40^{o}C (104^{o}F) to better define the tail end of the dynamic modulus master curve.)

($\alpha = 0.05$. If p-value < 0.05, it means there is a significant effect.
If p-value > 0.05, it means there is no significant effect.)

Table 5.2: P-values from General Linear Modeling of Dynamic Modulus Data Cont

4^oC Test Temperature	Frequency				
Factor	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.01 Hz
Aging Time	0.0336	0.0147	0.0033	0.0005	N/A
Additive/Temp Reduction	0.0003	0.0002	0.0002	0.0001	N/A
Interaction	0.1667	0.1470	0.1327	0.1535	N/A
20^oC Test Temperature					
Aging Time	<0.0001	<0.0001	<0.0001	<0.0001	N/A
Additive/Temp Reduction	0.0056	0.0022	0.0008	0.0020	N/A
Interaction	0.0149	0.0115	0.0085	0.0079	N/A
40^oC Test Temperatures					
Aging Time	0.0009	0.0160	0.2145	0.5047	0.9018
Additive/Temp Reduction	0.0095	0.0885	0.6304	0.8027	0.1986
Interaction	0.1428	0.2948	0.5517	0.7810	0.8179

(Testing at 0.01 Hz was only performed at 40^oC (104^oF) to better define the tail end of the dynamic modulus master curve.)
($\alpha = 0.05$. If p-value < 0.05, it means there is a significant effect. If p-value > 0.05, it means there is no significant effect.)

Table 5.2 displays wether or not aging time and the addition of the additive/temperature reduction had a statistically significant effect (p-value < 0.05) on the dynamic modulus at the given testing temperature and frequency.

The table shows an interaction between the reduction in temperatures and aging time at approximately the same temeperatures and frequencies which would note the divergence of the HMA and WMA dynamic modulus data.

The 0.5 and 8hr loose mix aging times produced mixes with little difference in their behavior. Mixes which were only aged for 0.5 hours likely did not experence enough aging for the material properties to diverge. The mixes which aged 8 hours could have experienced a “catch up” effect that is noted in Figure 5.2.

Dynamic modulus was plotted at 20°C (68°F) at one Hz for the various aging periods as a means of comparison. This temperature and loading rate were selected for comparison because they represent a very common loading rate and temperature for pavements.

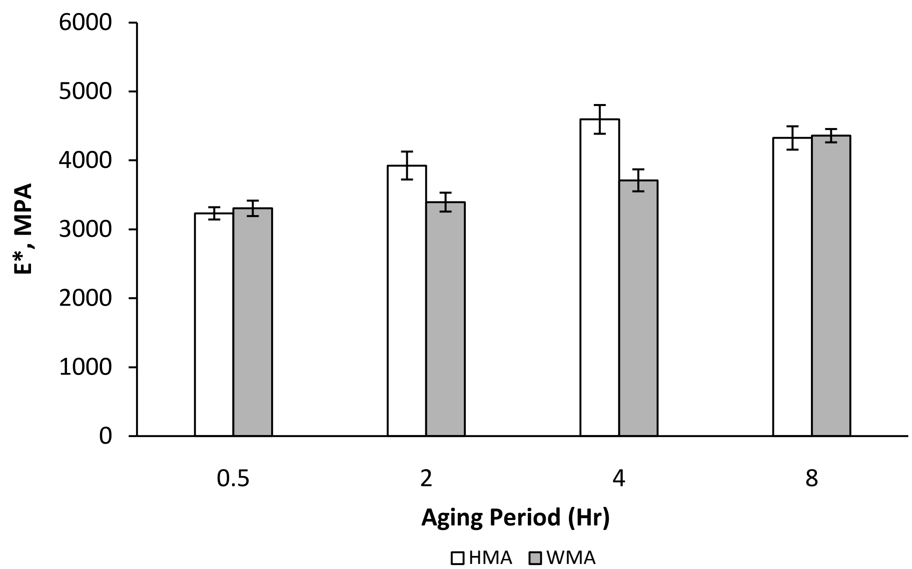

Figure 5.2: Dynamic Modulus Comparisons at 1Hz and 20°C
(Each data point represents the average of four tests.)
(Error bars represent standard error.)

The WMA and HMA mixes appear to be stiffening at a linear rate between 0.5 and 4 hours, with the HMA stiffening at a faster rate than the WMA. From 4 to 8 hours the WMA continues to stiffen at a linear rate while the HMA appears to experience limited additional aging, resulting in a “catch up” effect where the difference between the HMA and WMA dynamic modulus diminishes. A possible explanation for this can be found in the way which asphalt mixes typically stiffen as a result of aging. The stiffening tends to follow a logarithmic curve with the mix initially stiffening very rapidly before settling into a slower rate for the remainder of the aging.

Additional research investigating the rates at which warm and hot mixes age could add useful insight into this issue.

AMPT dynamic modulus testing also outputs phase angles for each modulus reading which can be found in Appendix A. These angles are used in calculating the storage and loss moduli, because our research was more focused on dynamic modulus and there were no significant trends in the phase angle data these values are not presented in the body of the report.

5.2 Flow Number Testing

A summary of Flow Number as a function of aging period and the addition of the chemical additive is summarized in Table 5.3 and Figure 5.3. The Flow Number was computed by the IPC software, version 1.41 (IPC Global 2010). The averaged data represents four samples per data point. According to AASHTO TP79, one can expect 10 percent coefficient of variance using four samples.

A similar relation can be found between aging period and potential rutting if the same test is run to a given strain, such as five percent permanent strain (50,000 micro-strain) and the ending cycles recorded. This relation can be seen in Figure 5.4.

Table 5.3: Flow Number Data Obtained from AMPT

Flow Number Test at 56°C			
	Aging Period (Hr)	Flow Number	Cycles to 5% Perm. Strain
HMA	0.5	26	62
WMA	0.5	30	69
HMA	2	35	87
WMA	2	38	92
HMA	4	42	108
WMA	4	35	87
HMA	8	79	195
WMA	8	55	126

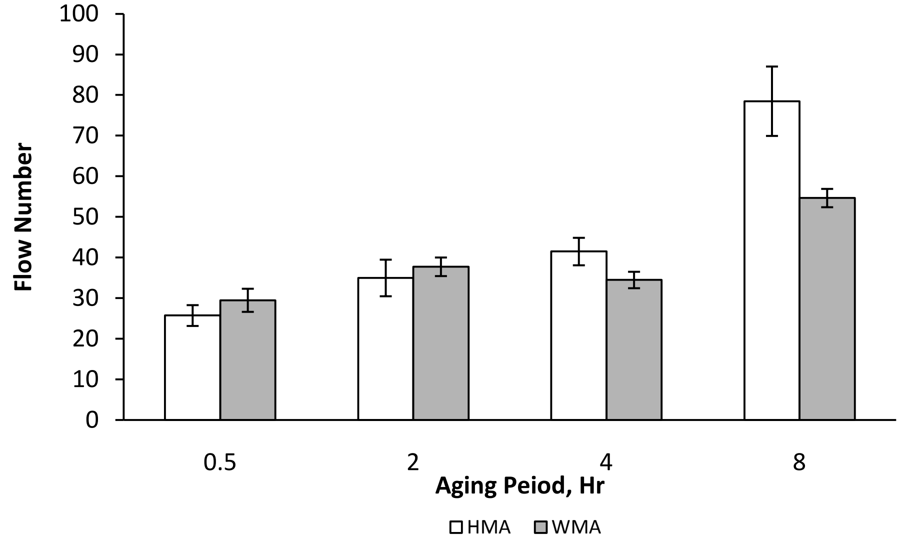

Figure 5.3: Flow Number (FN) of the Mixes as a Function of Agining Period
(Each data point represents the average of four tests.)
(Error bars represent standard error.)

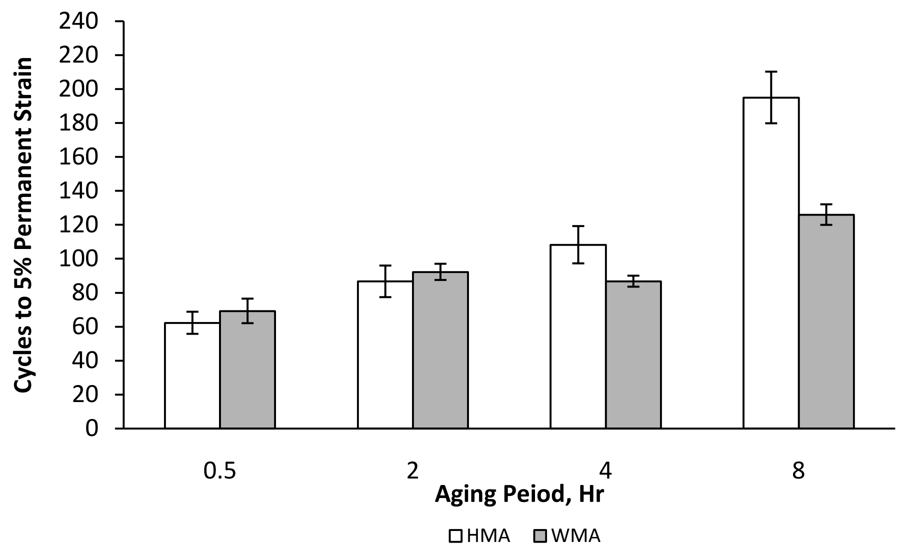

Figure 5.4: Cycles to 5% Permanent Strain Using the HMA and WMA Mixes as a Function of Aging Period
(Each data point represents the average of four tests.)
(Error bars represent standard error.)

Table 5.4: P-values from General Linear Modeling of Flow Number Data

Factor	P-value	Details
Flow Number Testing		
Aging Time	<0.0001	8hr>4hr>2hr>0.5hr
Additive/Temp Reduction	0.0715	
Interaction	0.0166	
Cycle to 5% Permanent Deformation Testing		
Aging Time	<0.0001	8hr>4hr>2hr>0.5hr
Additive/Temp Reduction	0.0262	HMA>WMA
Interaction	0.0092	

(α = 0.05. If p-value < 0.05, it means there is a significant effect.
If p-value > 0.05, it means there is no significant effect.)

As would be expected, the rutting resistance represented by the Flow Number decreases in the WMA mix, the number of cycles to five permanent strain also decrease in the WMA mix. It should be noted that the Flow Number test is less accurate when testing softer materials (FN<100) which accounts for the high standard error experienced in these experiments. This is likely the cause of the reduced mixing/compaction temperature not showing up as a main factor (p-value<0.05) in the Flow Number testing statistical analysis. However, the significance of the interaction shows that it is a factor in the test results. The cycles to five percent permanent strain testing (which is a longer test) shows the reduced mixing/compaction temperature as a significant factor. As would be expected aging period was a significant factor in the performance of the mixture for both Flow Number and cycles five percent permanent strain testing, as increased aging increases the stiffness of the mixture.

Dynamic modulus testing indicated a “catch up” effect between the 4 and 8hr aging periods where the WMA stiffened at a faster rate than the HMA. The Flow Number testing contradicts this because the difference between the Flow Number values for the

HMA and WMA increases with additional aging. This would indicate that the HMA continues to stiffen at a faster rate than the WMA from 4 to 8hrs.

Coefficient of variation increased with the addition of the chemical additive and reduction in temperature from 12.8% to 21.9%. This is likely a result of the continued softening of the WMA which degrades the precision of the Flow Number testing, because it further shortens the test.

