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Effect of Binder Modification and Aggregate Size on Modulus and Fatigue of Asphalt Concrete

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Effect of Binder Modification and Aggregate Size on Modulus and Fatigue of Asphalt Concrete

Elizabeth Bashiti

Thesis submitted to the
Benjamin Statler College of Engineering and Mineral Resources
at West Virginia University

in partial fulfillment of the requirements for the degree of

Master of Science in Civil Engineering

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2020

Keywords: Asphalt Concrete, Modified Binders Fatigue, Dynamic Modulus, AMPT, CoreLok,
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ABSTRACT

Evaluating the Effect of Binder Grade on Fatigue of Asphalt Concrete

Elizabeth Bashiti

Asphalt concrete is one of the main ingredients used in the paving of roadways across the globe. These roadways have been deteriorating from overuse, under design, and a lack of understanding of the engineering properties. In the asphalt community, it is agreed upon that polymer modifiers and aggregate size have comparable impacts on the performance of a pavement, such as, low creep at high temperatures, high ductility at low temperatures, high toughness, resistance to moisture and temperature, high cohesive and adhesive strength. With all of these advantages, it has been often assumed that polymer modifiers extend/improve the expected life of pavements. Currently, test methods to accurately predict performance of a pavement based on binder type and aggregate size have not been widely accepted in the pavement design community. This research aimed to evaluate the effect of polymer modifiers and aggregate size on the performance of a pavement, specifically the modulus and fatigue properties.

Six different hot-mix asphalt mixtures were evaluated in this research that were combinations of three (3) binder types; a PG 70-22, PG 70-22 Polymer Modified (PM), and PG 76-22 PM and two (2) different nominal maximum aggregate sizes (NMAS); 9.5 mm and 12.5 mm. Prior to testing the samples for their performance properties, three methods of measuring bulk specific gravity were used to evaluate air distribution within the samples: Saturated Surface-Dry, CoreLok, and Dimensional (volumetric mass density).

Finally, to evaluate samples for performance properties the Asphalt Mixture Performance Tester (AMPT) was utilized. The AMPT is a relatively new method to measure the performance of a mixture by measuring fatigue, dynamic modulus, and flow number. Only fatigue and dynamic modulus were measured in this research. To evaluate the data collected from the AMPT, both the Mastersolver Version 2.2 developed by Bonaquist and Asphalt Pavement Hierarchical Analysis Toolbox – Fatigue Program (Alpha-Fatigue™ software) developed by Kim were used.

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Chapter 1: Introduction

Background

Asphalt concrete has a primary use in the paving of roadways. These roadways have been deteriorating from overuse, under design, and a lack of understanding of the engineering properties. While there are many modes of pavement failure two structural failures are considered critical for design using mechanistic-empirical design methods (ARA, Inc., 2004): fatigue cracking and rutting (Miller and Bellinger, 2003) (Mohammad et al., 2014). The Superpave mixture design method developed during the Strategic Highway Research Program (SHRP) is used for proportioning asphalt concrete mixtures (FHWA, 2010). However, as implemented, the Superpave method lacks a method to quantitatively evaluate the quality of the asphalt concrete properties relative to fatigue cracking and rutting (FHWA, 2010).

The lack of a practical performance test for Superpave mixtures lead to the development of the Asphalt Mixture Performance Tester (AMPT) (Bonaquist, 2011a, Witczak et al., 2002). The research completed for the National Cooperative Highway Research Program (NCHRP) focused mainly on testing and evaluating dynamic modulus, fatigue, and flow number. The fatigue testing protocol was further enhanced by Kim et al. (2008) using uniaxial direct tension testing and visco-elastic continuum (VECD) damage theory.

These developments provide a methodology for evaluating the mechanistic behavior, and hence the expected field performance of asphalt concrete.

Problem Statement

This research was performed to evaluate and compare three different binder types and two different nominal maximum aggregate sizes (NMAS) using the Uniaxial Fatigue Test and Dynamic Modulus Test on the AMPT. The three binder types that were tested were PG (Performance Graded) 70-22 Neat, PG 70-22 Polymer Modified (PM), and a PG 76-22 PM¹. For each of the binder types, two different NMAS's were tested: a 9.5 mm and a 12.5 mm. In total, 72 AMPT specimens were tested: 54 S-VECD fatigue and 18 dynamic modulus samples. Results from the AMPT were analyzed using the Asphalt Pavement Hierarchical Analysis Toolbox-

¹ When this research was performed the original Performance Grade binder specifications were in place. These have subsequently been replaced with AASHTO M332. The PG 70-22 would now be specified as PG 64H-22 and the PG 76-22 would be specified as PG 64V-22.

Fatigue Program (ALPHA-F) (ALPHA-F User Guide, 2014), the Mastersolver workbook published by Bonaquist (2011b), in conjunction with other statistical methods. These results were then used to develop an expected life expectancy of the pavements which would provide a deeper insight into the performance in the field.

Objectives

The main objectives for this research are: 1) compare the effect of binder type on fatigue properties of asphalt concrete mixes with two aggregate structures, and 2) compare effects of binder type on dynamic modulus. The results of the laboratory evaluation were used with a mechanistic-empirical analysis to estimate expected pavement performance.

In addition, the samples were used to evaluate the air void distribution within samples, determine a correlation between the saturated surface dry, CoreLok®, and dimensional methods for bulk specific gravity, and AMPT sample height as well as the air void loss when the samples were cored and sawed.

Scope and Limitations

All samples were prepared, mixed and tested to meet the specifications set by the American Association of State Highways and Transportation Officials (AASHTO). All recommendations made within the specifications were also considered, though not all were applied. Randomization was performed wherever possible to reduce bias throughout mixing and testing. Also, all testing and preparation was limited to the equipment available to the Asphalt Technology Laboratory at West Virginia University. Materials were also limited to local asphalt plants in order to ensure that all mixes could realistically be mixed and paved in West Virginia.

Report Outline

This report is divided into five chapters. Chapter 1 consists of an introduction, background information, objectives, problem statement and scope and limitations. Chapter 2 contains a review of literature on other research performed on similar topics. Chapter 3 presents the methodology used throughout the research. Chapter 4 presents the analysis performed on the data. Chapter 5 presents conclusions and recommendations based on the results and analysis collected from this research. Lastly, appendices present the data collected during the research.

Chapter 2: Literature Review

Purpose

Approximately 94% of the 2.3-million miles of paved roads and highways across the nation have been paved using asphalt concrete in the form of hot mix asphalt (HMA) (Zhao, 2011). A combination of 3 ingredients make up HMA; binder, aggregates, and air. Finding the optimal balance between these three components while maintaining the strength properties required for the pavement is paramount to the design. The asphalt industry is a multi-billion-dollar industry that has various stakeholders. These stakeholders depend on higher quality pavements. This dependence greatly increases the value of furthering knowledge about asphalt material properties and the impacts different variations in the mix have on pavement performance.

Assumptions

Due to the visco-elastic nature of asphalt pavements in order to analyze the impact that variations have on the fatigue life of the pavement, any analysis must consider both rutting and fracture energy required to combat failure. Finding a method for predicting the impact of using a modifier in a pavement's mix design performance has a large value and though no method has been standardized or incorporated into the Superpave mix design, it is generally accepted that modifiers have the ability to improve the performance against rutting and fatigue. Key research performed on these failure modes as well as their conclusions were evaluated. Conclusions from these research articles were considered during the development of the methodology used for this report.

Polymer Modifiers

One of the key developments in improving the fatigue life in asphalt pavements is through the use of polymer modifiers. In the asphalt community, it is agreed upon that polymer modifiers have various advantages, such as, low creep at high temperatures, high ductility at low temperatures, high toughness, resistance to moisture and temperature, high cohesive and adhesive strength (Bhurke, 1999). Even with all the benefits of polymer modifiers, while developing the Superpave method which is heavily used in the industry, focused mostly on unmodified binders (Zhai, 2001). Without knowing the specific effects of choosing to utilize a modified binder over unmodified, this leaves a gap in the design process. Since the inception of

the Superpave specification, there has been extensive research on the comparison between modified and unmodified binders as well as the methodology to recommend ways to incorporate modified binders into the specification. The following paragraphs discuss a few examples of the research performed on modified binders.

Bhurke (1999) researched the effect that polymer modifiers had on an asphalt pavement mixture. Bhurke kept all binder contents at 5.7% in order to reduce the variables influencing performance of the asphalt concrete. Bhurke (1999) measured the fracture toughness and lap-shear adhesive strength to evaluate polymer modifier's impact on pavement performance. Specifically, the fracture toughness of the material can provide a valuable insight as it is strongly dependent on and correlated to the average thickness of the asphalt film between aggregates. Since fracture toughness is a method to determine the number of cycles a pavement can withstand before a fracture occurs, it is heavily related to the fatigue performance. Bhurke (1999) observed two forms of failure modes; adhesive and cohesive, where adhesive is where the crack propagation occurs at the asphalt binder-aggregate interface and cohesive is where the crack propagates only through the asphalt binder. Bhurke (1999) noted that in order to compare the effects that polymer modification had on the adhesion failure in different systems, the fracture toughness tests should be performed at temperatures relative to the glass transition of the asphalt binders. It was found that at temperatures above 0°C polymer modification does not significantly affect the properties of asphalt concrete as detected by lap shear tests (Bhurke, 1999). Bhurke's research is just an example of research performed utilizing a constant binder content to determine effects of binders on a mixture's performance.

Zhai (2001) focused his research on modifying the Superpave mix design method to evaluate fatigue damage behavior under repeated cyclic loading, accumulated permanent deformation under repeated loading, and storage stability of modified asphalts. Zhai (2001) hypothesized that the two primary factors that would affect fatigue response were asphalt content and air void content. For this reason, considering the upper and lower limits of asphalt content, as well as the role the gradation plays, are crucial in the mix design process. Zhai (2001) found that binder modification has a comparable impact on improving the performance of the pavement as the aggregate gradation meaning both of these factors are as crucial in the design process and analysis of pavement performance.

Bahia, et al (2001) researched the applicability of the Superpave specification and protocols developed for asphalt cements to modified asphalt binders. Bahia, et al (2001) assumed that binder behavior is independent of film thickness and sample geometry, as well as that binder should be evaluated based on properties within the linear viscoelastic range where behavior is independent of the strain or stress levels. It was found that classifying the modified binders as simple or complex was unnecessary as all binders should be screened for particulate additives and storage stability in order to be included in the performance-grading system. Simple binders are defined by Bahia, et al (2001) as asphalt binders that exhibit rheologically simple behavior which does not violate the following assumptions which the PG system is based on; independence of strain, non-thixotropy, isotropy, and independence of sample geometry.

Pavement Failure

The two key modes of failure in asphalt pavements are fatigue and rutting. Fatigue cracking is defined as when a repeated load is applied, and interconnected cracks occur at the surface. This cracking phenomenon has been found to initiate at both the top of the pavement (top down cracking) and the bottom of the pavement (bottom down cracking). Rutting, on the other hand, occurs when there is a permanent deformation in the pavement. Knowing the methods of failure provides insight to the material and the factors that lead to failure which may not be apparent.

In order for Bahia, et al (2001) to fully be able to expand the current Superpave specification to include modified asphalt binders, a study into the fatigue performance had to be completed. As stated by Bahia et al (2001), fatigue is believed by many researchers to be a pavement structure problem, while others believe it to be a mixture problem, however fatigue cracking starts then propagates in the binder. While collecting data from the Repeated Shear at Constant Height (RSCH) test, Bahia, et al (2001) found that the first 10 cycles highly influence the lack of fit of the model, therefore these first 10 cycles were not included in further analysis. Further Bahia, et al (2001) found that changing the binder modification had comparable effects as changing the aggregate gradation. This finding was also found by Zhai (2001). From studying the fatigue performance, Bahia, et al (2001) confirmed that fatigue life is sensitive to both the aggregate type and binder type during the Beam Fatigue Test.

Further research performed by Tsai, et al (2005) tested nine different binders in order to define their rheological response over a range in temperatures and times of loading as well as

studying and analyzing the simulated fatigue performance of the mixes by performing tests on mixes containing the binders. Similar to Bhurke (1999), Tsai et al (2005) held a constant asphalt content of 5% and a target air void content of $6 \pm 0.5\%$. However, different from Bhurke (1999), Tsai et al (2005) applied different tests and parameters to evaluate the fatigue performance including not only testing the fatigue performance of mixes, but binders as well. Utilizing mastercurves at a reference temperature of 25°C as well as other various tests, it was found that there seemed to be no relationship between the loss of stiffness of the binder ($G^*\sin\delta$) and ESALs for fatigue cracking. This finding supports the common industry conclusion that $G^*\sin\delta$ should be replaced with another parameter to accurately evaluate fatigue performance.