5.3 Disk Shaped Compact Tension Testing

Disk Shaped Compact Tension (DC(t)) testing was performed on the samples which were previously mentioned. The DC(t) test, ASTM D7313, was developed at University of Illinois-Urbana Champaign for the purpose of measuring mixtures properties of the thin core layers. Test temperatures of -2^{o}C (28^{o}F), -12^{o}C (10^{o}F), and -22^{o}C (-7^{o}F) were selected based on current recommendations by University of Illinois which is 10°C higher than the anticipated low temperature binder grade supplied or required in a specific climate. Additional testing was performed at +/-10°C increments from the recommended temperature to provide a better model of the materials low-temperature fracture characteristics.

Table 5.5: Disk Shaped Compact Tension Testing at -2^{o}C (28^{o}F)

	Aging Period, Hr	Fracture Energy, J/ms^2	Peak Load, KN
HMA	0.5	1007.9	2.6
WMA	0.5	1289.1	2.5
HMA	2	837.5	2.8
WMA	2	1135.0	2.4
HMA	4	915.8	2.5
WMA	4	897.4	2.6
HMA	8	666.7	2.7
WMA	8	720.2	2.6

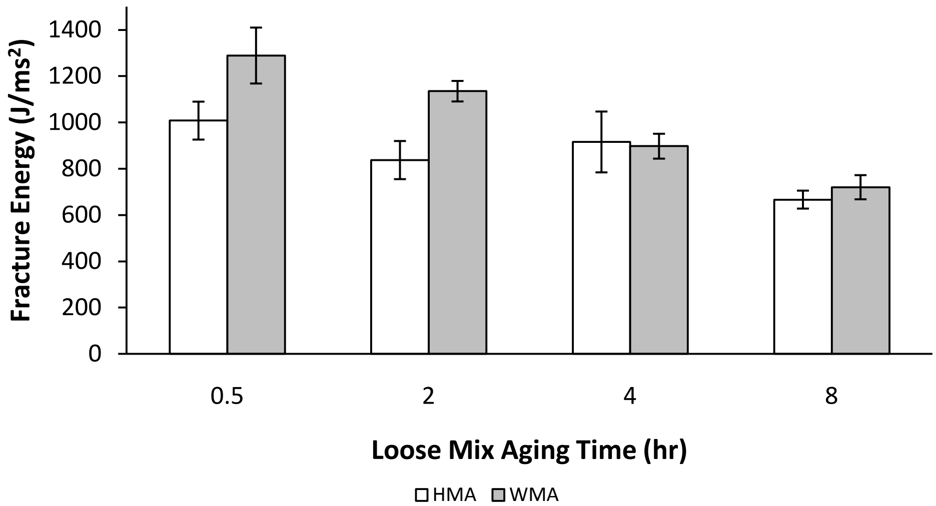

Figure 5.5: Fracture Energies of HMA and WMA at -2°C (28°F) at Various Aging Periods
(Each data point represents the average of three tests.)
(Error bars represent standard error.)

At -2°C (28°F) testing the asphalt has not yet entered the quasi-brittle state. The softer WMA mixes perform significantly better than the HMA mixes at this temperature because of their increased ductility,

this is also the cause of the HMA mixes having a higher peak load at this temperature which leads to a more brittle failure. A trend of decreasing fracture energy with increased aging period, these trends can be seen in Figure 5.5.

Table 5.6: Disk Shaped Compact Tension Testing at -12°C (10°F)

	Aging Period, Hr	Fracture Energy, J/ms^2	Peak Load, KN
HMA	0.5	464.3	2.7
WMA	0.5	424.1	2.7
HMA	2	478.0	3.0
WMA	2	420.4	2.9
HMA	4	431.7	2.8
WMA	4	462.1	3.0
HMA	8	347.9	2.8
WMA	8	426.6	2.8

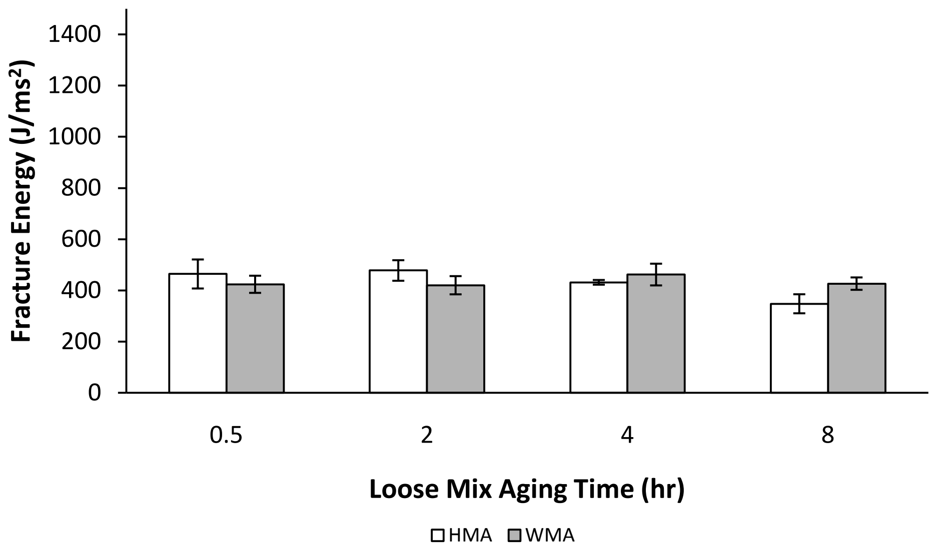

Figure 5.6: Fracture Energies of HMA and WMA at -12°C (10°F) at Various Aging Periods
(Each data point represents the average of three tests.)
(Error bars represent standard error.)

As the mixes enter the quasi-brittle state in -12°C (10°F) testing, the differences between the HMA and WMA mixes dimenish. There is also no significant difference between the different aging periods at these temperatures ($\alpha = 5\%$) . In this testing, all mixes performed well and did not appear to have a pre-disposition to low temperature cracking.

Table 5.7: Disk Shaped Compact Tension Testing at -22°C (-7°F)

	Aging Period, Hr	Fracture Energy, J/ms^2	Peak Load, KN
HMA	0.5	264.4	3.0
WMA	0.5	221.8	2.5
HMA	2	251.8	2.8
WMA	2	212.7	2.7
HMA	4	245.2	2.8
WMA	4	220.7	2.7
HMA	8	248.3	3.0
WMA	8	235.0	2.8

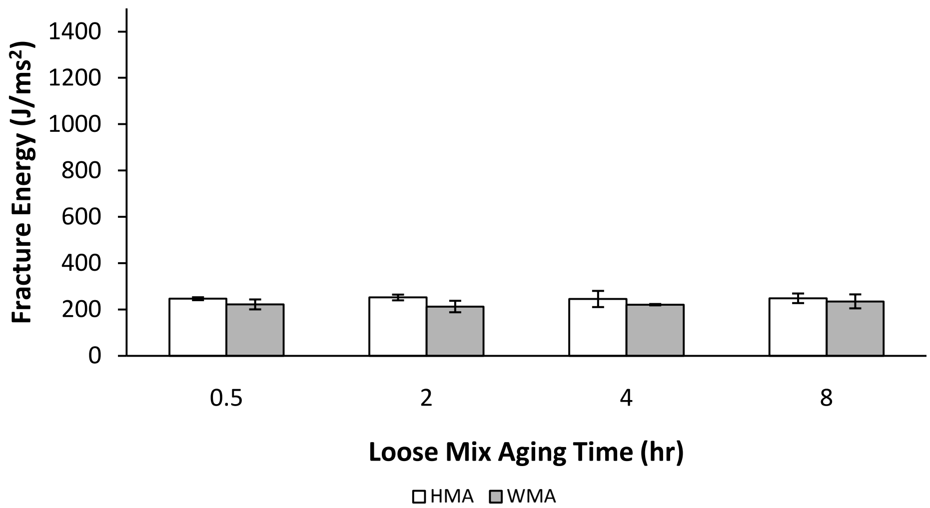

Figure 5.7: Fracture Energies of HMA and WMA at -22°C (-7°F) at Various Aging Periods
(Each data point represents the average of three tests.)
(Error bars represent standard error.)

At -22°C (-7°F) testing, the only significant difference appears to be peak load, with the HMA being greater than the WMA. This does not come as a surprise because the test may be approaching the low temperature craking point of the asphalt, and the WMA is likely softer and more ductile than the HMA.

In order to check the statistical significance of the results, general linear modeling is used to determine which factors have a significant impact on the testing results. Statistical significance was determined at $\alpha = 5\%$ level for this analysis. Table 5.8 shows whether or not individual factors were significant at different testing temperatures and aging periods.

Table 5.8: General Linear Modeling for Fracture Energy

Testing at -2°C		
Factor	P-value	Details
Aging Time	0.0005	0.5>4>2>0.5
Additive/Temp Reduction	0.0182	WMA>HMA
Interaction	0.1744	
Testing at -12°C		
Aging Time	0.3099	
Additive/Temp Reduction	0.8538	
Interaction	0.2854	
Testing at -22°C		
Aging Time	0.9897	
Additive/Temp Reduction	0.2629	
Interaction	0.9770	

($\alpha = 0.05$. If p-value < 0.05, it means there is a significant effect. If p-value > 0.05, it means there is no significant effect.)

Table 5.9: General Linear Modeling for Peak Load

Testing at -2°C		
Factor	P-value	Details
Aging Time	.4126	
Additive/Temp Reduction	.0379	HMA>WMA
Interaction	.0959	
Testing at -12°C		
Aging Time	0.1340	
Additive/Temp Reduction	0.6286	
Interaction	0.3962	
Testing at -22°C		
Aging Time	0.5061	
Additive/Temp Reduction	0.0308	HMA>WMA
Interaction	0.2585	

($\alpha = 0.05$. If p-value < 0.05, it means there is a significant effect. If p-value > 0.05, it means there is no significant effect.)

Table 5.8 confirms that the lower testing temperatures reduce the impact that aging period and temperature reductions have on the fracture energy. These trends correspond with data reported by (AMEC 2010).

Table 5.8 suggest that the chemical additive in the WMA allows for the lowering of the mixing and compaction temperatures by 31°C (35°F) without a significant effect on the low temperature performance. However, would appear to dispel the theory that the binder undergoes a grade shift to a lower critical low temperature and should therefore perform at a superior level at low tempratures.

5.4 Hamburg Wheel Tracking Testing

Hamburg Wheel-track testing was performed on the specimens identified previously. As recommended by KYTC two specimens were used to establish each data point. Hamburg Wheel Tracking testing evaluates the rutting and moisture susceptibility of the paving mixture. Tests were performed in accordance with AASHTO T 324 at 64°C (147°F) as requested by KYTC.

Table 5.10: Hamburg Wheel-Track Test at 64°C (147°F)

	Aging Period, Hr	**Passes to 12.5mm**	**Rut Rate**, Passes/mm
HMA	0.5	1160	92.8
WMA	0.5	840	67.2
HMA	2	2080	166.4
WMA	2	1070	85.6
HMA	4	3380	270.4
WMA	4	1440	115.2
WMA	8	1850	148

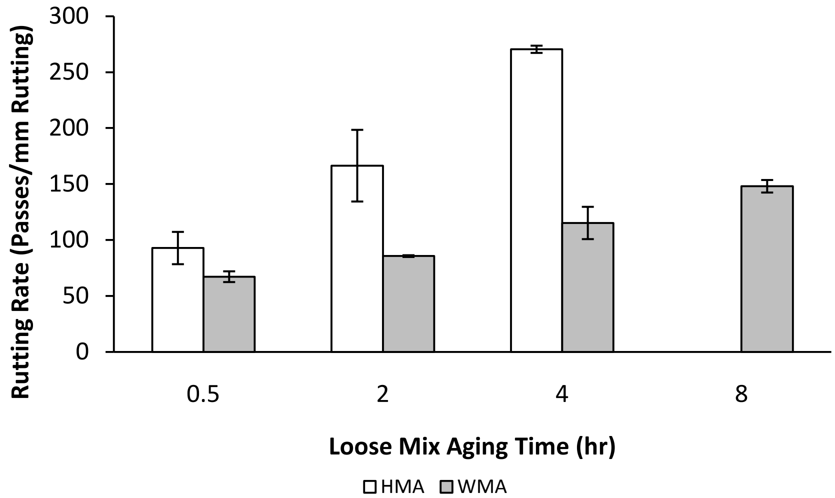

Figure 5.8 Comparisonn of HWT Rutting Rate at Varying Aging Periods
(Each data point represents the average of both wheels used in HWT testing.)
(Error bars represent standard error.)

Table 5.11: Gineral Linear Modeling for Hamburg Wheel Tracking Test

Testing at 64°C		
Factor	P-value	Details
Aging Time	0.0009	HMA>WMA
Additive/Temp Reduction	0.0004	HMA>WMA
Interaction	0.0148	HMA>WMA

(α = 0.05. If p-value < 0.05, it means there is a significant effect.
If p-value > 0.05, it means there is no significant effect.)

The WMA performed significantly worse than the HMA at all loose mix aging times in the HWT testing. Lower performance in HWT testing should be expected when using WMA, since it is a softer mix. The reduced aging from the temperature reduction decreases dynamic modulus which should correspond to a less stiff material. The test temperature of 64°C (147°F) is also significant because a PG 64-22 binder was tested. The lower temperatures at which WMA is produced may lower the effective grade of the binder making the 64°C test temperature higher than the effective PG of the WMA binder. HWT testing is normally run at 50°C (122°F) for PG 64-22 binders, therefore these test results can only be used for comparison between the control and warm mixes in this study. Both mixes failed before reaching the 10,000 passes required to pass a HWT test. It is possible that HWT testing is not a good indicator of field performance for WMA mixes. Currently TxDOT requires that WMA samples being used for HWT testing be aged for 4 instead of 2 hours at 135^{o}C (275^{o}F). Although this increased aging temperature does not accurately represent plant conditions, rutting has not been an issue in WMA field tests (TxDOT 2006). Additional research into the use of HWT testing for charectirization of warm mix aspahalts would be useful.

Chapter 6: Conclusions

The warm mix asphalt additive used in this experiment showed a significant amount of promise as a possible replacement for traditional HMA. Overall performance between the HMA and WMA was close, the reduction in mixing and compaction temperatures produces a more ductile mixture which will be more susceptible to rutting and less susceptible to low temperature fatigue related cracking. That being said both mixes performed at an acceptable level for a roadway with less than three million estimated single axis loads in all testing except for Hamburg wheel tracking. The following specific conclusions can be made based on this study.

1. The reduction in mixing and compaction temperatures and the chemical additive used in this experiment caused a reduction in the dynamic modulus of the material at all temperatures and loading rates, except for those less than 0.5 Hz at 40^{o}C. This is significant because it represents the slowest loading rates/hottest temperatures where asphalt is typically the most susceptible to rutting. Generally, increasing the aging period corresponded with an increase in dynamic modulus, this trend did not hold true at the extremes of the testing temperatures and frequencies. This may be due to stiffness offered by the aggregate structure and brittleness of the binder at low temperatures or high frequencies.
2. The WMA had a greater fracture energy than the control at the -2^{o}C (28^{o}F) testing, while the HMA had a higher peak load and failed in a more brittle manner at this temperature. There was also a decrease in fracture energy as both the HMA and WMA underwent longer aging periods, which might be due to aging induced brittleness. At -12^{o}C (10^{o}F) and -22^{o}C (-7.6^{o}F) testing there was no

significant difference in the fracture energy of the HMA and WMA mixes. However, at -22^{o}C (-7.6^{o}F) testing the WMA had a lower peak load than the HMA.

3. The WMA did not perform as well as the HMA in rutting related testing. Flow Number and cycles to five percent permanent deformation were both affected by the reduction in mixing and compaction temperatures, however this is only shown to be main effect in the statistical analysis of the cycles to five percent permanent deformation testing. The Performance in these tests increased as the aging period was increased in both the WMA and HMA mixes. Hamburg Wheel-Tracking Testing performed at the critical high temperature of the binder at 64^{o}C (147^{o}F) showed the WMA performing worse than the HMA. Neither mixture achieved an acceptable number of loading cycles for this testing, which is a result of the testing being run at the critical high temperature of the binder as opposed to the recommended 50^{o}C (122^{o}F). It should be noted that field data have not shown any premature failure as a result of the use of Warm Mix Asphalts.

Chapter 7: Recommendations for Future Research

1. WMA has consistently performed poorly on traditional testing for susceptibility to rutting (i.e. Hamburg Wheel Tracking and Flow Number); however, field studies have limited indications of increased rutting. Further research into the cause of an apparent lack of correlation between laboratory rutting data (Hamburg Wheel) and field performance is necessary.
2. The mix used in this research was designed for less traffic than highway type pavements would experience. That is, less than three million ESALs, for which there is currently no required minimum Flow Number in most states. Flow Number testing on a stronger aggregate structure would be useful. Additionally, the flow number test may not be a very effective test for soft asphalts (FN<100).
3. Fracture energy testing revealed that WMA performed better than or equal to HMA. However, the peak load at the critical low temperature was higher for the HMA mixtures. An investigation into the binder's role in fracture potential of the WMA would be useful.
4. This study suggests that the WMA mixtures are softer than the control HMA. Extraction and testing of binders from WMA mixtures could determine if the high temperature side of the performance grade should be adjusted. Future research could provide insight into mechanisms which may result in performance differences between WMA and conventional HMA.

Appendix A: Raw Experimental Data

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Table A-1: Dynamic Modulus and Phase Angle Output from AMPT

4°C (39°F)							
WMA							
Aging Period	ID	Frequency (Hz)	25	20	10	5	2
0.5hr	1	Dynamic Modulus (MPa)	15651	15342	14270	13196	11743
		Phase Angle (Degrees)	9.08	9.55	10.66	11.90	13.71
	2	Dynamic modulus (MPa)	14377	14074	13060	12024	10632
		Phase angle (Degrees)	9.53	9.97	11.16	12.46	14.46
	3	Dynamic modulus (MPa)	15085	14739	13640	12520	10998
		Phase angle (Degrees)	9.49	9.91	11.21	12.56	14.56
	4	Dynamic modulus (MPa)	15042	14678	13546	12441	10925
		Phase angle (Degrees)	10.35	10.82	12.10	13.54	15.71
2hr	1	Dynamic modulus (MPa)	15657	15332	14238	13105	11640
		Phase angle (Degrees)	9.57	9.94	11.16	12.44	14.64
	2	Dynamic modulus (MPa)	14713	14441	13413	12364	10952
		Phase angle (Degrees)	9.72	10.08	11.26	12.64	14.51
	3	Dynamic modulus (MPa)	15906	15592	14472	13334	11808
		Phase angle (Degrees)	9.34	9.79	10.95	12.24	14.11
	4	Dynamic modulus (MPa)	15181	14822	13677	12526	10951
		Phase angle (Degrees)	10.07	10.55	11.83	13.21	15.25
4hr	1	Dynamic modulus (MPa)	14849	14619	13711	12783	11467
		Phase angle (Degrees)	8.77	9.21	10.24	11.39	13.08
	2	Dynamic modulus (MPa)	16025	15651	14430	13212	11638
		Phase angle (Degrees)	10.16	10.51	11.70	13.00	14.91
	3	Dynamic modulus (MPa)	13571	13209	12142	11077	9693
		Phase angle (Degrees)	10.69	11.11	12.34	13.78	15.85
	4	Dynamic modulus (MPa)	13921	13809	12972	12044	10706
		Phase angle (Degrees)	9.76	10.17	11.38	12.64	14.62
8hr	1	Dynamic modulus (MPa)	14785	14544	13705	12840	11676
		Phase angle (Degrees)	8.09	8.46	9.35	10.27	11.69
	2	Dynamic modulus (MPa)	15696	15433	14469	13482	12164
		Phase angle (Degrees)	8.54	8.89	9.85	10.91	12.50
	3	Dynamic modulus (MPa)	N/A	N/A	N/A	N/A	N/A
		Phase angle (Degrees)	N/A	N/A	N/A	N/A	N/A
	4	Dynamic modulus (MPa)	16036	15713	14604	13488	11963
		Phase angle (Degrees)	8.98	9.36	10.39	11.51	13.18

Table A-1: Dynamic Modulus and Phase Angle Output from AMPT Cont.

4°C (39°F)						
WMA						
Aging Period	ID	Frequency (Hz)	1	0.5	0.2	0.1
0.5hr	1	Dynamic modulus (MPa)	10600	9483	8001	6967
		Phase angle (Degrees)	15.25	16.98	19.53	21.44
	2	Dynamic modulus (MPa)	9569	8497	7126	6190
		Phase angle (Degrees)	16.19	18.13	20.92	23.01
	3	Dynamic modulus (MPa)	9841	8715	7235	6254
		Phase angle (Degrees)	16.30	18.17	20.78	22.80
	4	Dynamic modulus (MPa)	9749	8559	7060	6065
		Phase angle (Degrees)	17.55	19.64	22.57	24.86
2hr	1	Dynamic modulus (MPa)	10464	9318	7864	6803
		Phase angle (Degrees)	16.38	17.57	20.32	22.39
	2	Dynamic modulus (MPa)	9869	8812	7425	6467
		Phase angle (Degrees)	16.24	17.92	20.50	22.32
	3	Dynamic modulus (MPa)	10621	9476	7985	7002
		Phase angle (Degrees)	15.72	17.47	20.04	21.85
	4	Dynamic modulus (MPa)	9740	8581	7115	6201
		Phase angle (Degrees)	16.94	18.79	21.49	23.32
4hr	1	Dynamic modulus (MPa)	10465	9425	8102	7198
		Phase angle (Degrees)	14.54	16.15	18.52	20.22
	2	Dynamic modulus (MPa)	10435	9206	7716	6707
		Phase angle (Degrees)	16.53	18.32	20.92	22.71
	3	Dynamic modulus (MPa)	8654	7702	6474	5681
		Phase angle (Degrees)	17.55	19.45	22.00	23.89
	4	Dynamic modulus (MPa)	9656	8624	7313	6477
		Phase angle (Degrees)	16.26	18.09	20.61	22.37
8hr	1	Dynamic modulus (MPa)	10816	9914	8682	7797
		Phase angle (Degrees)	12.93	14.33	16.40	18.10
	2	Dynamic modulus (MPa)	11151	10114	8786	7844
		Phase angle (Degrees)	13.86	15.40	17.66	19.32
	3	Dynamic modulus (MPa)	N/A	N/A	N/A	N/A
		Phase angle (Degrees)	N/A	N/A	N/A	N/A
	4	Dynamic modulus (MPa)	10832	9709	8293	7308
		Phase angle (Degrees)	14.57	16.15	18.42	20.13

Table A-1: Dynamic Modulus and Phase Angle Output from AMPT Cont.