Saboo and Kumar (2016) used four different asphalt binders and three different asphalt mixes to evaluate fatigue performance of elastomeric and plastomeric binders. Specifically, Saboo and Kumar (2016) evaluated the loss of stiffness parameter ($G^*\sin\delta$) similar to Tsai et al (2005) and agreed that this parameter does not accurately evaluate the fatigue performance. This study found that elastomeric modified binders and the mixes that used them, gave the best performance under fatigue loading where as plastomeric modification was found to be highly susceptible to strain and resulted in poor performance under fatigue. This finding was expected by Saboo and Kumar (2016) due to the properties of elastomers versus plastomers. While the research performed in this report did not evaluate the Superpave mix design process, the ideas presented in this research are highly applicable to pavement performance analysis.

Endurance Limit

In addition to the research performed on polymer modification and its impact on performance are the methods to evaluate the pavement's performance, and methods to extend the life of pavements. Witczak (2013) extended research from previous studies which indicated that if a strain level of 70 microstrain or less were maintained, they could guarantee a structural design will perform in the region of extended fatigue life, providing a “no damage” performance. This “limit” is known in the asphalt community as the endurance limit of a pavement and a pathway to designing perpetual pavements. The hypothesis of the research performed by Witczak (2013) was that endurance limit in hot mix asphalt is not a single value but will change based on the loading and environmental conditions. Witczak (2013) chose six main factors to evaluate the endurance limit, they were, binder type, binder content, air voids in the mix, testing temperature, amount of rest period applied between each loading cycle, and the number of cycles

till failure for the test without rest period (N_f). It is important to note that Witczak's research only used un-modified binders and that softer binder mixtures had higher endurance limit values than stiffer binder mixtures. The highest endurance limit values in Witczak's research came from high binder contents with low air void contents. While this concept is partially intuitive due to the fact that it would inherently increase the film thickness of the binder, which has been found to be correlated to the fracture toughness (Bhurke, 1999), it also seems to prioritize the binder content in evaluating performance of a pavement.

In addition to Witczak's research exploring the endurance limits of asphalt pavements, it was necessary to also explore the way asphalt mixes recover to some extent after a loading cycle as the result of asphalt relaxation. Pavement researchers and engineers rarely give any attention to healing; however, it is a common topic in polymer engineering, for example Prager and Tirrell which are cited by Witczak (2013) for their description of the healing phenomenon. This healing process is to credit that intermittent loading has a less damaging effect than continuous loading, though some researchers believe the rest period only leads to a temporary modulus recovery without extending the fatigue life. Other researchers have alternatively found that the modulus recovery does extend the fatigue life by a certain amount. Witczak (2013) cited research performed by Monismith, et al. which indicated that increasing the rest period from 1 to 19 seconds has no effect on fatigue performance, though this contradicts many other later research results which showed an increase in fatigue life due to rest periods. Similar to the research performed by Monismith et al, Witczak (2013) found that the rest period in some cases resulted in faster damage and lower fatigue life than the tests without a rest period.

Conclusions/Salient Points

- Fracture toughness is a valuable tool in understanding the failure mechanisms in asphalt pavements.
- Zhai (2001), Tsai et al (2005), and Witczak (2013) all considered asphalt content and air void content as primary factors in the fatigue performance and expected life of the pavement. In addition to these primary factors, both Zhai (2001) and Bahia, et al (2001) found that binder modification and aggregate gradation have comparable impacts and are equally as critical in the design process and analysis of pavement performance.

- In studies performed by both Tsai et al (2005) and Bhurke (1999) the binder content was held constant in order to minimize variables. Neither of these studies confirmed if keeping the binder content constant did minimize the variables in the analysis. Though not discussed, based on the other conclusions from these studies it can be implied that keeping the binder content constant achieved the goal of minimizing variables.
- The loss of stiffness of the binder ($G^* \sin \delta$) parameter currently used in the specifications for fatigue cracking has been shown to not correlate to actual performance in fatigue.
- Previous research on the existence of an endurance limit indicated that if a strain level of 70 microstrain or less were maintained, then it could be guaranteed that the fatigue life would be extended and provide a “no damage” performance. Further research into endurance limits has found that in the case of unmodified binders, mixtures that utilize softer binders had higher endurance limit values than stiffer mixtures
- It is believed by some researchers that allowing a mixture to have a rest period in loading only leads to a temporary modulus recovery and does not actually extend the fatigue life.

Table 1 : Summary of research studies and findings.

Researcher	Binder Studied	Test Method	Conclusions
Bahia, et al (2001)	PG 82-22 SBS Radial PG 82-22 SBR LMW PG 58-40 SB Di-block PG 82-22 PE Stabilized PG 76-22 EthyleneTerpoly PG 58-40 SBS Linear PG 82-22 Steam Distilled PG 76-22 Oxidized PG 52-40 Oxidized	RSCH Test Beam Fatigue Test	classifying modified binders as simple or complex is unnecessary all binders should be screened for particulate additives and storage stability to be included in the PG system
Bhurke (1999)	Viscosity Graded Binders (AC5 and AC10)	Measure Fracture Toughness and Lap-Shear Adhesive Strength	Polymer modification does not significantly affect properties of asphalt concrete
Saboo & Kumar (2016)	VG 20 VG 30 PMB (E) PMB (S)	Linear Amplitude Sweep Four Point Beam Bending Marshall Stability Indirect Tensile Strength	elastomeric modified binders/mixes had the best performance under fatigue loading plastomeric modification is highly susceptible to strain and resulted in poor fatigue performance

Researcher	Binder Studied	Test Method	Conclusions
Tsai & King (2005)	AR-4000 (California Valley Sourced) AR-4000 (California Coastal Sourced) AC20P polymer modified PBA-6a (modified binder) PG 70-28 (modified binder) PG 52-28 PG 64-22 PG 64-28 PG 76-16	AASHTO MP-1 requirements Determine $G^*\sin\delta$ Observe molecular weight distributions using size exclusion chromatography	no relationship between the loss of stiffness of the binder ($G^*\sin\delta$) and ESALs for fatigue cracking
Witczak (2013)	Unmodified binders		softer binder mixtures had higher endurance limit values than stiffer binder mixtures high binder contents with low air void contents had highest endurance limit values
Zhai (2001)	PG 82-22 SBS Radial PG 82-22 PE Stabilized PG 82-22 Steam Distilled PG 82-22 SBR LMW PG 76-22 Ethylene Terpoly PG76-22 Oxidized (Straight Run) PG 58-40 SB Diblock PG 58-40 SBS Linear PG 52-40 Oxidized (Back Blend)	Laboratory Asphalt Stability Test (LAST) Method	Binder modification has a comparable impact on improving the performance of the pavement as the aggregate gradation

Chapter 3: Methodology

To achieve the objectives stated in Chapter 1 and ensure the AMPT produced reasonable results, samples were carefully prepared, and all testing protocols were followed. This chapter outlines the methodology followed for sample and material preparation and testing protocol. These samples were prepared for two performance tests, fatigue and dynamic modulus.

Experimental Design

Sample preparation and testing was designed to evaluate three different asphalt binders: PG 70-22, PG 70-22 polymer modified (PM), and PG 76-22 PM, and two nominal maximum aggregate size (NMAS) gradations; a 9.5mm and a 12.5mm.

Figure 1 shows the sample types for each binder type. The sample configuration in this figure was repeated for each of the three binders. Three replicates were tested for each of the combination of factors and levels. In the dynamic modulus protocol, test results are obtained for each sample, so three samples were sufficient to provide the three replicates. The fatigue testing protocol requires three test results to provide a single result. Hence, it was necessary to make nine samples for each combination of factors and levels. Samples used for the dynamic modulus test were not used for the fatigue testing. In total, 72 samples were tested.

Figure 1: Experimental Design.

Percent Binder

The mixes used in this research are based on mix designs produced by Greer Industries, Morgantown, WV. The Job Mix Formula (JMF) sheets submitted by the contractor and approved by the WVDOH are provided in Appendix A. The mix designs were for a PG 76-22 PM binder. Under the current WVDOH mix design process, polymer modified mixes are compacted using 65 gyrations while mixes with non-modified binders are compacted using 80 gyrations. Per the JMF the design binder contents were 6.2 and 5.9 percent for the 9.5 and 12.5 mixes respectively.

Turner (2015) tested similar mixes for dynamic modulus and flow number. Design binder contents were determined using WVDOH procedures. For the unmodified PG 70-22 the compaction effort was 80 gyrations. For the polymer modified PG 70-22 both 65 and 80 gyrations were used. The resulting design binder contents are shown in Table 2. The design binder content determined by Turner (2015) was lower than the JMF binder contents for the PG 76-22 PM binder. The binder contents for the PG 70-22 PM binder was virtually identical for compaction efforts of 65 and 80 gyrations.

Table 2: Design binder contents from Turner (2015)

Binder Type	NMAS	N _{design}	Design Percent Binder
			Turner (2015)
PG 70-22	9.5 mm	80	6.2%
	12.5 mm	80	5.6%
PG 70-22 PM	9.5 mm	65	6.1%
	12.5 mm	65	5.4%
PG 70-22 PM	9.5 mm	80	6.2%
	12.5 mm	80	5.4%
PG 76-22 PM	9.5 mm	65	5.9%
	12.5 mm	65	5.2%

Verification of the mix designs agreed with the contractor's results rather than Turner's. A constant binder content of 6.1 percent was selected for this research. It was expected that the binder content for the 9.5 mm mixes would be a little higher than for the 12.5 mm mixes. However, the gradation for the 9.5 mm and 12.5 mm mixes, shown in Figure 2, are almost identical for the aggregate finer than the 4.75 mm sieve. The surface areas of the aggregate blends, using the procedure described by Roberts et al. (1996) were 23.9 and 24.2 ft²/lb for the 9.5 and 12.5 mm mixes respectively. This is a strong indication that the binder content of the mixes should be about the same. A constant binder was used in order to eliminate the

confounding variables that surfaced during the verification process. Because the binder content, gradation, and VTM are held relatively constant, binder type is the only variable tested.

Figure 2: Comparison between blend gradations for 9.5mm and 12.5mm mix designs.

Material Preparation

Aggregates

Aggregates used in the mix design process and sample preparation were from the Greer and Buckeye plants in Morgantown, West Virginia from the Buckeye 7, Buckeye 8, Greer Sand, and West Virginia (Buckeye) Sand stockpiles. Following collection, all aggregates were prepared using the following procedure.

1. Initial oven drying for 10 hours at 110°C
2. Initial sieving for 10 minutes
3. Wash aggregates
4. Final drying for 10 hours at 110°C
5. Final sieving for approximately 10 minutes
6. Separate and store by sieve size in sealed gallon zip lock bags
7. Batch using a blend gradation matching the Job Mix Formulas in Appendix A

During batching, each sample was divided into two one-gallon bags that were numbered to ensure that each mixture was consistent. Once batched, samples were mixed using randomly selected batched aggregates. Mixing order was randomized by binder type to ensure zero bias or contamination from the bucket in mixing. During mixing, samples were randomly assigned a sample designation based on the test in which they would be evaluated. Testing order was also randomized.

Extra samples were batched for determining the mass of material needed to produce samples with the correct air voids and for replacement samples in case of an error encountered during testing.

Binder

Asphalt binder was delivered in gallon cans. The binder was split into quart size cans with a mass about 100 grams over the expected mass of binder needed to mix one performance sample. The binder was heated at 100°C then poured into quart containers. This splitting process greatly reduced risk of excessive heating and cooling cycles and reduced the amount of wasted asphalt binder.

Mixing

Once aggregates were washed, batched, and assigned a random number, mixing could begin. A “dummy” sample was batched and mixed in order to “prime” the mixing bucket and paddle. The aggregates were heated overnight at the midpoint of the mixing temperature range, Table 3. At least three hours before mixing, ovens holding the asphalt binder, mixing bucket and paddle were heated to the midpoint of the mixing temperature range. Ovens holding the Superpave molds, the transfer funnel (Figure 3), and pans for aging were set to the midpoint of the compaction temperature. All other tools used for mixing were also heated to ensure minimal heat loss during mixing and compaction.

Table 3: Mixture and compaction temperature provided by binder supplier.