20°C (68°F)							
WMA							
Aging Period	ID	Frequency (Hz)	25	20	10	5	2
0.5hr	1	Dynamic Modulus (MPa)	8390	7969	6789	5707	4416
		Phase Angle (Degrees)	20.34	21	23.32	25.66	28.77
	2	Dynamic Modulus (MPa)	7514	7195	6111	5071	3873
		Phase Angle (Degrees)	21.26	21.9	24.37	26.79	29.87
	3	Dynamic Modulus (MPa)	8085	7729	6623	5578	4305
		Phase Angle (Degrees)	20.69	21.29	23.4	25.51	28.34
	4	Dynamic Modulus (MPa)	7754	7372	6221	5162	3950
		Phase Angle (Degrees)	21.31	21.89	24.43	27.05	30.4
2hr	1	Dynamic Modulus (MPa)	7767	7409	6308	5275	4044
		Phase Angle (Degrees)	21.2	21.75	24	26.22	29.08
	2	Dynamic Modulus (MPa)	7654	7305	6215	5208	4018
		Phase Angle (Degrees)	21.1	21.7	23.98	26.2	29.16
	3	Dynamic Modulus (MPa)	8789	8362	7155	6040	4703
		Phase Angle (Degrees)	19.82	20.45	22.7	24.98	28.01
	4	Dynamic Modulus (MPa)	8008	7610	6459	5411	4163
		Phase Angle (Degrees)	20.87	21.5	23.81	26.12	29.15
4hr	1	Dynamic Modulus (MPa)	8427	8095	6992	5951	4702
		Phase Angle (Degrees)	19.27	19.89	22.06	24.23	27.07
	2	Dynamic Modulus (MPa)	8501	8071	6904	5838	4558
		Phase Angle (Degrees)	20.04	20.72	22.88	25.03	27.92
	3	Dynamic Modulus (MPa)	7631	7295	6225	5210	4044
		Phase Angle (Degrees)	20.64	21.31	23.53	25.85	28.89
	4	Dynamic Modulus (MPa)	8843	8516	7352	6247	4903
		Phase Angle (Degrees)	19.26	19.94	22.14	24.39	27.25
8hr	1	Dynamic Modulus (MPa)	9030	8753	7714	6680	5424
		Phase Angle (Degrees)	17.42	18.06	19.93	21.89	24.43
	2	Dynamic Modulus (MPa)	8901	8581	7486	6458	5171
		Phase Angle (Degrees)	18.42	19	21.05	23.15	25.92
	3	Dynamic Modulus (MPa)	N/A	N/A	N/A	N/A	N/A
		Phase Angle (Degrees)	N/A	N/A	N/A	N/A	N/A
	4	Dynamic Modulus (MPa)	9172	8700	7483	6397	5098
		Phase Angle (Degrees)	18.58	19.16	21.19	23.22	25.97

Table A-1: Dynamic Modulus and Phase Angle Output from AMPT Cont.

20°C (68°F)						
WMA						
Aging Period	ID	Frequency (Hz)	1	0.5	0.2	0.1
0.5hr	1	Dynamic Modulus (MPa)	3546	2784	1978	1523
		Phase Angle (Degrees)	30.92	32.91	34.3	34.64
	2	Dynamic Modulus (MPa)	3076	2350	1670	1304
		Phase Angle (Degrees)	31.94	33.42	34.86	34.74
	3	Dynamic Modulus (MPa)	3438	2674	1883	1455
		Phase Angle (Degrees)	30.37	32.28	33.79	33.88
	4	Dynamic Modulus (MPa)	3156	2454	1715	1317
		Phase Angle (Degrees)	32.65	34.49	35.95	35.82
2hr	1	Dynamic Modulus (MPa)	3225	2517	1796	1414
		Phase Angle (Degrees)	31.07	32.86	34.04	33.98
	2	Dynamic Modulus (MPa)	3223	2534	1810	1418
		Phase Angle (Degrees)	31.11	32.85	34.16	34.09
	3	Dynamic Modulus (MPa)	3799	2997	2120	1583
		Phase Angle (Degrees)	30.18	32.04	34.21	35.55
	4	Dynamic Modulus (MPa)	3330	2603	1841	1425
		Phase Angle (Degrees)	31.24	32.89	34.43	34.4
4hr	1	Dynamic Modulus (MPa)	3858	3104	2265	1784
		Phase Angle (Degrees)	29.09	30.83	32.82	33.6
	2	Dynamic Modulus (MPa)	3694	2931	2100	1634
		Phase Angle (Degrees)	29.94	31.74	33.69	34.22
	3	Dynamic Modulus (MPa)	3275	2595	1852	1443
		Phase Angle (Degrees)	30.86	32.71	34.2	34.64
	4	Dynamic Modulus (MPa)	4015	3185	2282	1727
		Phase Angle (Degrees)	29.29	31.2	33.25	34.36
8hr	1	Dynamic Modulus (MPa)	4578	3762	2829	2240
		Phase Angle (Degrees)	26.23	28.02	30.25	31.48
	2	Dynamic Modulus (MPa)	4284	3479	2580	2020
		Phase Angle (Degrees)	27.99	29.91	32.05	33.01
	3	Dynamic Modulus (MPa)	N/A	N/A	N/A	N/A
		Phase Angle (Degrees)	N/A	N/A	N/A	N/A
	4	Dynamic Modulus (MPa)	4212	3402	2493	1930
		Phase Angle (Degrees)	27.98	29.97	32.27	33.39

Table A-1: Dynamic Modulus and Phase Angle Output from AMPT Cont.

40°C (104°F)							
WMA							
Aging Period	ID	Frequency (Hz)	25	20	10	5	2
0.5hr	1	Dynamic Modulus (MPa)	1959	1798	1366	1057	787
		Phase Angle (Degrees)	34.9	34.64	34.25	32.66	29.31
	2	Dynamic Modulus (MPa)	1626	1510	1159	909.1	688
		Phase Angle (Degrees)	36.53	35.72	34.64	32.35	28.62
	3	Dynamic Modulus (MPa)	1590	1481	1147	906.2	696.1
		Phase Angle (Degrees)	37.52	36.55	34.88	32.18	28.19
	4	Dynamic Modulus (MPa)	1759	1639	1254	982.4	743.1
		Phase Angle (Degrees)	37.58	36.7	35.35	32.86	29.05
2hr	1	Dynamic Modulus (MPa)	1936	1798	1374	1062	787.6
		Phase Angle (Degrees)	36.77	35.9	35.12	33.52	30.34
	2	Dynamic Modulus (MPa)	1795	1666	1284	1009	765.7
		Phase Angle (Degrees)	35.47	34.69	33.75	31.74	28.3
	3	Dynamic Modulus (MPa)	2027	1877	1429	1097	806.3
		Phase Angle (Degrees)	36.92	36.2	35.72	34.23	31.08
	4	Dynamic Modulus (MPa)	1770	1633	1249	973.3	731.8
		Phase Angle (Degrees)	36.16	35.57	34.65	32.53	28.92
4hr	1	Dynamic Modulus (MPa)	2186	2033	1548	1183	856.5
		Phase Angle (Degrees)	35.91	35.35	35.4	34.46	31.99
	2	Dynamic Modulus (MPa)	2094	1940	1470	1128	822.6
		Phase Angle (Degrees)	36.18	35.58	35.46	34.08	31.36
	3	Dynamic Modulus (MPa)	1798	1675	1285	1009	753.3
		Phase Angle (Degrees)	36.75	35.94	35.16	32.95	29.97
	4	Dynamic Modulus (MPa)	2044	1884	1416	1079	785.3
		Phase Angle (Degrees)	36.99	36.45	36.8	35.22	32.6
8hr	1	Dynamic Modulus (MPa)	2413	2255	1752	1364	1005
		Phase Angle (Degrees)	34.45	33.85	33.8	33.1	31.05
	2	Dynamic Modulus (MPa)	2217	2074	1595	1235	907.8
		Phase Angle (Degrees)	35.66	34.95	34.75	33.73	31.34
	3	Dynamic Modulus (MPa)	N/A	N/A	N/A	N/A	N/A
		Phase Angle (Degrees)	N/A	N/A	N/A	N/A	N/A
	4	Dynamic Modulus (MPa)	2198	2060	1601	1252	930
		Phase Angle (Degrees)	35.2	34.53	34.15	32.96	30.32

Table A-1: Dynamic Modulus and Phase Angle Output from AMPT Cont.

40°C (104°F)							
WMA							
Aging Period	Spec.	Frequency (Hz)	1	0.5	0.2	0.1	0.01
0.5hr	1	Dynamic Modulus (MPa)	655.5	567	497.8	465.6	421.6
		Phase Angle (Degrees)	26.09	22.53	18.38	15.04	10.01
	2	Dynamic Modulus (MPa)	579.8	508.4	448.4	422.9	390.9
		Phase Angle (Degrees)	25.43	22.27	18.09	15.04	10.49
	3	Dynamic Modulus (MPa)	593.6	525.5	469.3	445.5	409.3
		Phase Angle (Degrees)	24.92	21.67	17.57	14.63	9.83
	4	Dynamic Modulus (MPa)	626.9	548.6	484.6	456.4	413.5
		Phase Angle (Degrees)	25.87	22.44	18.4	15.48	10.12
2hr	1	Dynamic Modulus (MPa)	654.5	565	489.7	454.8	412
		Phase Angle (Degrees)	27.29	23.67	19.78	16.24	10.93
	2	Dynamic Modulus (MPa)	644.6	563.7	496.3	469.6	424.3
		Phase Angle (Degrees)	25.38	22.23	18.22	15.65	10.3
	3	Dynamic Modulus (MPa)	662.6	573.4	493.9	456.7	397.5
		Phase Angle (Degrees)	28.07	24.6	20.27	17.13	11.08
	4	Dynamic Modulus (MPa)	614.1	535.8	471.4	446.7	405.9
		Phase Angle (Degrees)	25.79	22.38	18.33	15.5	10.5
4hr	1	Dynamic Modulus (MPa)	696.1	586	491.1	447.3	375.8
		Phase Angle (Degrees)	29.45	26.56	22.58	19.59	12.53
	2	Dynamic Modulus (MPa)	664.6	558.3	492.5	511.4	452.3
		Phase Angle (Degrees)	28.86	26	21.83	17.49	10.85
	3	Dynamic Modulus (MPa)	634.3	552.1	481.1	451.2	410.8
		Phase Angle (Degrees)	27.03	23.97	20.17	17.13	11.7
	4	Dynamic Modulus (MPa)	647.1	547.2	465.2	440.3	431.9
		Phase Angle (Degrees)	29.82	26.9	22.81	19.57	12.95
8hr	1	Dynamic Modulus (MPa)	824	696.2	586.1	533.2	448.2
		Phase Angle (Degrees)	28.87	26.18	22.63	19.66	13
	2	Dynamic Modulus (MPa)	752.9	654	559.1	515.5	451
		Phase Angle (Degrees)	28.91	25.96	21.85	19.03	12.31
	3	Dynamic Modulus (MPa)	N/A	N/A	N/A	N/A	N/A
		Phase Angle (Degrees)	N/A	N/A	N/A	N/A	N/A
	4	Dynamic Modulus (MPa)	765.4	653	555.9	511	440.8
		Phase Angle (Degrees)	28	25.16	20.9	18.24	11.55

Table A-1: Dynamic Modulus and Phase Angle Output from AMPT Cont.