Binder Grade	Mixture Temperature (°C)		Compaction Temperature (°C)	
	Minimum	Maximum	Minimum	Maximum
PG 70-22	163	169	152	157
PG 70-22 PM	165	171	146	163
PG 76-22 PM	165	171	146	163

Figure 3: Funnel used to insert mix into the Superpave compaction molds.

Aging and Compaction

After the samples were thoroughly mixed, the needed amount of material was weighed into pans and placed in an oven at the compaction temperature, Table 3, for two hours; with mixing after one hour. After, the samples were transferred to the mold and compacted with a Superpave Gyratory Compactor (SGC).

After compaction, the molds were removed from the compactor and left for a minimum of 30 minutes to allow the sample to become firm enough for handling. All samples were labeled on the bottom for consistency. Samples were then left overnight to cool before running bulk specific gravity testing using both the CoreLok® and SSD methods. This is an optional step in AASHTO PP 60 as it may identify an improperly made sample. None of the samples prepared for this research were rejected for this reason.

Mix Mass Determination

Before compacting performance samples, some samples were prepared to determine the mass of mix required to compact a 180mm tall sample with $7\% \pm 0.5\%$ air voids per AASHTO PP 60.

From previous WVU laboratory experience (Smith, 2015 & Turner, 2015 & Dalton, 2016) all samples to be used in performance testing were compacted to 150mm diameter and 180mm height, which satisfied both AASHTO PP 61 and TP 107 minimum height requirements.

Equation 1 was used to determine an initial estimate for mass of mix required to reach $7\% \pm 0.5\%$ air voids. A higher and lower mass of mix were compacted. If required, an adjusted mass was then calculated using Equation 2. The mass used in Equations 1 and 2 was based on the mass that was compacted in the Superpave Gyratory Compactor, while the air void levels were based on the cored and sawed VTM values for a dynamic modulus sample computed from G_{mb} results from the CoreLok® test.

$$Mass = \left[\frac{100 (V_{at} + F)}{100} \right] \times G_{mm} \times (176.7147) \times H \quad (1)$$

Where:

$Mass$ = estimated mass of mixture needed (g)

V_{at} = target air void content of the specimen (%)

G_{mm} = Theoretical maximum specific gravity

H = height of the gyratory compacted sample (mm)

F = air void adjustment factor, 1.5 for 9.5 mm mixes and 1.0 for 12.5 mm mixes

$$Mass_{adj} = \left[\frac{100 - V_{at}}{100 - V_{am}} \right] \times Mass \quad (2)$$

Where:

$Mass_{adj}$ = adjusted mass of mixture needed (g)

V_{at} = target air void content of the specimen (%)

V_{am} = measured trial test specimen air void content (%)

$Mass$ = mass used to prepare the trial test specimen (g)

Mass corrections were made, and samples were prepared for the experimental testing. Samples were cored and sawed to meet the dimension requirements for the Dynamic Modulus and Fatigue tests. All samples were compacted to a 180 mm height. However, trimmed samples for fatigue tests are shorter than the Dynamic Modulus samples. It was assumed this would not affect the air voids of the trimmed samples.

Volumetric Verification and Sample Preparation

The CoreDry® machine was used to remove water from the coring and sawing process. The G_{mb} of each sample was determined using the CoreLok®. Subsequently, the sample was dried once again and then the SSD method for G_{mb} was performed.

Performance samples were measured for their geometry and checked for end flatness and perpendicularity specifications provided in Table 4. All samples complied with these

requirements. Samples were also labeled after coring and sawing, noting the top and bottom of the sample from compaction. This labeling was done to keep the top, middle, and bottom consistent from compaction through testing. The samples were tested within two weeks of trimming as recommended by AASHTO PP 60.

Table 4: Test specimen tolerances for Dynamic Modulus and Fatigue testing

	Dynamic Modulus	Fatigue
Average Diameter	98 to 104 mm	98 to 104 mm
Standard Deviation of Diameter	≤ 1.0 mm	≤ 1.0 mm
Height	147.5 to 152.5 mm	127.5 to 132.5 mm
End Flatness	≤ 0.5 mm	≤ 0.5 mm
End Perpendicularity	≤ 1.0 mm	≤ 1.0 mm

Dynamic Modulus Testing on AMPT

After the samples had been measured for air voids, dimensional, flatness and perpendicularity specifications, dynamic modulus samples were stored until gage points were glued on using the jig shown in Figure 4, which ensured proper spacing of the LVDT's on the sample. The six gage points were attached using Devcon 5-minute epoxy at 120° intervals around the sample. The specimen was left in the gluing jig to cure for at least one hour prior to temperature conditioning. An example of a specimen prepared for conditioning is shown in Figure 5. The samples were oriented to match the way they were compacted, e.g. the top of the sample when compacted was the top of the sample when tested. Each sample was first tested at the low temperature followed by the medium then high temperature.

Figure 4: Gluing jig for gage points used for dynamic modulus samples.

Figure 5: Dynamic modulus sample with gage points attached ready to be conditioned for testing.

During conditioning, a “dummy” sample with an internal thermometer was conditioned with the performance sample to ensure that the testing temperature was achieved. All samples were left in the conditioning chamber with a “dummy” sample for a minimum of 6 hours as this was found to be a sufficient time period for conditioning. It should be noted that samples mixed with the PG 70-22 PM binder type were tested at 40°C, unlike in the research performed by Turner (2015). This was done in order to compare it to the unmodified binder with the same PG rating. Table 5 shows the order for Dynamic Modulus testing. Samples were labeled with the designation number, NMAS, and binder grade. All samples were tested in accordance with AASHTO TP 79.

Once the specimen had been properly conditioned, it was quickly removed from the conditioning chamber and placed into the AMPT between two end platens with Teflon spacers in between the platens and the specimen. The LVDT’s were attached and adjusted to zero displacement using the levels tool within the AMPT software from Instron®. After the LVDTs were attached to the sample and adjusted, the testing chamber was closed, and temperature allowed to stabilize before starting the test. The test set up for Dynamic Modulus is provided in Figure 6.

Table 5: Dynamic Modulus sample testing order. Testing temperature was kept in the following order, low (4), medium (20), and high (40 or 45).

Test Number	Sample Designation	NMAS	Binder Grade
1	DM 1	12.5 mm	PG 70-22
2	DM 1	9.5 mm	PG 76-22 PM
3	DM 1	12.5 mm	PG 76-22 PM
4	DM 1	9.5 mm	PG 70-22
5	DM 2	9.5 mm	PG 76-22 PM
6	DM 1	9.5 mm	PG 70-22 PM
7	DM 1	12.5 mm	PG 70-22 PM
8	DM 2	9.5 mm	PG 70-22
9	DM 2	12.5 mm	PG 70-22 PM
10	DM 3	12.5 mm	PG 70-22 PM
11	DM 3	12.5 mm	PG 76-22 PM
12	DM 2	9.5 mm	PG 70-22 PM
13	DM 3	9.5 mm	PG 70-22
14	DM 3	12.5 mm	PG 70-22
15	DM 3	9.5 mm	PG 70-22 PM
16	DM 2	12.5 mm	PG 76-22 PM
17	DM 3	9.5 mm	PG 76-22 PM
18	DM 2	12.5 mm	PG 70-22

Figure 6: Dynamic Modulus sample in AMPT.

Temperature was carefully monitored through the levels tool and attached gage within the testing chamber. The software used for dynamic modulus testing was the UTS006, which automatically applies the loads at the desired frequency while collecting the required data for analysis. Once the test was complete, the sample was removed from the testing chamber and conditioned for the next temperature level. After a sample had been tested at all required frequencies and temperatures, the gage points were carefully removed and soaked in acetone to remove the epoxy for future use.

Once testing was completed, the data was exported to an Excel file that could be used in the MasterSolver worksheet developed by Bonaquist (2011b).

Sample Bulk Specific Gravity Uniformity

Samples tested for dynamic modulus were also evaluated for bulk specific gravity, G_{mb} , uniformity by sawing the sample into thirds per AASHTO PP 60. This method specifies a target air void content of $5.0 \pm 0.5\%$. However, the Dynamic Modulus tests in this research have air void target of $7.0 \pm 0.5\%$. It was decided that testing at the actual air void target is more beneficial since this is the actual VTM used for testing the material. Each sample was cut into three slices, approximately 50 mm thick. The air voids of the top, middle and bottom slices were measured using the saturated surface dry, CoreLok® and dimensional methods. Complete results of these tests, including bulk specific gravities (G_{mb}) and air voids (VTM), are provided in Appendix B.

Fatigue Testing on AMPT

All samples were produced in accordance with AASHTO PP 60 and AASHTO TP 107. Fatigue sample preparation was a similar process as dynamic modulus, but samples are cut shorter, 130 mm. The gluing jig for fatigue gage points is the same device as dynamic modulus apart from the base platen. The base platen for fatigue is taller to ensure that the gage points were located at the third points of the height of the sample. Gage points are attached using 5-minute epoxy.

Fatigue samples require end platens to be attached using Devcon 10110 (steel putty). Following previous failures in other research involving the end platens breaking off of the sample during fatigue testing, it was recommended to heat the end platens to 40°C before attaching them. Steel putty was cured for 4 hours on the gluing jig shown in Figure 7. After

initially curing, samples were carefully removed from the jig and set aside for an additional 12 hours of curing before temperature conditioning.

All fatigue samples were tested at a temperature of 15°C based on values from the Long-Term Pavement Performance Binder (LTPP Bind) software. This temperature was determined by selecting the high and low temperature range for the performance grade binder from LTPP Bind for the station at Morgantown Municipal Airport in Morgantown, West Virginia. With a reliability of 98%, the binder grade was PG 58-22, which yields a testing temperature of 15°C using Equation 3.

Figure 7: Fatigue end platen gluing jig with sample in place.

$$\text{Test Temperature} = \frac{\text{High PG} + \text{L PG}}{2} - 3 \quad (3)$$

The conditioning chamber used for fatigue samples was set to 15°C. Similar to dynamic modulus, a dummy sample containing an internal thermometer was placed in the conditioning chamber.

Following the conditioning process, the sample was quickly transferred to the testing chamber. The metal ball placed on the top end platen to minimize eccentricity, and the bottom platen was bolted to the bottom actuator. All bolts were tightened to six-foot-pounds using a torque wrench. Once the actuator is raised with an applied seating load of 0.09 kN, the top end platen was bolted in place with six-foot-pounds of torque. Then the LVDTs are attached and adjusted to slightly above the minimum displacement allowed (typically around -0.3mm). The

displacement levels are monitored within the levels tool within the software. Because fatigue is a tensile test, the LVDTs were adjusted to a minimum displacement to allow for more range during measurements. Once the LVDTs were adjusted, the chamber was closed. The temperature of the chamber was allowed to stabilize at the testing temperature before beginning the test, typically, 45 minutes to an hour. In order to begin the test, the load was zeroed and a Dynamic Modulus Fingerprint test was started. Following the Dynamic Modulus Fingerprint test, there was a rest period of 20 minutes. After this rest period, the fatigue test automatically started.

Samples were tested within two weeks of coring and sawing. Table 6 displays the order of testing. The test protocol requires three samples to provide a single test result. The three samples required for a test result were tested in sequence. The first sample of the set is tested at $\epsilon_{os1} = 300$ microstrain, and the following two samples' microstrain, ϵ_{os2} and ϵ_{os3} are determined based on the number of cycles to failure (N_f) of the first sample; the adjustments are provided in Table 7 per AASHTO TP 107.

Once the testing was complete, the gage points were carefully removed from the sample and cleaned for use on future samples. Once the gage points were removed, the sample was placed in the oven at 100°C for at least an hour to soften the steel putty for removal and cleaning of the end platens. End platens were cleaned with acetone to ensure that there was no residue left behind. Samples were discarded.

Table 6: Fatigue testing order.

Test sequence no.	Sample Designation	NMAS	Binder Grade
1	FT 3	9.5 mm	PG 76-22 PM
2	FT 1	9.5 mm	PG 76-22 PM
3	FT 3	9.5 mm	PG 70-22
4	FT 2	12.5 mm	PG 76-22 PM
5	FT 1	9.5 mm	PG 70-22
6	FT 2	9.5 mm	PG 76-22 PM
7	FT 1	9.5 mm	PG 70-22 PM
8	FT 3	9.5 mm	PG 70-22 PM
9	FT 2	12.5 mm	PG 70-22
10	FT 3	12.5 mm	PG 70-22
11	FT 3	12.5 mm	PG 76-22 PM
12	FT 1	12.5 mm	PG 76-22 PM
13	FT 3	12.5 mm	PG 70-22 PM
14	FT 2	9.5 mm	PG 70-22 PM
15	FT 1	12.5 mm	PG 70-22
16	FT 2	9.5 mm	PG 70-22
17	FT 1	12.5 mm	PG 70-22 PM
18	FT 2	12.5 mm	PG 70-22 PM

Table 7: On-specimen strain adjustment for second and third fatigue samples

Case	ϵ_{os2}	ϵ_{os3}
$500 < N_{fl} < 1,000$	$\epsilon_{os1} - 100$	$\epsilon_{os1} - 150$
$1,000 < N_{fl} < 5,000$	$\epsilon_{os1} - 50$	$\epsilon_{os1} - 100$
$5,000 < N_{fl} < 20,000$	$\epsilon_{os1} + 50$	$\epsilon_{os1} - 50$
$20,000 < N_{fl} < 100,000$	$\epsilon_{os1} + 100$	$\epsilon_{os1} + 50$
$100,000 < N_{fl}$	$\epsilon_{os1} + 150$	$\epsilon_{os1} + 100$

Chapter 4: Results and Discussion

This chapter describes the results collected and analyses performed on samples in regard to the effect of binder type on the air void distribution, dynamic modulus and fatigue testing.

Bulk Specific Gravity Methods

Although the volumetric parameters used in this research are based on the CoreLok® method, the G_{mb} was also determined with the SSD and volumetric methods. Similar to Dalton (2016), line of equality graphs were produced in order to compare the three methods. Figures 8-10 display these plots as well as the lines of “best fit” for both before and after coring and sawing as well as an R^2 value for each of these best fit lines.

Figure 8: Line of Equality Chart for SSD versus CoreLok® Methods

Figure 9: Line of Equality Chart for SSD versus Dimensional Methods

Figure 10: Line of Equality Chart for Dimensional versus CoreLok® Methods

From these figures, it is obvious that all of the methods had a very low correlation before coring and sawing but a much higher correlation after. The Dimensional vs. CoreLok® methods was almost parallel to the line of equality, though it had the lowest R^2 value. These plots do not

lead to the conclusion that the results of each test are comparable in a laboratory setting. SSD compared to the dimensional method resulted in the highest R^2 after coring and sawing which was similar to the research performed by Dalton (2016). These results also are comparable to the conclusion that Griffith (2009) determined, which was that the difference between SSD and CoreLok® methods G_{mb} values diverge at higher air void contents. High air void contents are defined by Griffith (2009) as being in the range of 5% to 8%. All samples within this research were qualified as high air voids by Griffith (2009).

Bulk Specific Gravity Uniformity of Dynamic Modulus Samples

The means and standard deviations for the uniformity tests are presented in Table 8. Per AASHTO T 31, Bulk Specific Gravity and Density of Compacted HMA using Automatic Vacuum Sealing Method, the standard deviation of replicate samples tested by one technician in one lab should be less than 0.0124. As shown by bolded numbers in Table 8, six of the mixes had larger standard deviations. Figure 11 is a histogram of the average air voids for the three slices of each of the mixes. Air voids are used on this figure since G_{mm} varies with binder type limiting the utility of comparing G_{mb} . All but the PG 76-22 PM – 12.5 mm mix show the top and bottom slices are similar and have a higher G_{mb} and lower air voids than the middle slice. AASHTO PP 60 prescribes the t-test for comparing the G_{mb} of the top to middle and the middle to bottom slices. The method does not call for comparing the top to bottom slices; this comparison is included in the analysis herein. The test analysis results are presented in Table 9. To conclude that the bulk specific gravity between each third were *equal*², the t-statistic must be lower than 2.78. As indicated by the bold values in Table 9, for half the mixes the null hypothesis of equal means was rejected. None of the comparisons of the top to bottom slices indicated a problem.

² This is based on the terminology stated in AASHTO PP 60. The word “*equal*” is used to mean there is insufficient evidence to reject the null hypothesis of equal means.

Table 8: Averages for G_{mb} thirds by test method

Mix Type		Top	Middle	Bottom
PG 70-22 9.5mm	Mean	2.301	2.270	2.295
	Standard Deviation	0.005	0.008	0.004
PG 70-22 12.5mm	Mean	2.296	2.266	2.289
	Standard Deviation	0.007	0.007	0.007
PG 70-22 PM 9.5mm	Mean	2.300	2.271	2.307
	Standard Deviation	0.006	0.003	0.003
PG 70-22 PM 12.5mm	Mean	2.298	2.258	2.296
	Standard Deviation	0.014	0.031	0.010
PG 76-22 PM 9.5mm	Mean	2.298	2.256	2.296
	Standard Deviation	0.016	0.025	0.018
PG 76-22 PM 12.5mm	Mean	2.248	2.276	2.299
	Standard Deviation	0.070	0.009	0.012

Figure 11: Sample thirds Air Void Histogram

Table 9: *t*-Statistic for G_{mb} thirds for CoreLok results

Mix Type	T-M	B-M	T-B
PG 70-22 9.5mm	5.47	4.73	1.55
PG 70-22 12.5mm	5.07	3.94	1.17
PG 70-22 PM 9.5mm	7.06	13.74	1.66
PG 70-22 PM 12.5mm	2.04	2.02	0.20
PG 76-22 PM 9.5mm	2.48	2.24	0.14
PG 76-22 PM 12.5mm	0.69	2.68	1.24

The equivalence test is an alternative method for a comparative analysis of samples if limits can be established for an acceptable difference between the means. Per AASHTO T 331 the standard deviation of a single operator in a single lab is 0.0124, for a two-tailed test the means between two similar populations should be different by no more than ± 2 standard deviations 95 percent of the time. Thus, a threshold of 0.05 was used for performing an equivalency test using an alpha level of 0.05. The software JMP was used for the analysis. If p-values were less than the alpha value, we would accept the hypothesis that the sections are equal. A complete output from JMP of the equivalency test is provided in Appendix D and are summarized in Table 10. With an alpha level of 0.05, the hypothesis of equal means is accepted for all comparisons.

Table 10: *P*-values from JMP output for equivalency test of G_{mb} between sections.

	CoreLok®		
	T-M	M-B	T-B
Lower Threshold	0.0004	<0.0001	< 0.0001
Upper Threshold	< 0.0001	0.0063	< 0.0001
Max of Both	0.0004	0.0063	< 0.0001

Another analysis was performed to compare the averages of the samples cut into thirds to the averages of the full or intact samples. Among most of the samples, there was a difference less than 0.5% VTM between the full sample and when it had been cut into thirds as revealed in Table 11. The only sample that did not fall under 0.5% difference was the PG 76-22 PM 12.5

mm, which had an apparent outlier in the data that was possibly attributed to a problem encountered in the CoreLok® test. This issue was not further analyzed; therefore, the reason for this difference is unknown.

Table 11: Comparison of Sample Third Air Void Averages to Full Sample Air Void

Binder Type	NMAS	Designation	Average			Thirds Average	Intact Sample	Difference
			T	M	B			
PG 70-22	9.5mm	DM 1	7.1%	8.4%	6.8%	7.4%	7.3%	0.1%
		DM 2	6.6%	8.0%	7.0%	7.2%	7.0%	0.2%
		DM 3	6.4%	7.7%	7.1%	7.0%	6.9%	0.1%
PG 70-22	12.5mm	DM 1	6.8%	8.2%	7.3%	7.5%	7.2%	0.2%
		DM 2	6.8%	7.7%	7.1%	7.2%	6.8%	0.4%
		DM 3	6.7%	8.0%	6.9%	7.2%	6.8%	0.4%
PG 70-22 PM	9.5mm	DM 1	7.0%	8.0%	6.6%	7.2%	6.9%	0.2%
		DM 2	6.6%	7.9%	6.5%	7.0%	7.0%	0.0%
		DM 3	6.8%	7.5%	6.4%	6.9%	6.8%	0.1%
PG 70-22 PM	12.5mm	DM 1	7.0%	7.7%	6.4%	7.1%	6.9%	0.1%
		DM 2	6.3%	7.6%	7.0%	7.0%	6.8%	0.2%
		DM 3	6.7%	8.3%	7.2%	7.4%	7.0%	0.4%
PG 76-22 PM	9.5mm	DM 1	7.6%	9.0%	7.4%	8.0%	7.7%	0.3%
		DM 2	6.7%	7.9%	6.0%	6.9%	6.8%	0.0%
		DM 3	6.3%	7.6%	6.6%	6.8%	6.7%	0.1%
PG 76-22 PM	12.5mm	DM 1	7.1%	7.8%	7.1%	7.3%	7.2%	0.1%
		DM 2	7.0%	7.9%	6.7%	7.2%	7.0%	0.2%
		DM 3	8.5%	7.5%	6.4%	7.4%	6.7%	0.7%

Apart from the analysis comparing the thirds to the intact samples, further analysis of the thirds was performed on the distribution. Previous research performed in the West Virginia University Asphalt Technology Laboratory yielded various results in terms of the air void distribution. This research aimed to collect more data and provide a comparison to the research performed by Dalton (2016). Based on the air voids of each section, a rank was assigned for each sample, for example, the third assigned with a 1 had the highest air voids, and -1 had the lowest air voids. Table 12 displays the results of this ranking analysis.

Table 12: Ranking of sections based on air voids

Binder Type	NMAS	Designation	Ranking		
			T	M	B
PG 70-22	9.5mm	DM 1	0	1	-1
		DM 2	-1	1	0
		DM 3	-1	1	0
PG 70-22	12.5mm	DM 1	-1	1	0
		DM 2	-1	1	0
		DM 3	-1	1	0
PG 70-22 PM	9.5mm	DM 1	0	1	-1
		DM 2	0	1	-1
		DM 3	0	1	-1
PG 70-22 PM	12.5mm	DM 1	0	1	-1
		DM 2	-1	1	0
		DM 3	-1	1	0
PG 76-22 PM	9.5mm	DM 1	0	1	-1
		DM 2	0	1	-1
		DM 3	-1	1	0
PG 76-22 PM	12.5mm	DM 1	-1	1	0
		DM 2	0	1	-1
		DM 3	1	0	-1
Total		1's	1	17	0
		0's	8	1	9
		-1's	9	0	9

In 17 of the 18 samples, the middle section had the highest air voids. The only exception had an apparent outlier in the CoreLok® data which possibly affected this result. About half of the tops had the lowest air voids and half of the time the bottoms had the lowest air voids. This suggests that the top and bottom thirds of the samples get similar compaction effort while the middle third is not as well compacted.

Dynamic Modulus and Phase Angle

Dynamic Modulus testing was performed as per AASHTO TP 79 on the AMPT. All testing was run and data was collected and analyzed. Tables containing the output from MEPDG are provided in Appendix F and are sorted by mix type.

All dynamic modulus in MPa obtained through testing on the AMPT were tabulated in Table 13. The averages, standard deviation and coefficients of variation were calculated and tabulated in Table 14. Along with the dynamic modulus, Phase Angle values were also collected from the dynamic modulus testing. Table 15 displays the average, standard deviation, and coefficient of variance of Phase Angle based on the testing temperature and frequency. Since dynamic modulus is not considered to be a destructive test, each sample was run at all temperatures and frequencies.

The dynamic modulus decreases based on frequency and testing temperature as expected. Standard deviation of the dynamic modulus decreased as temperature increased and frequency decreased suggesting these results are more accurate. The coefficient of variation did not seem to have any obvious trends but remained relatively low in most cases and never exceeded 23 percent.

Phase angle typically increased with testing temperature and decreased based on frequency. This result was expected based on previous knowledge of asphalt concrete properties as well as previous dynamic modulus testing (Dalton, 2016, Smith, 2015, Turner 2015). The standard deviations did not show any obvious trends just as in dynamic modulus. A coefficient of variation was calculated for the phase angles, these values never exceeded 15.9%, but again, were typically much lower.

Table 13: Dynamic Modulus values at each test temperature.