4°C (39°F)							
HMA							
Aging Period	ID	Frequency (Hz)	25	20	10	5	2
0.5hr	1	Dynamic Modulus (MPa)	18055	17654	16492	15323	13750
		Phase Angle (Degrees)	8.19	8.59	9.56	10.62	12.2
	2	Dynamic Modulus (MPa)	16020	15648	14487	13327	11790
		Phase Angle (Degrees)	9.12	9.53	10.74	12.01	13.89
	3	Dynamic Modulus (MPa)	15938	15641	14624	13578	12159
		Phase Angle (Degrees)	8.24	8.68	9.74	10.86	12.56
	4	Dynamic Modulus (MPa)	15385	15013	13921	12814	11363
		Phase Angle (Degrees)	9.28	9.67	10.82	12.09	13.95
2hr	1	Dynamic Modulus (MPa)	15000	14657	13577	12487	11044
		Phase Angle (Degrees)	9.48	9.73	10.95	12.44	14.06
	2	Dynamic Modulus (MPa)	16024	15694	14555	13402	11876
		Phase Angle (Degrees)	9.42	9.87	11.05	12.32	14.15
	3	Dynamic Modulus (MPa)	15811	15398	14254	13175	11726
		Phase Angle (Degrees)	9.07	9.57	10.61	11.74	13.41
	4	Dynamic Modulus (MPa)	16173	15765	14540	13322	11719
		Phase Angle (Degrees)	9.43	10.03	11.31	12.58	14.5
4hr	1	Dynamic Modulus (MPa)	17368	16947	15753	14521	12888
		Phase Angle (Degrees)	8.72	9.4	10.31	11.44	13.01
	2	Dynamic Modulus (MPa)	15403	15100	14108	13132	11831
		Phase Angle (Degrees)	8.46	8.84	9.76	10.76	12.22
	3	Dynamic Modulus (MPa)	16236	15907	14786	13687	12209
		Phase Angle (Degrees)	8.61	9.31	10.11	11.21	12.81
	4	Dynamic Modulus (MPa)	17721	17327	16152	14975	13434
		Phase Angle (Degrees)	7.79	8.23	9.22	10.21	11.66

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Table A-1: Dynamic Modulus and Phase Angle Output from AMPT Cont.

4°C (39°F)						
HMA						
Aging Period	ID	Frequency (Hz)	1	0.5	0.2	0.1
0.5hr	1	Dynamic Modulus (MPa)	12498	11253	9599	8373
		Phase Angle (Degrees)	13.59	15.12	17.49	19.4
	2	Dynamic Modulus (MPa)	10621	9447	7926	6866
		Phase Angle (Degrees)	15.49	17.28	19.95	21.97
	3	Dynamic Modulus (MPa)	11097	9986	8526	7452
		Phase Angle (Degrees)	14.03	15.66	18.19	20.14
	4	Dynamic Modulus (MPa)	10266	9180	7724	6682
		Phase Angle (Degrees)	15.53	17.33	20.02	22.05
2hr	1	Dynamic Modulus (MPa)	9948	8859	7493	6533
		Phase Angle (Degrees)	15.59	17.34	19.83	21.71
	2	Dynamic Modulus (MPa)	10737	9659	8203	7237
		Phase Angle (Degrees)	15.67	17.33	19.75	21.57
	3	Dynamic Modulus (MPa)	10602	9500	8049	7067
		Phase Angle (Degrees)	14.77	16.41	19.35	20.74
	4	Dynamic Modulus (MPa)	10564	9420	7930	6930
		Phase Angle (Degrees)	16.1	17.88	20.39	22.25
4hr	1	Dynamic Modulus (MPa)	11666	10455	8920	7866
		Phase Angle (Degrees)	14.47	16.03	18.26	19.95
	2	Dynamic Modulus (MPa)	10833	9824	8527	7625
		Phase Angle (Degrees)	13.5	14.9	17.08	18.77
	3	Dynamic Modulus (MPa)	11102	9963	8536	7551
		Phase Angle (Degrees)	14.23	15.56	17.97	19.81
	4	Dynamic Modulus (MPa)	12254	11089	9564	8420
		Phase Angle (Degrees)	12.87	14.21	16.28	17.9

Table A-1: Dynamic Modulus and Phase Angle Output from AMPT Cont.

20°C (68°F)							
HMA							
Aging Period	ID	Frequency (Hz)	25	20	10	5	2
0.5hr	1	Dynamic Modulus (MPa)	8024	7632	6405	5357	4083
		Phase Angle (Degrees)	21.07	21.78	24.24	26.57	29.48
	2	Dynamic Modulus (MPa)	7729	7430	6308	5246	4007
		Phase Angle (Degrees)	21.37	22.04	24.46	26.82	29.8
	3	Dynamic Modulus (MPa)	7528	7177	6062	5029	3821
		Phase Angle (Degrees)	21.88	22.62	25.25	27.89	31.23
	4	Dynamic Modulus (MPa)	8126	7733	6623	5588	4311
		Phase Angle (Degrees)	20.25	20.95	23.28	25.61	28.67
2hr	1	Dynamic Modulus (MPa)	7761	7365	6287	5321	4139
		Phase Angle (Degrees)	20.21	20.9	23.17	25.41	28.32
	2	Dynamic Modulus (MPa)	8851	8463	7295	6197	4880
		Phase Angle (Degrees)	19.33	19.93	22.15	24.32	27.16
	3	Dynamic Modulus (MPa)	9036	8643	7484	6392	5064
		Phase Angle (Degrees)	18.67	19.19	21.25	23.36	26.2
	4	Dynamic Modulus (MPa)	9227	8835	7676	6568	5191
		Phase Angle (Degrees)	18.54	19.16	21.37	23.59	26.55
4hr	1	Dynamic Modulus (MPa)	10311	9841	8622	7466	6060
		Phase Angle (Degrees)	16.56	17.11	18.98	20.8	23.31
	2	Dynamic Modulus (MPa)	9397	9050	7924	6830	5509
		Phase Angle (Degrees)	17.61	18.2	20.14	22.21	24.99
	3	Dynamic Modulus (MPa)	9469	9113	7960	6849	5486
		Phase Angle (Degrees)	17.3	17.86	19.87	21.83	24.56
	4	Dynamic Modulus (MPa)	8592	8246	7218	6206	4942
		Phase Angle (Degrees)	18	18.6	20.59	22.57	25.25

Table A-1: Dynamic Modulus and Phase Angle Output from AMPT Cont.

20°C (68°F)						
HMA						
Aging Period	ID	Frequency (Hz)	1	0.5	0.2	0.1
0.5hr	1	Dynamic Modulus (MPa)	3245	2520	1782	1393
		Phase Angle (Degrees)	31.45	33.1	34.12	33.7
	2	Dynamic Modulus (MPa)	3187	2482	1741	1359
		Phase Angle (Degrees)	31.74	33.29	34.27	33.91
	3	Dynamic Modulus (MPa)	3032	2353	1658	1281
		Phase Angle (Degrees)	33.43	35.02	36.31	35.86
	4	Dynamic Modulus (MPa)	3462	2715	1913	1458
		Phase Angle (Degrees)	30.8	32.59	34.16	34.16
2hr	1	Dynamic Modulus (MPa)	3339	2651	1920	1503
		Phase Angle (Degrees)	30.26	31.76	33.19	33.15
	2	Dynamic Modulus (MPa)	3975	3157	2275	1762
		Phase Angle (Degrees)	29.12	30.79	32.46	32.88
	3	Dynamic Modulus (MPa)	4162	3355	2439	1888
		Phase Angle (Degrees)	28.25	30.18	32.53	33.31
	4	Dynamic Modulus (MPa)	4224	3361	2422	1862
		Phase Angle (Degrees)	28.7	30.61	32.88	33.55
4hr	1	Dynamic Modulus (MPa)	5099	4207	3191	2543
		Phase Angle (Degrees)	25.2	27.01	29.35	30.26
	2	Dynamic Modulus (MPa)	4628	3768	2799	2158
		Phase Angle (Degrees)	27.08	29.27	31.23	32.44
	3	Dynamic Modulus (MPa)	4570	3738	2775	2175
		Phase Angle (Degrees)	26.57	28.43	30.75	31.91
	4	Dynamic Modulus (MPa)	4080	3330	2455	1936
		Phase Angle (Degrees)	27.15	29.14	30.84	31.72

Table A-1: Dynamic Modulus and Phase Angle Output from AMPT Cont.

40°C (104°F) HMA							
HMA							
Aging Period	ID	Frequency(Hz)	25	20	10	5	2
0.5hr	1	Dynamic Modulus (MPa)	1708	1594	1227	968.5	732.9
		Phase Angle (Degrees)	35.65	35.02	34.07	31.36	27.76
	2	Dynamic Modulus (MPa)	2102	1933	1474	1150	851.9
		Phase Angle (Degrees)	35.13	34.64	34.58	32.74	29.7
	3	Dynamic Modulus (MPa)	1605	1474	1068	778.6	514.5
		Phase Angle (Degrees)	38.75	38.2	38.13	36.68	34.91
	4	Dynamic Modulus (MPa)	1929	1784	1353	1047	774
		Phase Angle (Degrees)	35.79	35.28	34.99	32.94	29.57
2hr	1	Dynamic Modulus (MPa)	2143	1987	1535	1199	888.2
		Phase Angle (Degrees)	34.95	34.3	34.16	32.52	29.74
	2	Dynamic Modulus (MPa)	2425	2238	1711	1328	978.2
		Phase Angle (Degrees)	33.32	33.1	33.25	32.09	29.57
	3	Dynamic Modulus (MPa)	2470	2281	1747	1348	983.2
		Phase Angle (Degrees)	33.96	33.8	34.1	33.32	31.16
	4	Dynamic Modulus (MPa)	2204	2040	1548	1190	860
		Phase Angle (Degrees)	35.52	35.05	35.25	33.69	31.45
4hr	1	Dynamic Modulus (MPa)	2834	2634	2051	1594	1159
		Phase Angle (Degrees)	32.87	32.61	32.97	32.53	30.83
	2	Dynamic Modulus (MPa)	2315	2136	1610	1207	821.2
		Phase Angle (Degrees)	34.39	34.31	35.03	34.75	33.96
	3	Dynamic Modulus (MPa)	2732	2534	1957	1511	1099
		Phase Angle (Degrees)	33.42	33.22	33.52	33.02	31.09
	4	Dynamic Modulus (MPa)	3149	2933	2286	1770	1275
		Phase Angle (Degrees)	31.94	31.89	32.67	32.72	31.53

Table A-1: Dynamic Modulus and Phase Angle Output from AMPT Cont.