Mix Type	Sample	4°C			20°C			40°C*				45°C*			
		10	1.0	0.1	10	1.0	0.1	10	1.0	0.1	0.01	10	1.0	0.1	0.01
PG 70-22 9.5 mm	DM 1	12,459	9,144	6,124	6,249	3,562	1,810	1,786	760	315	147				
	DM 2	13,199	9,825	6,671	5,613	3,123	1,539	1,436	605	258	128				
	DM 3	13,939	10,173	6,770	6,134	3,404	1,678	1,594	672	283	139				
PG 70-22 12.5 mm	DM 1	11,342	8,061	5,204	3,754	1,895	894	972	393	169	95				
	DM 2	12,283	8,589	5,487	4,429	2,285	1,088	1,011	412	178	99				
	DM 3	12,505	9,122	6,078	5,142	2,769	1,359	1,195	508	222	113				
PG 70-22 PM 9.5 mm	DM 1	10,243	7,342	4,795	4,275	2,260	1,081	874	366	172	102				
	DM 2	12,295	8,681	5,584	4,754	2,510	1,214	924	391	185	114				
	DM 3	11,024	7,941	5,222	4,357	2,320	1,121	949	407	195	119				
PG 70-22 PM 12.5 mm	DM 1	11,232	7,964	5,150	4,502	2,391	1,165	996	429	210	128				
	DM 2	11,168	7,860	5,048	4,373	2,292	1,086	943	401	193	117				
	DM 3	10,142	7,242	4,688	3,832	1,979	935	869	365	173	106				
PG 76-22 PM 9.5 mm	DM 1	9,788	6,850	4,381	3,252	1,607	763					664	297	165	113
	DM 2	11,857	8,518	5,600	5,013	2,735	1,364					1,039	472	252	156
	DM 3	11,717	8,307	5,353	4,340	2,243	1,079					751	337	185	124
PG 76-22 PM 12.5 mm	DM 1	10,110	7,130	4,597	3,549	1,762	840					641	288	160	111
	DM 2	11,063	7,763	4,984	3,852	1,958	949					770	343	195	131
	DM 3	10,324	7,295	4,709	3,895	1,995	958					737	338	187	121

*Per the test protocol the highest temperature for the PG 76-22 PM samples was 45°C rather than 40°C used for the other samples.

Table 14: Dynamic Modulus averages, standard deviations, and coefficients of variation

		Table 17. Dynamic Modulus Averages, Standard Deviations, and Coefficients of Variation													
		Test Temperature													
		4°C			20°C			40°C*				45°C*			
Mix Type		10	1	0.1	10	1	0.1	10	1	0.1	0.01	10	1	0.1	0.01
PG 70-22 9.5 mm	Avg.	13,199	9,714	6,522	5,999	3,363	1,676	1,605	679	285	138				
	SD	604	427	284	277	182	111	143	63	23	8				
	CV (%)	4.6%	4.4%	4.4%	4.6%	5.4%	6.6%	8.9%	9.4%	8.2%	5.7%				
PG 70-22 12.5 mm	Avg.	12,043	8,591	5,590	4,442	2,316	1,114	1,059	438	190	102				
	SD	504	433	364	567	357	191	97	51	23	8				
	CV (%)	4.2%	5.0%	6.5%	12.8%	15.4%	17.1%	9.2%	11.6%	12.1%	7.6%				
PG 70-22 PM 9.5 mm	Avg.	11,187	7,988	5,200	4,462	2,363	1,139	916	388	184	111				
	SD	846	548	322	209	107	56	31	17	9	7				
	CV (%)	7.6%	6.9%	6.2%	4.7%	4.5%	4.9%	3.4%	4.4%	5.1%	6.6%				
PG 70-22 PM 12.5 mm	Avg.	10,847	7,689	4,962	4,236	2,221	1,062	936	398	192	117				
	SD	499	319	198	290	176	95	52	26	15	9				
	CV (%)	4.6%	4.1%	4.0%	6.9%	7.9%	9.0%	5.6%	6.6%	7.8%	7.7%				
PG 76-22 PM 9.5 mm	Avg.	11,121	7,892	5,111	4,202	2,195	1,069					818	369	201	131
	SD	944	742	526	726	462	246					160	75	37	18
	CV (%)	8.5%	9.4%	10.3%	17.3%	21.0%	23.0%					19.6%	20.3%	18.6%	13.8%
PG 76-22 PM 12.5 mm	Avg.	10,499	7,396	4,763	3,765	1,905	916					716	323	180	121
	SD	408	268	163	154	102	54					55	25	15	8
	CV (%)	3.9%	3.6%	3.4%	4.1%	5.4%	5.9%					7.6%	7.7%	8.1%	6.7%

*Per the test protocol the highest temperature for the PG 76-22 PM samples was 45°C rather than 40°C used for the other samples.

Table 15: Phase Angle averages, standard deviations, and coefficients of variation

Binder Type		Test Temperature													
		4°C			20°C			40°C*				45°C*			
		10	1	0.1	10	1	0.1	10	1	0.1	0.01	10	1	0.1	0.01
PG 70-22 9.5 mm	Avg.	10.89	14.53	19.36	21.59	27.20	31.10	33.88	32.72	29.29	24.70				
	SD	0.29	0.42	0.46	0.83	0.95	0.78	1.74	1.48	0.87	0.50				
	CV (%)	2.6%	2.9%	2.4%	3.9%	3.5%	2.5%	5.1%	4.5%	3.0%	2.0%				
PG 70-22 12.5 mm	Avg.	11.88	15.75	20.73	25.35	30.31	32.41	35.51	32.92	28.46	23.31				
	SD	0.47	0.71	0.85	1.44	1.34	0.92	0.52	0.16	0.49	0.99				
	CV (%)	3.9%	4.5%	4.1%	5.7%	4.4%	2.8%	1.5%	0.5%	1.7%	4.3%				
PG 70-22 PM 9.5 mm	Avg.	12.28	16.07	20.85	24.58	29.15	31.14	34.78	31.52	26.79	22.31				
	SD	0.17	0.16	0.20	0.10	0.08	0.13	0.10	0.17	0.15	0.38				
	CV (%)	1.3%	1.0%	1.0%	0.4%	0.3%	0.4%	0.3%	0.5%	0.5%	1.7%				
PG 70-22 PM 12.5 mm	Avg.	12.68	16.61	21.41	25.13	29.56	31.37	34.89	31.41	26.50	21.78				
	SD	0.14	0.11	0.17	0.49	0.49	0.46	0.27	0.28	0.18	0.44				
	CV (%)	1.1%	0.7%	0.8%	2.0%	1.7%	1.5%	0.8%	0.9%	0.7%	2.0%				
PG 76-22 PM 9.5 mm	Avg.	12.39	16.26	20.90	25.15	29.32	30.67					34.09	30.06	28.44	20.70
	SD	0.38	0.56	0.67	1.57	1.37	0.72					0.50	0.23	4.53	0.40
	CV (%)	3.1%	3.4%	3.2%	6.2%	4.7%	2.4%					1.5%	0.8%	15.9%	2.0%
PG 76-22 PM 12.5 mm	Avg.	12.87	16.84	21.58	26.35	30.41	31.30					33.85	29.89	24.97	20.42
	SD	0.14	0.16	0.27	0.46	0.48	0.37					0.90	0.99	0.64	0.63
	CV (%)	1.1%	0.9%	1.2%	1.7%	1.6%	1.2%					2.7%	3.3%	2.6%	3.1%

*Per the test protocol the highest temperature for the PG 76-22 PM samples was 45°C rather than 40°C used for the other samples.

The average dynamic modulus for the replicate samples were calculated based on frequency and mix type, then plotted by temperature. These plots are provided in Figures 12 through 14. From these plots, it is easy to compare the mix types by temperature and frequency. At higher frequencies, all mix types obviously had higher dynamic modulus values. This trend was expected and has been found in most testing that has been performed in the WVU Asphalt Technology Laboratory (Dalton, 2016) (Smith, 2015) (Turner, 2015). It is also apparent that at all testing temperatures, the PG 70-22 9.5 mm mix type had the highest dynamic modulus, while the PG 76-22 PM 12.5 mm had the lowest. As discussed in the literature review, it is generally accepted that modifiers can improve performance against rutting and fatigue and therefore should also demonstrate an improvement in dynamic modulus testing. This result is contradictory to what was expected due to the differences in binder grades, as well as the addition of polymer modifiers. The research performed by Turner (2015) exhibited expected results of the non-modified binder having lower dynamic modulus than the PG 76-22 PM binder type.

All samples were further analyzed by mix type using the Mastersolver Version 2.2 workbook that was published by Bonaquist (2011b). This workbook requires entering data collected from the exported files from the AMPT software. Excel's solver tool is then used to generate the master curves. The final curve uses a reduced frequency and five parameters; β , γ , E_{min} , E_{max} , and ΔEA . These five parameters are provided in Table 16 based on mix type. Along with the parameters used to develop the MasterCurves, a goodness of fit output is displayed as well.

Figure 12: Average Dynamic Modulus at the lowest testing temperature, or 4°C.

Figure 13: Average Dynamic Modulus at the intermediate testing temperature, or 20°C.

Figure 14: Average Dynamic Modulus at the highest testing temperature, which was 40°C for PG 70-22 and PG 70-22 PM binder types, and 45°C for the PG 76-22 PM binder type.

Table 16: Master Curve final parameters

							Goodness of Fit	
Binder Type	NMAS	Max E* (ksi)	Min E* (ksi)	β	γ	ΔEA	R ²	S _e /S _y
PG 70-22	9.5	3114.2	3.5	-1.02615	-0.50489	186518	0.9978	0.03
	12.5	3123.4	3.9	-0.76526	-0.51003	193866	0.9934	0.06
PG 70-22 PM	9.5	3123.8	4.3	-0.70157	-0.48597	206527	0.9986	0.03
	12.5	3126.7	5	-0.63605	-0.49319	199898	0.9976	0.03
PG 76-22 PM	9.5	3111.5	8.9	-0.52479	-0.52602	184575	0.9912	0.07
	12.5	3121.3	8.8	-0.43464	-0.52658	186385	0.9887	0.08

All Master Curves for a reference temperature of 20°C were consolidated into one plot for comparison, Figure 15. All curves are very consistent with little to no variation between binder type or NMAS. Similar to the results found by Dalton (2016), there is a higher variation at lower frequencies and converging at the higher frequencies.

Figure 15: Dynamic Modulus Master Curves created using a reference temperature of 20°C.

To determine the dynamic modulus from the mastercurves, a frequency must be calculated using the inverse of the duration equation which is provided as Equation 4 (Huang, 2004). The parameters used in this equation are defined as a dual axle loading with a 4,500-pound load per tire (18-kip ESAL) and 110 psi tire pressure. The contact radius is 3.61 inches, and the vehicle was assumed to be traveling at a speed of 55 mph. This equation yields a frequency of 1.866 Hz. The values calculated are provided in Table 17. The parameters used to calculate the frequency are provided in Table 18.

$$d = \frac{12a}{s} \quad (4)$$

Where:

d = duration (seconds)

a = contact radius (in)

s = speed (ft/s)

Table 17: Dynamic Modulus values calculated.

Binder Type	NMAS	E* (ksi)	E* (MPa)
PG70-22	9.5 mm	616	4252
PG70-22	12.5 mm	454	3130
PG70-22 PM	9.5 mm	425	2932
PG70-22 PM	12.5 mm	407	2807
PG76-22 PM	9.5 mm	427	2946
PG76-22 PM	12.5 mm	378	2608

Table 18: Values used to calculate Frequency.

Axle Type	Dual Axle
Load	4,500 lbs.
Tire Pressure	110 Psi
Contact Radius	3.61 Inches
Speed	55 Mph
Frequency	1.866 Hz

Fatigue

The fatigue test protocol (as embodied in the software purchased from InstronTek© used in this research terminates the testing when one of three failure criterion is achieved:

- 1) 10% of the initial dynamic modulus is reached,
- 2) an increase in phase angle followed by an immediate drop, or
- 3) the number of cycles exceeding 100,000.

The test can be prematurely terminated due to testing issues such as an LVDT signal error or separation of the sample from the platen.

A summary of fatigue testing is displayed in Tables 19 through 21. Most samples either met the maximum number of cycles or ten percent modulus. One sample had an LVDT error and another had end platen separation. However, both these samples met the phase angle drop criteria before the issue occurred. Therefore, their results were kept in the data set.

Only two replicates of the PG 76-22 PM 9.5 mm mix type were tested as the VTM of one sample was outside of the accepted range for air voids. It was decided that introducing new materials would possibly create more variability to the results, therefore a replacement sample was not made. Not analyzing this replicate may have impacted the accuracy of the analysis when compared to the other mix types but will not be further explored. A replacement sample was not prepared due to time and material constraints.

Table 19: Fatigue testing compilation for PG 70-22 binder type.