40°C (104°F)							
HMA							
Aging Period	ID	Frequency(Hz)	1	0.5	0.2	0.1	0.01
0.5hr	1	Dynamic Modulus (MPa)	621.3	547.1	486.9	461.9	399.2
		Phase Angle (Degrees)	24.38	21.09	16.57	14.16	10.76
	2	Dynamic Modulus (MPa)	710	609.1	523.6	485.4	433.7
		Phase Angle (Degrees)	26.41	22.79	19.18	16.83	9.87
	3	Dynamic Modulus (MPa)	395.7	325.6	249.5	248.6	220
		Phase Angle (Degrees)	32.3	28.75	24.51	19.74	13.47
	4	Dynamic Modulus (MPa)	644.2	554.5	460.2	404.8	371.6
		Phase Angle (Degrees)	26.4	23.2	18.84	16.27	10
2hr	1	Dynamic Modulus (MPa)	736.2	624.2	533.6	489.4	431.2
		Phase Angle (Degrees)	26.79	23.39	19.71	16.66	10.46
	2	Dynamic Modulus (MPa)	806.1	687	583.7	535	466.1
		Phase Angle (Degrees)	26.83	23.93	19.68	15.93	10.15
	3	Dynamic Modulus (MPa)	800.2	674.2	563.5	510.7	445.7
		Phase Angle (Degrees)	28.75	25.91	21.77	19.48	11.4
	4	Dynamic Modulus (MPa)	700.6	590.1	490.9	437.7	328.5
		Phase Angle (Degrees)	28.69	25.86	21.82	18.55	12.67
4hr	1	Dynamic Modulus (MPa)	937.2	785.5	646.5	577.3	467.6
		Phase Angle (Degrees)	28.88	26.35	22.58	19.24	11.89
	2	Dynamic Modulus (MPa)	613.1	448.5	276.8	181.6	71.6
		Phase Angle (Degrees)	32.92	32.07	31.88	31.62	26.85
	3	Dynamic Modulus (MPa)	890	742.4	614.1	553.9	449.3
		Phase Angle (Degrees)	28.88	25.98	22.43	19.27	11.91
	4	Dynamic Modulus (MPa)	1018	833.9	672.1	588.3	456.6
		Phase Angle (Degrees)	29.86	27.46	23.81	20.29	11.97

Table A-2: Flown Number and Cycles to 5% Permanent Strain Output from AMPT

WMA			
Aging Period	ID	Flow Number (Cycles)	Cycles to 5% Permanent Strain
0.5hr	1	21	48
	2	33	80
	3	32	73
	4	32	76
2hr	1	43	105
	2	37	86
	3	39	94
	4	32	84
4hr	1	34	84
	2	29	86
	3	38	81
	4	37	96
8hr	1	59	147
	2	55	147
	3	N/A	N/A
	4	50	126
HMA			
Aging Period	ID	Flow Number	Cycles to 5% Permanent Strain
0.5hr	1	20	50
	2	29	73
	3	31	74
	4	23	52
2hr	1	26	67
	2	35	89
	3	44	104
	4	N/A	N/A
4hr	1	50	139
	2	43	105
	3	34	87
	4	39	102

Table A-3: CMOD and Peak Load Output from DC(t) Testing

4°C (39°F)			
HMA			
Aging Period	ID	CMOD (J/ms^2)	Peak Load (kN)
0.5hr	0.5-3	967.4	2.4
	0.5-7	1165.7	2.6
	0.5-9	890.7	2.8
2hr	2-2-B	893.5	2.9
	2-3-B	675.3	2.8
	2-4-B	943.6	2.8
4hr	4-2-B	777.2	2.7
	4-3-A	1178.5	2.4
	4-4-B	791.6	2.5
8hr	8-3-A	737.4	2.7
	8-3-B	659.1	2.7
	8-4-A	603.6	2.7
4°C (39°F)			
WMA			
Aging Period	ID	CMOD (J/ms^2)	Peak Load (kN)
0.5hr	0.5-1-A	1466.5	2.4
	0.5-2-A	1058.3	2.6
	0.5-3-A	1342.5	2.5
2hr	2-1-A	1223.6	2.6
	2-2-A	1087.3	2.3
	2-3-A	1094.2	2.4
4hr	4-2-A	923.0	2.7
	4-3-A	975.0	2.7
	4-4-A	794.2	2.3
8hr	8-1-A	800.7	2.7
	8-2-A	622.4	2.5
	8-3-A	737.4	2.7

Table A-3: CMOD and Peak Load Output from DC(t) Testing Cont.

20°C (68°F)			
HMA			
Aging Period	ID	CMOD (J/ms^2)	Peak Load (kN)
0.5hr	0.5-1	572.9	2.6
	0.5-2	381.9	2.8
	0.5-4	438.1	2.8
2hr	2-1-A	514.5	3.0
	2-2-A	521.5	3.3
	2-5-A	397.9	2.6
4hr	4-1-A	429.8	2.8
	4-1-B	448.4	2.9
	4-5-A	416.8	2.7
8hr	8-1-A	384.8	2.8
	8-1-B	385.3	2.7
	8-5-B	273.6	2.9
20°C (68°F)			
WMA			
Aging Period	ID	CMOD (J/ms^2)	Peak Load (kN)
0.5hr	0.5-1-B	383.0	2.6
	0.5-3-B	465.1	2.7
	N/A	N/A	N/A
2hr	2-1-B	354.7	2.9
	2-2-B	429.6	2.7
	2-3-B	476.8	3.1
4hr	4-1-B	530.7	3.1
	4-2-B	471.0	3.0
	4-3-B	384.5	3.0
8hr	8-1-B	383.5	2.9
	8-2-B	429.2	2.7
	8-4-A	467.2	2.9

Table A-3: CMOD and Peak Load Output from DC(t) Testing

40°C (104°F)			
HMA			
Aging Period	ID	CMOD (J/ms^2)	Peak Load (kN)
0.5hr	0.5-5	N/A	N/A
	0.5-6	254.1	3.2
	0.5-8	238.7	2.8
2hr	2-3-A	236.6	2.9
	2-4-A	266.9	2.7
	N/A	N/A	N/A
4hr	4-3-B	311.6	3.0
	4-4-A	193.1	2.7
	4-5-B	231.0	2.6
8hr	8-4-B	N/A	N/A
	8-5-A	222.9	3.1
	8-5-B	273.6	2.9
40°C (104°F)			
WMA			
Aging Period	ID	CMOD (J/ms^2)	Peak Load (kN)
0.5hr	0.5-6-A	221.8	2.3
	N/A	N/A	N/A
	N/A	N/A	N/A
2hr	2-6-A	243.0	2.6
	2-6-B	182.3	2.7
	N/A	N/A	N/A
4hr	4-1-A	217.1	2.8
	4-4-B	224.2	2.5
	4-5-B	N/A	N/A
8hr	8-3-B	198.0	2.7
	8-4-B	N/A	N/A
	8-5-B	271.9	2.9

Appendix B: Raw Statistical Analysis Data

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B-1: Dynamic Modulus Statistical Analysis

B-1.1: 4^{o}C Dynamic Modulus Analysis at 25Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y25 y25

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	19388169.54	2769738.51	3.77	0.0073
Error	23	16901625.17	734853.27		
Corrected Total	30	36289794.71			

R-Square	Coeff Var	Root MSE	y25 Mean
0.534260	5.426884	857.2358	15796.10

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	3018592.03	1006197.34	1.37	0.2771
B	1	13384106.84	13384106.84	18.21	0.0003
A*B	3	2985470.68	995156.89	1.35	0.2816

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	2187467.90	729155.97	0.99	0.4140
B	1	13462008.33	13462008.33	18.32	0.0003
A*B	3	2985470.68	995156.89	1.35	0.2816

B-1.2: 4°C Dynamic Modulus Analysis at 20Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read	31
Number of Observations Used	31

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The GLM Procedure

Dependent Variable: y20 y20

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	18167154.30	2595307.76	3.81	0.0069
Error	23	15669317.25	681274.66		
Corrected Total	30	33836471.55			

R-Square	Coeff Var	Root MSE	y20 Mean
0.536910	5.337372	825.3936	15464.42

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	3165035.49	1055011.83	1.55	0.2289
B	1	12137466.91	12137466.91	17.82	0.0003
A*B	3	2864651.90	954883.97	1.40	0.2677

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	2349084.08	783028.03	1.15	0.3503
B	1	12206077.23	12206077.23	17.92	0.0003
A*B	3	2864651.90	954883.97	1.40	0.2677

B-1.3: $4^{o}C$ Dynamic Modulus Analysis at 10Hz

```
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                                  The GLM Procedure

                               Class Level Information

                          Class         Levels    Values

                          A                  4    0.5 2 4 8

                          B                  2    + -


                       Number of Observations Read          31
                       Number of Observations Used          31
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                                  The GLM Procedure

Dependent Variable: y10   y10

                                             Sum of
      Source                      DF        Squares     Mean Square    F Value    Pr > F

      Model                        7    16191506.93      2313072.42       3.90    0.0061

      Error                       23    13635804.17       592861.05

      Corrected Total             30    29827311.10


                       R-Square     Coeff Var      Root MSE      y10 Mean

                       0.542842      5.357704      769.9747      14371.35


      Source                      DF      Type I SS     Mean Square    F Value    Pr > F

      A                            3     3235964.10      1078654.70       1.82    0.1718
      B                            1    10334986.80     10334986.80      17.43    0.0004
      A*B                          3     2620556.04       873518.68       1.47    0.2480


      Source                      DF    Type III SS     Mean Square    F Value    Pr > F

      A                            3     2525887.48       841962.49       1.42    0.2624
      B                            1    10328269.65     10328269.65      17.42    0.0004
      A*B                          3     2620556.04       873518.68       1.47    0.2480
```

B-1.4: 4^{o}C Dynamic Modulus Analysis at 5Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y5 y5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	14724142.87	2103448.98	4.06	0.0049
Error	23	11928213.00	518617.96		
Corrected Total	30	26652355.87			

R-Square	Coeff Var	Root MSE	y5 Mean
0.552452	5.426887	720.1513	13270.06

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	3340110.532	1113370.177	2.15	0.1219
B	1	8975893.524	8975893.524	17.31	0.0004
A*B	3	2408138.815	802712.938	1.55	0.2291

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	2724828.037	908276.012	1.75	0.1846
B	1	8906187.000	8906187.000	17.17	0.0004
A*B	3	2408138.815	802712.938	1.55	0.2291

B-1.5: 4^oC Dynamic Modulus Analysis at 2Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y2 y2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	13577968.92	1939709.85	4.38	0.0032
Error	23	10183425.92	442757.65		
Corrected Total	30	23761394.84			

R-Square	Coeff Var	Root MSE	y2 Mean
0.571430	5.639850	665.4004	11798.19

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	3593625.910	1197875.303	2.71	0.0689
B	1	7717428.892	7717428.892	17.43	0.0004
A*B	3	2266914.120	755638.040	1.71	0.1935

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	3076527.898	1025509.299	2.32	0.1023
B	1	7582074.163	7582074.163	17.12	0.0004
A*B	3	2266914.120	755638.040	1.71	0.1935

B-1.6: 4^oC Dynamic Modulus Analysis at 1Hz

```
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                                 The GLM Procedure

                              Class Level Information

                         Class         Levels    Values

                         A                  4    0.5 2 4 8

                         B                  2    + -


                      Number of Observations Read          31
                      Number of Observations Used          31
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                                 The GLM Procedure

Dependent Variable: y1   y1

                                             Sum of
      Source                      DF        Squares     Mean Square    F Value    Pr > F

      Model                        7     13191579.94      1884511.42       4.88    0.0017

      Error                       23      8890190.25       386530.01

      Corrected Total             30     22081770.19


                       R-Square     Coeff Var      Root MSE       y1 Mean

                       0.597397      5.822853      621.7154      10677.16


      Source                      DF       Type I SS     Mean Square    F Value    Pr > F

      A                            3     3986536.711     1328845.570       3.44    0.0336
      B                            1     7062250.149     7062250.149      18.27    0.0003
      A*B                          3     2142793.083      714264.361       1.85    0.1667


      Source                      DF     Type III SS     Mean Square    F Value    Pr > F

      A                            3     3537682.454     1179227.485       3.05    0.0489
      B                            1     6872046.750     6872046.750      17.78    0.0003
      A*B                          3     2142793.083      714264.361       1.85    0.1667
```

B-1.7: 4^oC Dynamic Modulus Analysis at 0.5Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y05 y05

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	12824821.01	1832117.29	5.44	0.0009
Error	23	7739070.67	336481.33		
Corrected Total	30	20563891.68			