Mix Type	Sample Designation	Air Voids (%)	μ (strain)	Cycles at Failure	Initial Dynamic Modulus	Final Dynamic Modulus	Notes
PG 70-22 9.5 mm	FT 1A	6.6	300	26,360	7,623	1,100.0	LVDT #2 Signal Error. Phase Angle drop.
	FT 1B	6.7	400	7,800	5,194	3,504.0	Bottom End Platen broke off. Phase Angle drop.
	FT 1C	6.6	350	20,280	5,570	550.1	Completed 10% Modulus criteria.
	FT 2A	6.8	300	35,480	6,419	636.6	Completed 10% Modulus criteria.
	FT 2B	6.6	400	8,980	5,694	564.8	Completed 10% Modulus criteria.
	FT 2C	6.5	350	13,280	6,990	685.1	Completed 10% Modulus criteria.
	FT 3A	6.5	300	47,100	5,770	573.4	Completed 10% Modulus criteria.
	FT 3B	6.7	400	3,510	6,618	625.3	Bottom End Platen had to be re-glued.
	FT 3C	6.7	350	16,460	5,767	571.8	Completed 10% Modulus criteria.
PG 70-22 12.5 mm	FT 1A	6.6	300	24,680	7,449	740.1	Completed 10% Modulus criteria.
	FT 1B	6.0	400	5,530	6,844	668.0	Completed 10% Modulus criteria.
	FT 1C	6.3	350	13,570	7,187	704.3	Completed 10% Modulus criteria.
	FT 2A	6.6	300	32,150	6,280	623.9	Completed 10% Modulus criteria.
	FT 2B	6.7	400	2,940	6,558	648.8	Completed 10% Modulus criteria.
	FT 2C	6.7	350	10,140	7,008	693.9	Completed 10% Modulus criteria.
	FT 3A	7.1	300	37,200	5,984	596.2	Completed 10% Modulus criteria.
	FT 3B	6.5	400	4,560	6,666	644.9	Completed 10% Modulus criteria.
	FT 3C	7.3	350	16,510	5,678	561.0	Completed 10% Modulus criteria.

Table 20: Fatigue testing compilation for PG 70-22 PM binder type.

Mix Type	Sample Designation	Air Voids (%)	μ (strain)	Cycles at Failure	Initial Dynamic Modulus	Final Dynamic Modulus	Notes
PG 70-22 PM 9.5 mm	FT 1A	6.6	300	99,610	5,581	557.9	Completed 10% Modulus criteria.
	FT 1B	6.8	400	17,780	5,122	511.0	Completed 10% Modulus criteria.
	FT 1C	7.2	350	36,950	5,341	530.6	Completed 10% Modulus criteria.
	FT 2A	6.8	300	99,810	5,436	542.2	Completed 10% Modulus criteria.
	FT 2B	6.6	400	16,450	4,991	496.0	Completed 10% Modulus criteria.
	FT 2C	6.3	350	24,050	5,631	558.0	Completed 10% Modulus criteria.
	FT 3A	6.7	300	83,370	5,687	568.7	Completed 10% Modulus criteria.
	FT 3B	6.8	400	15,570	5,359	535.1	Completed 10% Modulus criteria.
	FT 3C	6.8	350	25,140	5,719	568.9	Completed 10% Modulus criteria.
PG 70-22 PM 12.5 mm	FT 1A	6.6	300	93,380	5,393	538.3	Completed 10% Modulus criteria.
	FT 1B	6.2	400	18,220	5,234	519.9	Completed 10% Modulus criteria.
	FT 1C	6.6	350	29,310	5,405	536.8	Completed 10% Modulus criteria.
	FT 2A	6.6	300	86,640	5,205	518.8	Completed 10% Modulus criteria.
	FT 2B	6.7	400	18,100	5,302	526.8	Completed 10% Modulus criteria.
	FT 2C	7.5	350	61,290	4,802	479.4	Completed 10% Modulus criteria.
	FT 3A	6.7	300	94,390	5,229	521.5	Completed 10% Modulus criteria.
	FT 3B	6.7	400	15,770	5,165	512.3	Completed 10% Modulus criteria.
	FT 3C	7.3	350	31,250	5,076	506.7	Completed 10% Modulus criteria.

Table 21: Fatigue testing compilation for PG 76-22 PM binder type.

Mix Type	Sample Designation	Air Voids (%)	μ (strain)	Cycles at Failure	Initial Dynamic Modulus	Final Dynamic Modulus	Notes
PG 76-22 PM 9.5 mm	FT 1A2	6.8	300	100,000	5,941	1,550.0	Completed 10% Modulus criteria.
	FT 1B2	6.6	450	7,630	5,298	526.7	Completed 10% Modulus criteria.
	FT 1C	6.6	400	21,440	5,457	544.0	Completed 10% Modulus criteria.
	FT 2A	6.3	300	88,680	6,356	634.9	Completed 10% Modulus criteria.
	FT 2B	6.2					Sample not tested.
	FT 2C	6.6	350	77,670	5,239	523.0	Completed 10% Modulus criteria.
	FT 3A	6.5	300	100,000	5,634	2,013.0	Completed 10% Modulus criteria.
	FT 3B	6.5	450	12,800	4,910	488.0	Completed 10% Modulus criteria.
	FT 3C	6.5	400	19,100	5,338	532.7	Completed 10% Modulus criteria.
PG 76-22 PM 12.5 mm	FT 1A	6.3	300	100,000	5,415	1,934.0	Completed 10% Modulus criteria.
	FT 1B	6.5	450	11,270	4,919	491.1	Completed 10% Modulus criteria.
	FT 1C	6.3	400	20,320	5,479	547.0	Completed 10% Modulus criteria.
	FT 2A	6.4	300	100,000	5,939	1,230.0	Completed 10% Modulus criteria.
	FT 2B	6.2	450	19,600	4,886	488.3	Completed 10% Modulus criteria.
	FT 2C	6.3	400	22,460	5,401	538.2	Completed 10% Modulus criteria.
	FT 3A	6.9	300	100,000	5,152	2,218.0	Completed 10% Modulus criteria.
	FT 3B	6.6	450	11,500	5,042	501.5	Completed 10% Modulus criteria.
	FT 3C	6.3	400	27,210	4,938	492.1	Completed 10% Modulus criteria.

ALPHA-Fatigue

The damage model parameters used for the S-VECD and G^R models are given in Table 22. Results are provided for both the default and peak phase angle method of identifying the number of cycles to failure. These parameters are provided for potential use by future researchers.

Table 22: Damage Model Coefficients for both analysis failure criteria

Method	a		b		α	r		s	
	Default	Peak	Default	Peak		Default	Peak	Default	Peak
PG 70-22 9.5 mm	-1.29E-04	-1.05E-04	0.77	0.79	3.701	1.01E+05	7.58E+05	-0.53	-0.73
PG 70-22 12.5 mm	-3.43E-04	-2.28E-04	0.69	0.74	3.694	9.99E+04	5.65E+05	-0.58	-0.75
PG 70-22 PM 9.5 mm	-1.19E-04	-1.45E-04	0.79	0.77	3.866	2.83E+04	1.03E+06	-0.28	-0.73
PG 70-22 PM 12.5 mm	-1.62E-04	-1.55E-04	0.76	0.77	3.883	2.80E+04	9.30E+05	-0.28	-0.72
PG 76-22 PM 9.5 mm	-2.69E-04	-2.36E-04	0.71	0.72	3.947	3.19E+04	6.79E+05	-0.30	-0.64
PG 76-22 PM 12.5 mm	-2.31E-04	-2.25E-04	0.72	0.73	3.929	2.29E+04	4.52E+05	-0.24	-0.57

The ALPHA-fatigue estimates of endurance limits, in microstrain, are given in Table 23. Though the AMPT fatigue test was run at 15°C, ALPHA-Fatigue uses transfer functions to estimate the endurance limits at other temperatures. A common trend between all mixes and analysis methods is an increase in endurance limit as the temperature increases. Default output values are also much lower than the values obtained with the peak method. The PG 70-22 PM 9.5mm mix type had the highest overall peak values for endurance limit, while the PG 76-22 PM 12.5 mm had the lowest. This ranking of microstrain is not consistent between the peak and default methods. The only values that compare to accepted ranges were obtained through the peak analysis, therefore, from here forth, only the peak method values will be considered.

Table 23: Endurance Limits from ALPHA-Fatigue Outputs

	Default					Peak				
	5°C	10°C	15°C	20°C	25°C	5°C	10°C	15°C	20°C	25°C
PG 70-22 9.5 mm	16	17	20	23	29	66	73	89	107	146
PG 70-22 12.5 mm	19	21	26	31	43	65	77	96	123	179
PG 70-22 PM 9.5 mm	5	5	6	7	9	85	104	132	174	260
PG 70-22 PM 12.5 mm	5	5	6	6	8	80	97	125	163	242
PG 76-22 PM 9.5 mm	4	4	4	5	6	58	67	85	106	149
PG 76-22 PM 12.5 mm	4	4	5	6	7	39	45	57	71	99

A range of strain values, dynamic modulus values from the mastercurves as described previously in Table 17, and the K-values provided in Table 24 were applied to the fatigue failure equation displayed in Equation 5. The plot in Figure 16 and data in Table 25 were produced. The purpose of Figure 16 is to compare life cycles of the different mix types. Along with each of the six mix types, the Asphalt Institute values were also plotted in this method for comparison. The suggested limit of 50 million cycles by Underwood et.al (2012) was included in Figure 16 as a comparison for endurance limit values.

$$N_f = K_1 \left(\frac{1}{\varepsilon_t} \right)^{K_2} (E)^{K_3} \quad (5)$$

Where:

K_1, K_2, K_3 = constants

ε_t = strain

E = dynamic modulus

While most of the mixes are consistently close to this limitation, the PG 70-22 PM 9.5 mm mix type reached this endurance limitation around 100 microstrain which approximately corresponds to ALPHA-Fatigue's 10°C prediction value from the peak method. Not all mixes corresponded to the values that ALPHA-Fatigue gave as a prediction, for example, the PG 76-22 PM 12.5 mm mix type doesn't cross the endurance limit line at all in this plotted range,

therefore, the value is below 50 microstrain which is lower than the peak values displayed in Table 24. It should also be noted that almost all mixes begin higher than the Asphalt Institute line, but all of them fall below it at the highest microstrain plotted. This shows that the Asphalt Institute's values may not be exact, but on average, they may be a good indication of the mix design's performance.

KENPAVE Pavement Life Prediction

Similar to Dalton (2016) and Smith (2015), the dynamic modulus and fatigue data was also analyzed in comparison to results using the KENPAVE software. Following these analyses, modulus versus strain graphs were created for a range of moduli using both conventional and full-depth pavement models which are provided in Figure 17. Subbase material modulus were assumed based on past knowledge and the pavement was analyzed as linear rather than viscoelastic.

The plot of strain versus dynamic modulus for both the conventional and full-depth pavement models are provided in Figure 18. For the conventional pavement the entire surface layer was assumed to be uniform material of each mix type. This assumption was also applied to the full depth pavement. This is a concerning limitation the analysis of the base of the full depth pavement should be a different mix with a larger nominal maximum aggregate size.

The dynamic modulus values from Table 17 were used with Figure 18 to determine the critical fatigue strain for each mix. These strains and dynamic modulus values were used with the peak fatigue K values from Table 24 in Equation 5 to compute the fatigue life of each pavement. The resulting strain and life expectancy are provided in Table 26.

Calculated values for the full-depth pavement are much lower than the accepted value for perpetual pavements of 70 micro-strain (Witczak et al., 2013). From these values, the full-depth analysis indicates that only the PG 70-22 9.5 mm mix design would be considered a perpetual pavement. With an expected fatigue life greater than 5 million ESALS the pavements would be considered suitable for most roads in the state of West Virginia other than interstates. Full-depth pavements consistently had higher fatigue life expectancies than the conventional.

Table 24: K-Values from ALPHA-Fatigue in units of psi

	Default			Peak		
	K1	K2	K3	K1	K2	K3
PG 70-22 9.5 mm	3.21E+06	3.058	-2.245	5.79E+14	5.579	-4.899
PG 70-22 12.5 mm	1.69E+08	3.591	-2.886	1.61E+16	6.196	-5.588
PG 70-22 PM 9.5 mm	1.09E+05	1.306	-0.971	9.26E+16	5.715	-5.280
PG 70-22 PM 12.5 mm	1.35E+05	1.291	-0.978	1.36E+16	5.428	-4.990
PG 76-22 PM 9.5 mm	2.66E+05	1.391	-1.083	3.49E+12	4.179	-3.681
PG 76-22 PM 12.5 mm	1.02E+05	1.054	-0.816	1.97E+10	3.287	-2.821

Figure 16: Plot of fatigue equations using peak analyzed K-values and collected Dynamic Modulus values.

Table 25: N_f at 50 microstrain for each mix type

Mix Type	N_f
PG 70-22 9.5 mm	6.16E+08
PG 70-22 12.5 mm	5.27E+08
PG 70-22 PM 9.5 mm	1.77E+09
PG 70-22 PM 12.5 mm	9.00E+08
PG 76-22 PM 9.5 mm	9.98E+07
PG 76-22 PM 12.5 mm	1.50E+07
Asphalt Institute	6.78E+07
Shell	5.91E+08
Illinois DOT	4.00E+07
TRRL	6.32E+08

Figure 17: Full-Depth and Conventional Pavement Structures used in KENPAVE analysis.

Figure 18: Modulus versus Strain for Conventional and Full-Depth pavement models.

Table 26: KENPAVE Full-Depth and Conventional N_f values

Mix Type	E (ksi)	Conventional		Full Depth	
		Strain (Microstrain)	N_f	Strain (Microstrain)	N_f
PG 70-22 9.5 mm	616	127	1.39E+08	60	9.18E+09
PG 70-22 12.5 mm	453	140	3.04E+08	76	1.30E+10
PG 70-22 PM 9.5 mm	424	143	1.69E+09	80	4.54E+10
PG 70-22 PM 12.5 mm	406	145	9.67E+08	83	1.97E+10
PG 76-22 PM 9.5 mm	426	142	7.81E+07	80	8.73E+08
PG 76-22 PM 12.5 mm	377	148	1.41E+07	88	7.79E+07

Air Voids Effect on Performance

Due to the variation in air voids just below 6.5%, an analysis on the impact air voids had on the number of cycles to failure was performed. Figure 19 displays a plot of measured air voids in percent versus the measured number of cycles to failure measured during fatigue testing for the respective sample. Measured data points were used since the predicted values using the G^R method has been found to be extremely accurate to the measured AMPT data (Underwood et al., 2012). There are no obvious trends in the data and an extremely low coefficient of determination. This data implies that the impact of air voids on fatigue performance is not statistically significant. Due to this analysis, it was decided to continue using the data collected on these samples for their respective test's analysis even though they did not meet the AASHTO air void specification of $7.0\% \pm 0.5\%$.

Figure 19: Air Voids versus Number of Cycles to Failure during fatigue testing.

Chapter 5: Conclusions and Recommendations

Conclusions

Sample Uniformity and Air Voids

All samples made for Dynamic Modulus testing were also tested for their air void uniformity. Fatigue samples were not tested for uniformity for two reasons. The first being that in order to remove the end platens, the samples would have to be heated until the asphalt was essentially liquid, and the sample could no longer maintain its cylindrical shape. The second reason is that the fatigue samples can be assumed to have the same air void distribution as the dynamic modulus samples due to the randomization of the mixing and compacting process.

By analyzing the sections, it was found that there was a much higher variation than the specification allows, however one possible explanation for the samples falling outside of the specified range is that all samples had very low variances and small replicate sample sizes. It was also found that though there was high variation statistically within the samples, none of them were outside of accepted ranges of G_{mb} as found in the equivalency test. There was also a slight difference between the average of the sections and the intact samples just as found by Dalton (2016).

Weak correlations were found between the three G_{mb} methods tested (CoreLok®, SSD, and Dimensional), though the correlation was stronger with samples after coring and sawing. The reasoning for the weak correlations between methods was unexpected and unexplainable. Dalton (2016) found that the dimensional method was the most accurate for samples with cut faces and also recommended that this process be included in AASHTO PP60 as a requirement. This research points to the CoreLok® method, not the dimensional, as the most accurate for cored and sawed samples.

When testing for uniformity, both plots containing the SSD method had higher correlations, though the SSD versus dimensional after coring and sawing had the highest correlation at 0.89. Visually, the SSD versus CoreLok® data points were the closest to the line of equality, though the coefficient of determination was rather low at 0.78. This conclusion contradicts the findings of Dalton (2016) who found that the Dimensional method was the most accurate.

Dynamic Modulus

Both Dynamic Modulus and Phase Angle values fell within an expected range of values and coefficient of variations, more so at the lower testing temperatures. The low coefficient of variation leads to the conclusion that the AMPT can produce reliable and repeatable data from the dynamic modulus test.

All MasterCurves produced using the worksheet developed by Bonaquist (2011b) followed a similar fit and trends. All data tended to vary at lower reduced frequencies, then converged at higher frequencies, just as Dalton (2016) discovered. It was also found that binder type and nominal maximum aggregate size (NMAS) does not have an obvious impact on the mastercurves fit or trends. The PG 70-22 9.5 mm mix type had higher average modulus values while PG 76-22 PM 12.5 mm mix type had the lowest. This trend should be explored further since this result contradicts other research on modifier's impact on Dynamic Modulus.

ALPHA-Fatigue

As previously mentioned, all fatigue data was analyzed using both the default and user selected peak failure point methods and the exponential model within the ALPHA-Fatigue software. The peak criteria typically resulted in reasonable microstrain endurance limits, while the default method resulted in much lower values. Against previous knowledge of binder types, the PG 70-22 PM binder typically resulted in higher predicted endurance limits, while, again, the PG 76-22 PM had lower values.

It was also found that when compared to the Asphalt Institute K-values, most of the mixes had higher cycles to failure at lower strain values, but at higher strain values, all mixes fell below the Asphalt Institute's predicted values.

KENPAVE

Following previous research using KENPAVE values, it was found that the full-depth pavement yielded values implying that almost all pavements met the criteria for a perpetual pavement with respect to fatigue by having low strain values and higher estimates for fatigue life. Conventional pavements however yielded much greater strain values than the full depth which is why they were used in further analysis.

It was also found that using the ALPHA-Fatigue K-values gave higher fatigue life estimates than the results using the Asphalt Institute values in all cases. Most importantly, it was

found that the only mix type that met the qualifications to be considered a perpetual pavement by Witczak et al. (2013) was the PG 70-22 9.5mm. All of the other mix types did not qualify as perpetual pavements by the full depth method and none of the mix types qualified per the conventional method.

Recommendations

Testing Protocol

Effects of air voids on dynamic modulus and fatigue should be further evaluated to determine a definitive effect of lower air voids on fatigue life. Better methods of evaluating air voids and sample uniformity should also be explored as the test methods and t-statistic analysis in use now do not account for low variances and replicate sample sizes.

More data needs to be collected using the AMPT and analyzed using the ALPHA-Fatigue software. Data collected and analyzed in this research as well as other projects in the WVU Asphalt Technology Laboratory not been very consistent with the Asphalt Institute. In terms of the ALPHA-Fatigue software, more development needs to be addressed, especially in the terms of ease of use. A common problem within the software is that, when running multiple replicates, there is no way to change just one selection such as the selection of a failure point or which model to analyze.

Material Evaluation

The PG 70-22 9.5 mm mix type performed better than the others in the dynamic modulus test, and the PG 76-22 PM binder type overall did the worst in both the dynamic modulus and fatigue tests. This conclusion goes against the expected outcome based on the fact that the worst performing binder was rated for higher temperatures and contains modifiers that should stiffen the binder causing an increase in dynamic modulus and fatigue life. More data should be collected on this relationship to determine whether it was the binder type's effect that lowered dynamic modulus and fatigue resistance, or if it was simply the effect of having a richer mix than optimum.

Though the PG 70-22 binder type had higher dynamic modulus values, it performed slightly worse in the fatigue testing overall than its modified counterpart. Turner (2015) discovered a similar relationship in the dynamic modulus test between the PG 70-22 neat and polymer modified binder types.

A further designed experiment should be performed analyzing more binder types and nominal maximum aggregate sizes with varying percent binders, gradations, and air voids to eliminate all factors that could statistically affect the mix. Considering all of these factors and performing all of these tests would also increase the database of measured samples allowing a deeper understanding of the data collected and analyzed from the AMPT in ALPHA-Fatigue and MasterSolver.

Another suggestion is that during the mixing process, the mix should be quartered and re-mixed directly before compaction to avoid segregation of the mix which would give a more precise air void distribution.

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List of Test Methods Used

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- AASHTO PP 61: *Developing Dynamic Modulus Master Curves using AMPT*. Washington, DC: American Association of State Highway and Transportation Officials, 2015.
- AASHTO TP 79: *Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixture Performance Tester (AMPT)* Washington, DC: American Association of State Highway and Transportation Officials, 2013.
- AASHTO TP 107: *Determining the Damage Characteristics Curve of Asphalt Mixtures from Direct Tension Cyclic Fatigue Tests*. Washington, DC: American Association of State Highway and Transportation Officials, 2015.
- AASHTO T 166: *Bulk Specific Gravity of Compacted Hot Mix Asphalt (HMA) Using Saturated Surface-Dry Specimens*. Washington, DC: American Association of State Highway and Transportation Officials, 2015.

AASHTO T 209: Theoretical Maximum Specific Gravity (Gmm) and Density of Hot Mix Asphalt (HMA). Washington, DC: American Association of State Highway and Transportation Officials, 2015.

AASHTO T 269: Percent of Air Voids in Compacted Dense and Open Asphalt Mixtures. Washington, DC: American Association of State Highway and Transportation Officials, 2015.

AASHTO T 312: Preparing and Determining the Density of Hot Mix Asphalt (HMA) by Means of the Superpave Gyratory Compactor. Washington, DC: American Association of State Highway Transportation Officials, 2015.

AASHTO T 331: Bulk Specific Gravity and Density of Compacted Hot Mix Asphalt (HMA) Using Automatic Vacuum Sealing Method. Washington, DC: American Association of State Highway and Transportation Officials, 2015.

AASHTO T 342: Determining Dynamic Modulus of Hot Mix Asphalt. Washington, DC: American Association of State Highway and Transportation Officials, 2015.

Appendix A – Job Mix Formulas

T400 SP
04-10

WEST VIRGINIA DIVISION OF HIGHWAYS JOB MIX FORMULA FOR SUPERPAVE HOT-MIX ASPHALT

Report Number:		1397289		Date Accepted:		June 3, 2010	
HMA Type:		9.5 mm Skid		HMA Code:		13244	
Producer:		Buckeye Asphalt		Plant Location:		Blaney Hollow, WV	
Designed By:		Rich Nuzum		Design Lab:		Clarksburg Asphalt, Bridgeport, WV	
Plant Type:		Drum		Plant Make:		Fab Spec	
Plant Code:		B1670		Design ESALs:		3 < 30 million (3)	

MIX COMPOSITION							
Coarse Aggregate Source			Code	Fine Aggregate Source			Code
CA1	Buckeye Stone, Blaney Hollow, WV		B1660	FA1	Buckeye Stone, Blaney Hollow, WV		B1660
CA2				FA2	Greer Limestone, Greer, WV		G0120
CA3				FA3			
	CA1	CA2	CA3	FA1	FA2	FA3	
Agg. Type	# 8 Limestone			Limestone	Limestone		
Agg. Code	1135			1116	1116		
% Total Agg.	45			35	20		
% RAP Total Agg.:		Blended Binder G*/sin delta if > 25% RAP:					
% Binder In RAP Design:		Binder Type:		PG 76-22	Binder Code:		1086
Binder Source:		Marathon Petroleum, Floreffe Pa.			Binder Source Code:		A022B

Sieve Fraction							Fines / Effective Asphalt Ratio	Tensile Strn. Ratio	
Sieve Size	Target	Allowable		Sieve Size	Target	Allowable			
		Min.	Max.			Min.	Max.		
2" (50 mm)				#4 (4.75)	62		90	Temperature Range Completed Mixture (°F) Desirable Mean Temp. 305	Temp. Range Min. Max. 280 330
1.5" (37.5 mm)				#8 (2.36)	39	33	45		
1" (25 mm)				#16 (1.18)	24				
3/4" (19 mm)				#30 (600)	15				
1/2" (12.5 mm)	100	100	100	#50 (300)	10				
3/8" (9.5 mm)	97	90	100	#200 (75)	4.8				