R-Square	Coeff Var	Root MSE	y05 Mean
0.623657	6.062258	580.0701	9568.548

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	4370647.088	1456882.363	4.33	0.0147
B	1	6468138.524	6468138.524	19.22	0.0002
A*B	3	1986035.398	662011.799	1.97	0.1470

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	3959065.565	1319688.522	3.92	0.0213
B	1	6257718.613	6257718.613	18.60	0.0003
A*B	3	1986035.398	662011.799	1.97	0.1470

B-1.8: 4^oC Dynamic Modulus Analysis at 0.2Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y02 y02

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	12484962.89	1783566.13	6.33	0.0003
Error	23	6476561.50	281589.63		
Corrected Total	30	18961524.39			

R-Square	Coeff Var	Root MSE	y02 Mean
0.658437	6.518812	530.6502	8140.290

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	5138606.512	1712868.837	6.08	0.0033
B	1	5601413.255	5601413.255	19.89	0.0002
A*B	3	1744943.120	581647.707	2.07	0.1327

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	4754286.083	1584762.028	5.63	0.0048
B	1	5393233.920	5393233.920	19.15	0.0002
A*B	3	1744943.120	581647.707	2.07	0.1327

B-1.9: 4^{o}C Dynamic Modulus Analysis at 0.1Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y01 y01

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	11972484.00	1710354.86	7.50	<.0001
Error	23	5244327.42	228014.24		
Corrected Total	30	17216811.42			

R-Square	Coeff Var	Root MSE	y01 Mean
0.695395	6.667970	477.5084	7161.226

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	5859904.669	1953301.556	8.57	0.0005
B	1	4795093.852	4795093.852	21.03	0.0001
A*B	3	1317485.481	439161.827	1.93	0.1535

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	5445546.648	1815182.216	7.96	0.0008
B	1	4632412.803	4632412.803	20.32	0.0002
A*B	3	1317485.481	439161.827	1.93	0.1535

B-1.10: $20^{o}C$ Dynamic Modulus Analysis at 25Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y25 y25

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	9536717.27	1362388.18	5.16	0.0012
Error	23	6075850.67	264167.42		
Corrected Total	30	15612567.94			

R-Square	Coeff Var	Root MSE	y25 Mean
0.610836	6.020343	513.9722	8537.258

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	6256312.971	2085437.657	7.89	0.0009
B	1	1449809.788	1449809.788	5.49	0.0282
A*B	3	1830594.509	610198.170	2.31	0.1030

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	6220756.731	2073585.577	7.85	0.0009
B	1	1342147.853	1342147.853	5.08	0.0340
A*B	3	1830594.509	610198.170	2.31	0.1030

B-1.11: $20^{o}C$ Dynamic Modulus Analysis at 20Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read	31
Number of Observations Used	31

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The GLM Procedure

Dependent Variable: y20 y20

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	9284555.52	1326365.07	5.53	0.0008
Error	23	5514305.25	239752.40		
Corrected Total	30	14798860.77			

R-Square	Coeff Var	Root MSE	y20 Mean
0.627383	6.000056	489.6452	8160.677

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	6128225.310	2042741.770	8.52	0.0005
B	1	1331796.214	1331796.214	5.55	0.0273
A*B	3	1824534.000	608178.000	2.54	0.0817

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	6120856.333	2040285.444	8.51	0.0006
B	1	1220749.230	1220749.230	5.09	0.0338
A*B	3	1824534.000	608178.000	2.54	0.0817

B-1.12: 20^{o}C Dynamic Modulus Analysis at 10Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y10 y10

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	9439896.05	1348556.58	6.61	0.0002
Error	23	4690487.50	203934.24		
Corrected Total	30	14130383.55			

R-Square	Coeff Var	Root MSE	y10 Mean
0.668057	6.424150	451.5908	7029.581

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	6312233.584	2104077.861	10.32	0.0002
B	1	1292206.881	1292206.881	6.34	0.0192
A*B	3	1835455.583	611818.528	3.00	0.0514

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	6304590.509	2101530.170	10.30	0.0002
B	1	1183905.720	1183905.720	5.81	0.0244
A*B	3	1835455.583	611818.528	3.00	0.0514

B-1.13: 20^{o}C Dynamic Modulus Analysis at 5Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y5 y5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	9084517.19	1297788.17	7.68	<.0001
Error	23	3884388.17	168886.44		
Corrected Total	30	12968905.35			

R-Square	Coeff Var	Root MSE	y5 Mean
0.700485	6.884425	410.9580	5969.387

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	6149785.980	2049928.660	12.14	<.0001
B	1	1211024.921	1211024.921	7.17	0.0134
A*B	3	1723706.287	574568.762	3.40	0.0348

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	6147997.398	2049332.466	12.13	<.0001
B	1	1106561.333	1106561.333	6.55	0.0175
A*B	3	1723706.287	574568.762	3.40	0.0348

B-1.14: 20^{o}C Dynamic Modulus Analysis at 2Hz

The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read	31
Number of Observations Used	31

The GLM Procedure

Dependent Variable: y2 y2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	8262839.69	1180405.67	9.47	<.0001
Error	23	2867290.50	124664.80		
Corrected Total	30	11130130.19			

R-Square	Coeff Var	Root MSE	y2 Mean
0.742385	7.518977	353.0790	4695.839

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	5761310.336	1920436.779	15.40	<.0001
B	1	1026172.024	1026172.024	8.23	0.0087
A*B	3	1475357.333	491785.778	3.94	0.0209

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	5751965.481	1917321.827	15.38	<.0001
B	1	939456.480	939456.480	7.54	0.0115
A*B	3	1475357.333	491785.778	3.94	0.0209

B-1.15: 20^oC Dynamic Modulus Analysis at 1Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y1 y1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	7541473.621	1077353.374	11.22	<.0001
Error	23	2207948.250	95997.750		
Corrected Total	30	9749421.871			

R-Square	Coeff Var	Root MSE	y1 Mean
0.773530	8.070587	309.8350	3839.065

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	5403646.621	1801215.540	18.76	<.0001
B	1	894590.796	894590.796	9.32	0.0056
A*B	3	1243236.204	414412.068	4.32	0.0149

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	5384165.333	1794721.778	18.70	<.0001
B	1	822156.750	822156.750	8.56	0.0076
A*B	3	1243236.204	414412.068	4.32	0.0149

B-1.16: 20°C Dynamic Modulus Analysis at 0.5Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y05 y05

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	6564045.922	937720.846	13.76	<.0001
Error	23	1567308.917	68143.866		
Corrected Total	30	8131354.839			

R-Square	Coeff Var	Root MSE	y05 Mean
0.807251	8.492526	261.0438	3073.806

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	4817568.749	1605856.250	23.57	<.0001
B	1	805516.006	805516.006	11.82	0.0022
A*B	3	940961.167	313653.722	4.60	0.0115

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	4772901.593	1590967.198	23.35	<.0001
B	1	749500.083	749500.083	11.00	0.0030
A*B	3	940961.167	313653.722	4.60	0.0115

B-1.17: 20^oC Dynamic Modulus Analysis at 0.2Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y02 y02

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	4802020.242	686002.892	16.83	<.0001
Error	23	937315.500	40752.848		
Corrected Total	30	5739335.742			

R-Square	Coeff Var	Root MSE	y02 Mean
0.836686	9.010127	201.8733	2240.516

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	3584415.992	1194805.331	29.32	<.0001
B	1	612101.907	612101.907	15.02	0.0008
A*B	3	605502.343	201834.114	4.95	0.0085

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	3520139.083	1173379.694	28.79	<.0001
B	1	579217.080	579217.080	14.21	0.0010
A*B	3	605502.343	201834.114	4.95	0.0085

B-1.18: 20^{o}C Dynamic Modulus Analysis at 0.1Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y01 y01

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	3392846.503	484692.358	20.14	<.0001
Error	23	553634.917	24071.083		
Corrected Total	30	3946481.419			

R-Square	Coeff Var	Root MSE	y01 Mean
0.859714	8.846554	155.1486	1753.774

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	2564661.044	854887.015	35.52	<.0001
B	1	464766.588	464766.588	19.31	0.0002
A*B	3	363418.870	121139.623	5.03	0.0079

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	2487310.148	829103.383	34.44	<.0001
B	1	449229.603	449229.603	18.66	0.0003
A*B	3	363418.870	121139.623	5.03	0.0079

B-1.19: $40^{o}C$ Dynamic Modulus Analysis at 25Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read	31
Number of Observations Used	31

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The GLM Procedure

Dependent Variable: y25 y25

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	4250556.089	607222.298	15.70	<.0001
Error	23	889732.750	38684.033		
Corrected Total	30	5140288.839			

R-Square	Coeff Var	Root MSE	y25 Mean
0.826910	8.985836	196.6826	2188.806

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	2487920.982	829306.994	21.44	<.0001
B	1	1372223.876	1372223.876	35.47	<.0001
A*B	3	390411.231	130137.077	3.36	0.0361

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	2336018.120	778672.707	20.13	<.0001
B	1	1368090.270	1368090.270	35.37	<.0001
A*B	3	390411.231	130137.077	3.36	0.0361

B-1.20: $40^{o}C$ Dynamic Modulus Analysis at 20Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y20 y20

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	3805491.220	543641.603	16.17	<.0001
Error	23	773369.167	33624.746		
Corrected Total	30	4578860.387			

R-Square	Coeff Var	Root MSE	y20 Mean
0.831100	9.016553	183.3705	2033.710

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	2279500.209	759833.403	22.60	<.0001
B	1	1180596.892	1180596.892	35.11	<.0001
A*B	3	345394.120	115131.373	3.42	0.0340

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	2135856.417	711952.139	21.17	<.0001
B	1	1179136.213	1179136.213	35.07	<.0001
A*B	3	345394.120	115131.373	3.42	0.0340

B-1.21: 40°C Dynamic Modulus Analysis at 10Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y10 y10

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	2485896.253	355128.036	15.91	<.0001
Error	23	513525.167	22327.181		
Corrected Total	30	2999421.419			

R-Square	Coeff Var	Root MSE	y10 Mean
0.828792	9.561383	149.4228	1562.774

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	1506772.955	502257.652	22.50	<.0001
B	1	729785.399	729785.399	32.69	<.0001
A*B	3	249337.898	83112.633	3.72	0.0257

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	1405532.917	468510.972	20.98	<.0001
B	1	731712.853	731712.853	32.77	<.0001
A*B	3	249337.898	83112.633	3.72	0.0257

B-1.22: 40^{o}C Dynamic Modulus Analysis at 5Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read	31
Number of Observations Used	31

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The GLM Procedure

Dependent Variable: y5 y5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	1458271.260	208324.466	13.82	<.0001
Error	23	346737.379	15075.538		
Corrected Total	30	1805008.639			

R-Square	Coeff Var	Root MSE	y5 Mean
0.807903	10.15324	122.7825	1209.294

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	885886.9378	295295.6459	19.59	<.0001
B	1	412391.4408	412391.4408	27.36	<.0001
A*B	3	159992.8809	53330.9603	3.54	0.0306

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	825822.9270	275274.3090	18.26	<.0001
B	1	413464.8376	413464.8376	27.43	<.0001
A*B	3	159992.8809	53330.9603	3.54	0.0306

B-1.23: 40°C Dynamic Modulus Analysis at 2Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y2 y2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	650426.5230	92918.0747	9.18	<.0001
Error	23	232890.2525	10125.6632		
Corrected Total	30	883316.7755			

R-Square	Coeff Var	Root MSE	y2 Mean
0.736346	11.38768	100.6264	883.6419

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	402510.5044	134170.1681	13.25	<.0001
B	1	160795.5938	160795.5938	15.88	0.0006
A*B	3	87120.4248	29040.1416	2.87	0.0586

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	377856.5731	125952.1910	12.44	<.0001
B	1	160512.9483	160512.9483	15.85	0.0006
A*B	3	87120.4248	29040.1416	2.87	0.0586

B-1.24: 40°C Dynamic Modulus Analysis at 1Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y1 y1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	325914.2253	46559.1750	5.34	0.0010
Error	23	200531.1567	8718.7459		
Corrected Total	30	526445.3819			

R-Square	Coeff Var	Root MSE	y1 Mean
0.619085	12.96533	93.37423	720.1839

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	203884.5139	67961.5046	7.79	0.0009
B	1	69845.5372	69845.5372	8.01	0.0095
A*B	3	52184.1742	17394.7247	2.00	0.1428

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	194309.6206	64769.8735	7.43	0.0012
B	1	68669.0181	68669.0181	7.88	0.0100
A*B	3	52184.1742	17394.7247	2.00	0.1428

B-1.25: 40^{o}C Dynamic Modulus Analysis at 0.5Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read	31
Number of Observations Used	31

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The GLM Procedure

Dependent Variable: y05 y05

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	159974.9658	22853.5665	2.83	0.0278
Error	23	185706.3317	8074.1883		
Corrected Total	30	345681.2974			

R-Square	Coeff Var	Root MSE	y05 Mean
0.462782	14.78515	89.85649	607.7484

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	102615.5544	34205.1848	4.24	0.0160
B	1	25550.5557	25550.5557	3.16	0.0885
A*B	3	31808.8556	10602.9519	1.31	0.2942

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	99689.89120	33229.96373	4.12	0.0178
B	1	24520.09613	24520.09613	3.04	0.0948
A*B	3	31808.85565	10602.95188	1.31	0.2942

B-1.26: 40^{o}C Dynamic Modulus Analysis at 0.2Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y02 y02

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	62156.9093	8879.5585	1.03	0.4367
Error	23	198029.4417	8609.9757		
Corrected Total	30	260186.3510			

R-Square	Coeff Var	Root MSE	y02 Mean
0.238894	18.23829	92.78995	508.7645

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	41577.64793	13859.21598	1.61	0.2145
B	1	2047.04794	2047.04794	0.24	0.6304
A*B	3	18532.21343	6177.40448	0.72	0.5517

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	42198.12898	14066.04299	1.63	0.2091
B	1	1726.08053	1726.08053	0.20	0.6585
A*B	3	18532.21343	6177.40448	0.72	0.5517

B-1.27: 40^{o}C Dynamic Modulus Analysis at 0.1Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y01 y01

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	31777.2089	4539.6013	0.51	0.8185
Error	23	205283.6550	8925.3763		
Corrected Total	30	237060.8639			

R-Square	Coeff Var	Root MSE	y01 Mean
0.134047	20.30957	94.47421	465.1710

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	21515.11423	7171.70474	0.80	0.5047
B	1	570.30288	570.30288	0.06	0.8027
A*B	3	9691.79176	3230.59725	0.36	0.7810

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	22675.49509	7558.49836	0.85	0.4824
B	1	728.20920	728.20920	0.08	0.7777
A*B	3	9691.79176	3230.59725	0.36	0.7810

B-1.28: 40^{o}C Dynamic Modulus Analysis at 0.01Hz

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 31
Number of Observations Used 31

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The GLM Procedure

Dependent Variable: y001 y001

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	26687.2638	3812.4663	0.46	0.8498
Error	23	188657.6517	8202.5066		
Corrected Total	30	215344.9155			

R-Square	Coeff Var	Root MSE	y001 Mean
0.123928	22.80968	90.56769	397.0581

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	4686.99745	1562.33248	0.19	0.9018
B	1	14371.41683	14371.41683	1.75	0.1986
A*B	3	7628.84954	2542.94985	0.31	0.8179

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	5294.85287	1764.95096	0.22	0.8849
B	1	15100.28853	15100.28853	1.84	0.1880
A*B	3	7628.84954	2542.94985	0.31	0.8179

B-2: Flow Number Analysis

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 30
Number of Observations Used 30

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The GLM Procedure

Dependent Variable: yFN yFN

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	7936.800000	1133.828571	16.61	<.0001
Error	22	1502.166667	68.280303		
Corrected Total	29	9438.966667			

R-Square	Coeff Var	Root MSE	yFN Mean
0.840855	19.68989	8.263190	41.96667

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	6823.948810	2274.649603	33.31	<.0001
B	1	244.786401	244.786401	3.59	0.0715
A*B	3	868.064789	289.354930	4.24	0.0166

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	6132.410943	2044.136981	29.94	<.0001
B	1	273.282051	273.282051	4.00	0.0579
A*B	3	868.064789	289.354930	4.24	0.0166

B-3: Cycles to 5% Permanent Deformation Analysis

The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 30
Number of Observations Used 30

The GLM Procedure

Dependent Variable: yC5 yC5

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	51523.08333	7360.44048	24.02	<.0001
Error	22	6742.41667	306.47348		
Corrected Total	29	58265.50000			

R-Square	Coeff Var	Root MSE	yC5 Mean
0.884281	16.75252	17.50638	104.5000

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	45261.42857	15087.14286	49.23	<.0001
B	1	1740.70330	1740.70330	5.68	0.0262
A*B	3	4520.95147	1506.98382	4.92	0.0092

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	41125.51190	13708.50397	44.73	<.0001
B	1	1885.54167	1885.54167	6.15	0.0213
A*B	3	4520.95147	1506.98382	4.92	0.0092

B-4: Disk Shaped Compact Tension Testing Statistical Analysis

B-4.1: -2^{o}C Fracture Energy Analysis

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read	24
Number of Observations Used	24

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The GLM Procedure

Dependent Variable: yDCT yDCT

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	900421.476	128631.639	6.30	0.0011
Error	16	326712.853	20419.553		
Corrected Total	23	1227134.330			

R-Square	Coeff Var	Root MSE	yDCT Mean
0.733760	15.30445	142.8970	933.6958

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	644226.5246	214742.1749	10.52	0.0005
B	1	141296.7604	141296.7604	6.92	0.0182
A*B	3	114898.1913	38299.3971	1.88	0.1744

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	644226.5246	214742.1749	10.52	0.0005
B	1	141296.7604	141296.7604	6.92	0.0182
A*B	3	114898.1913	38299.3971	1.88	0.1744

B-4.2: -2°C Peak Load Analysis

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 24
Number of Observations Used 24

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The GLM Procedure

Dependent Variable: yPL yPL

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	0.32666667	0.04666667	2.24	0.0861
Error	16	0.33333333	0.02083333		
Corrected Total	23	0.66000000			

R-Square	Coeff Var	Root MSE	yPL Mean
0.494949	5.551445	0.144338	2.600000

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	0.06333333	0.02111111	1.01	0.4126
B	1	0.10666667	0.10666667	5.12	0.0379
A*B	3	0.15666667	0.05222222	2.51	0.0959

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	0.06333333	0.02111111	1.01	0.4126
B	1	0.10666667	0.10666667	5.12	0.0379
A*B	3	0.15666667	0.05222222	2.51	0.0959

B-4.3: -12^{o}C Fracture Energy Analysis

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 23
Number of Observations Used 23

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The GLM Procedure

Dependent Variable: yDCT yDCT

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	34017.25993	4859.60856	1.16	0.3813
Error	15	62967.97833	4197.86522		
Corrected Total	22	96985.23826			

R-Square	Coeff Var	Root MSE	yDCT Mean
0.350747	14.99066	64.79093	432.2087

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	16411.89826	5470.63275	1.30	0.3099
B	1	147.54386	147.54386	0.04	0.8538
A*B	3	17457.81781	5819.27260	1.39	0.2854

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	15798.37289	5266.12430	1.25	0.3254
B	1	44.93422	44.93422	0.01	0.9190
A*B	3	17457.81781	5819.27260	1.39	0.2854

B-4.4: -12^{o}C Peak Load Analysis

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 23
Number of Observations Used 23

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The GLM Procedure

Dependent Variable: yPL yPL

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	0.28572464	0.04081781	1.42	0.2688
Error	15	0.43166667	0.02877778		
Corrected Total	22	0.71739130			

R-Square	Coeff Var	Root MSE	yPL Mean
0.398283	5.956829	0.169640	2.847826

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	0.18739130	0.06246377	2.17	0.1340
B	1	0.00701754	0.00701754	0.24	0.6286
A*B	3	0.09131579	0.03043860	1.06	0.3962

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	0.19517544	0.06505848	2.26	0.1233
B	1	0.00480392	0.00480392	0.17	0.6886
A*B	3	0.09131579	0.03043860	1.06	0.3962

B-4.5: -22°C Testing Temperature

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read 16
Number of Observations Used 16

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The GLM Procedure

Dependent Variable: yDCT yDCT

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	3026.57833	432.36833	0.25	0.9576
Error	8	13785.93167	1723.24146		
Corrected Total	15	16812.51000			

R-Square	Coeff Var	Root MSE	yDCT Mean
0.180019	17.53964	41.51194	236.6750

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	192.230000	64.076667	0.04	0.9897
B	1	2499.023276	2499.023276	1.45	0.2629
A*B	3	335.325057	111.775019	0.06	0.9770

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	227.545057	75.848352	0.04	0.9868
B	1	2381.347756	2381.347756	1.38	0.2736
A*B	3	335.325057	111.775019	0.06	0.9770

B-4.6: $-22^{o}C$ Peak Load Analysis

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	4	0.5 2 4 8
B	2	+ -

Number of Observations Read	16
Number of Observations Used	16

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The GLM Procedure

Dependent Variable: yPL yPL

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	0.49333333	0.07047619	2.04	0.1698
Error	8	0.27666667	0.03458333		
Corrected Total	15	0.77000000			

R-Square	Coeff Var	Root MSE	yPL Mean
0.640693	6.701476	0.185966	2.775000

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	3	0.08783333	0.02927778	0.85	0.5061
B	1	0.23669253	0.23669253	6.84	0.0308
A*B	3	0.16880747	0.05626916	1.63	0.2585

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	3	0.12742816	0.04247605	1.23	0.3611
B	1	0.31410256	0.31410256	9.08	0.0167
A*B	3	0.16880747	0.05626916	1.63	0.2585

B-4.7: Hamburg Wheel Tracking Testing Analysis

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The GLM Procedure

Class Level Information

Class	Levels	Values
A	3	0.5 2 4
B	2	+ -

Number of Observations Read	14
Number of Observations Used	12

The SAS System 19:17 Friday, November 5, 2010 13

The GLM Procedure

Dependent Variable: yH yH

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	8827441.667	1765488.333	25.13	0.0006
Error	6	421450.000	70241.667		
Corrected Total	11	9248891.667			

R-Square	Coeff Var	Root MSE	yH Mean
0.954432	15.95774	265.0314	1660.833

Source	DF	Type I SS	Mean Square	F Value	Pr > F
A	2	3978016.667	1989008.333	28.32	0.0009
B	1	3553408.333	3553408.333	50.59	0.0004
A*B	2	1296016.667	648008.333	9.23	0.0148

Source	DF	Type III SS	Mean Square	F Value	Pr > F
A	2	3978016.667	1989008.333	28.32	0.0009
B	1	3553408.333	3553408.333	50.59	0.0004
A*B	2	1296016.667	648008.333	9.23	0.0148

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