JOB MIX FORMULA VALUES				
Specific gravity stone bulk (Gsb): 2.66	Job Mix Formula		Job Mix Formula Tolerances	
	Design Property	Design Targets	Minimum	Maximum
	Asphalt (%)	6.2	5.8	6.6
	Air Voids (%)	4	2.8	5.2
	VMA (%)	17.6	16.6	18.6
Maximum Density (kg/m³)	VFA (%)	77	74	80
2435				
Gyrations @ Ndesign:	65	Desirable Mean Temp. for Lab. Specimens (°F):		Comp. Temp. : 296 Mixing Temp. : 315

Remarks: This design was formulated in accordance with memorandum dated 1/21/2010 "Superpave Mix Design Gyrations Level Changes". Additional mix design data for this JMF can be found under T-400 # 1390010

T400 SP
04-10

WEST VIRGINIA DIVISION OF HIGHWAYS
JOB MIX FORMULA FOR SUPERPAVE HOT-MIX ASPHALT

Report Number: 1397265				Date Accepted: May 26, 2010			
HMA Type: 12.5 mm Skid				HMA Code: 13244			
Producer: Buckeye Asphalt				Plant Location: Blaney Hollow, WV			
Designed By: Rich Nuzum				Design Lab: Clarksburg Asphalt, Bridgeport, WV			
Plant Type: Drum				Plant Make: Fab Spec			
Plant Code: B1670				Design ESALs: 3 < 30 million (3)			

MIX COMPOSITION									
Coarse Aggregate Source			Code		Fine Aggregate Source			Code	
CA ₁	Buckeye Stone, Blaney Hollow, WV		B1660		FA ₁	Greer Limestone, Greer, WV		G0120	
CA ₂	Buckeye Stone, Blaney Hollow, WV		B1660		FA ₂	Greer Limestone, Greer, WV		G0120	
CA ₃					FA ₃				
	CA ₁	CA ₂	CA ₃		FA ₁	FA ₂	FA ₃		
Agg. Type	# 7 Limestone	# 8 Limestone			Limestone	Limestone			
Agg. Code	1133	1135			1116	1116			
% Total Agg.	25	20			35	20			
% RAP Total Agg.:			Blended Binder G*/sin delta if > 25% RAP:						
% Binder In RAP Design:			Binder Type:		PG 76-22	Binder Code:		1086	
Binder Source:			Marathon Petroleum, Floreffe Pa.			Binder Source Code:		A022B	

Sieve Fraction								Fines / Effective Asphalt Ratio		Tensile Strn. Ratio	
Sieve Size	Target	Allowable		Sieve Size	Target	Allowable					
		Min.	Max.			Min.	Max.	1.0	91.0		
2" (50 mm)				#4 (4.75)	60		90	Temperature Range Completed Mixture (°F)			
1.5" (37.5 mm)				#8 (2.36)	39	33	45				
1" (25 mm)				#16 (1.18)	24			Desirable Mean Temp.	Temp. Range		
3/4" (19 mm)	100	100	100	#30 (600)	13				305	Min.	Max.
1/2" (12.5 mm)	94	90	100	#50 (300)	9					280	330
3/8" (9.5 mm)	86		90	#200 (75)	5.4	2.0	10.0				

JOB MIX FORMULA VALUES								
Specific gravity stone bulk (Gsb): 2.658	Design Property		Job Mix Formula		Job Mix Formula Tolerances			
			Design Targets		Minimum			
					Maximum			
	Asphalt (%)		5.9		5.5			
	Maximum Air Voids (%)		4		2.8			
Density (kg/m³)	VMA (%)		16.4		15.4			
	VFA (%)		76		72			
Gyrations @ Ndesign:	65	Desirable Mean Temp. for Lab. Specimens (°F):			Comp. Temp. :	296	Mixing Temp. :	315

Remarks: This design was formulated in accordance with memorandum dated 1/21/2010 "Superpave Mix Design Gyrations Level Changes". Additional mix design data for this JMF can be found under T-400 # 1365867

Appendix B – Performance Sample Volumetrics

Bulk Specific Gravities (G_{mb}) for Full Size Samples

Binder Type	NMAS	Sample Designation	Before			After		
			SSD	CoreLok	Dimensional	SSD	CoreLok	Dimensional
PG 70-22	9.5 mm	FT 1A	2.278	2.265	2.238	2.307	2.303	2.298
PG 70-22	9.5 mm	FT 1B	2.279	2.263	2.236	2.305	2.301	2.300
PG 70-22	9.5 mm	FT 1C	2.280	2.259	2.238	2.308	2.304	2.302
PG 70-22	9.5 mm	FT 2A	2.283	2.262	2.237	2.300	2.299	2.287
PG 70-22	9.5 mm	FT 2B	2.283	2.266	2.237	2.303	2.303	2.294
PG 70-22	9.5 mm	FT 2C	2.285	2.265	2.239	2.304	2.305	2.296
PG 70-22	9.5 mm	FT 3A	2.281	2.264	2.237	2.311	2.306	2.300
PG 70-22	9.5 mm	FT 3B	2.283	2.256	2.235	2.305	2.302	2.297
PG 70-22	9.5 mm	FT 3C	2.279	2.263	2.236	2.306	2.301	2.295
PG 70-22	9.5 mm	DM 1	2.278	2.225	2.236	2.291	2.289	2.281
PG 70-22	9.5 mm	DM 2	2.281	2.263	2.245	2.298	2.298	2.285
PG 70-22	9.5 mm	DM 3	2.283	2.248	2.239	2.300	2.301	2.288

Binder Type	NMAS	Sample Designation	Before			After		
			SSD	CoreLok	Dimensional	SSD	CoreLok	Dimensional
PG 70-22	12.5 mm	FT 1A	2.285	2.268	2.238	2.303	2.301	2.298
PG 70-22	12.5 mm	FT 1B	2.289	2.264	2.237	2.314	2.316	2.305
PG 70-22	12.5 mm	FT 1C	2.280	2.266	2.237	2.307	2.308	2.299
PG 70-22	12.5 mm	FT 2A	2.280	2.268	2.238	2.307	2.301	2.301
PG 70-22	12.5 mm	FT 2B	2.276	2.263	2.239	2.305	2.300	2.296
PG 70-22	12.5 mm	FT 2C	2.277	2.265	2.238	2.304	2.299	2.296
PG 70-22	12.5 mm	FT 3A	2.283	2.266	2.237	2.300	2.289	2.293
PG 70-22	12.5 mm	FT 3B	2.285	2.266	2.238	2.308	2.304	2.302
PG 70-22	12.5 mm	FT 3C	2.265	2.251	2.237	2.287	2.283	2.279
PG 70-22	12.5 mm	DM 1	2.277	2.261	2.235	2.288	2.287	2.282
PG 70-22	12.5 mm	DM 2	2.285	2.265	2.237	2.298	2.303	2.288
PG 70-22	12.5 mm	DM 3	2.287	2.268	2.238	2.301	2.301	2.290

Binder Type	NMAS	Sample Designation	Before			After		
			SSD	CoreLok	Dimensional	SSD	CoreLok	Dimensional
PG 70-22 PM	9.5 mm	FT 1A	2.281	2.265	2.238	2.306	2.302	2.300
PG 70-22 PM	9.5 mm	FT 1B	2.275	2.258	2.235	2.302	2.299	2.297
PG 70-22 PM	9.5 mm	FT 1C	2.272	2.252	2.235	2.295	2.288	2.287
PG 70-22 PM	9.5 mm	FT 2A	2.278	2.264	2.237	2.302	2.299	2.297
PG 70-22 PM	9.5 mm	FT 2B	2.282	2.266	2.239	2.304	2.304	2.297
PG 70-22 PM	9.5 mm	FT 2C	2.281	2.265	2.238	2.308	2.310	2.302
PG 70-22 PM	9.5 mm	FT 3A	2.274	2.264	2.237	2.306	2.300	2.300
PG 70-22 PM	9.5 mm	FT 3B	2.281	2.265	2.238	2.302	2.299	2.296
PG 70-22 PM	9.5 mm	FT 3C	2.277	2.259	2.234	2.304	2.299	2.298
PG 70-22 PM	9.5 mm	DM 1	2.283	2.262	2.236	2.297	2.299	2.289
PG 70-22 PM	9.5 mm	DM 2	2.276	2.263	2.229	2.297	2.298	2.288
PG 70-22 PM	9.5 mm	DM 3	2.282	2.263	2.237	2.302	2.302	2.929

Binder Type	NMAS	Sample Designation	Before			After		
			SSD	CoreLok	Dimensional	SSD	CoreLok	Dimensional
PG 70-22 PM	12.5 mm	FT 1A	2.285	2.268	2.239	2.301	2.301	2.292
PG 70-22 PM	12.5 mm	FT 1B	2.286	2.264	2.238	2.310	2.312	2.303
PG 70-22 PM	12.5 mm	FT 1C	2.277	2.259	2.234	2.299	2.302	2.292
PG 70-22 PM	12.5 mm	FT 2A	2.284	2.267	2.238	2.300	2.301	2.291
PG 70-22 PM	12.5 mm	FT 2B	2.282	2.265	2.235	2.298	2.298	2.290
PG 70-22 PM	12.5 mm	FT 2C	2.279	2.259	2.237	2.290	2.278	2.280
PG 70-22 PM	12.5 mm	FT 3A	2.282	2.264	2.237	2.295	2.298	2.288
PG 70-22 PM	12.5 mm	FT 3B	2.285	2.266	2.237	2.298	2.299	2.292
PG 70-22 PM	12.5 mm	FT 3C	2.282	2.261	2.237	2.294	2.285	2.288
PG 70-22 PM	12.5 mm	DM 1	2.282	2.268	2.238	2.295	2.297	2.286
PG 70-22 PM	12.5 mm	DM 2	2.282	2.265	2.237	2.300	2.301	2.289
PG 70-22 PM	12.5 mm	DM 3	2.284	2.258	2.239	2.295	2.300	2.282

Binder Type	NMAS	Sample Designation	Before			After		
			SSD	CoreLok	Dimensional	SSD	CoreLok	Dimensional
PG 76-22 PM	9.5 mm	FT 1A	2.282	2.268	2.237	2.309	2.305	2.299
PG 76-22 PM	9.5 mm	FT 1A2	2.283	2.266	2.236	2.307	2.299	2.301
PG 76-22 PM	9.5 mm	FT 1B	2.282	2.259	2.238	2.310	2.305	2.302
PG 76-22 PM	9.5 mm	FT 1B2	2.284	2.264	2.238	2.309	2.304	2.301
PG 76-22 PM	9.5 mm	FT 1C	2.284	2.267	2.238	2.311	2.304	2.303
PG 76-22 PM	9.5 mm	FT 2A	2.284	2.264	2.237	2.314	2.312	2.307
PG 76-22 PM	9.5 mm	FT 2B	2.283	2.265	2.237	2.312	2.313	2.304
PG 76-22 PM	9.5 mm	FT 2C	2.281	2.264	2.237	2.307	2.304	2.300
PG 76-22 PM	9.5 mm	FT 3A	2.283	2.265	2.238	2.309	2.305	2.298
PG 76-22 PM	9.5 mm	FT 3B	2.279	2.265	2.238	2.306	2.306	2.286
PG 76-22 PM	9.5 mm	FT 3C	2.278	2.263	2.237	2.310	2.305	2.301
PG 76-22 PM	9.5 mm	DM 1	2.268	2.243	2.221	2.278	2.280	2.273
PG 76-22 PM	9.5 mm	DM 2	2.284	2.265	2.236	2.302	2.300	2.290
PG 76-22 PM	9.5 mm	DM 3	2.282	2.265	2.237	2.303	2.303	2.294

Binder Type	NMAS	Sample Designation	Before			After		
			SSD	CoreLok	Dimensional	SSD	CoreLok	Dimensional
PG 76-22 PM	12.5 mm	FT 1A	2.286	2.268	2.238	2.308	2.308	2.302
PG 76-22 PM	12.5 mm	FT 1B	2.287	2.269	2.238	2.305	2.303	2.297
PG 76-22 PM	12.5 mm	FT 1C	2.284	2.268	2.239	2.308	2.308	2.299
PG 76-22 PM	12.5 mm	FT 2A	2.285	2.269	2.237	2.311	2.307	2.308
PG 76-22 PM	12.5 mm	FT 2B	2.283	2.267	2.238	2.315	2.311	2.307
PG 76-22 PM	12.5 mm	FT 2C	2.280	2.267	2.237	2.311	2.309	2.305
PG 76-22 PM	12.5 mm	FT 3A	2.281	2.261	2.236	2.297	2.295	2.290
PG 76-22 PM	12.5 mm	FT 3B	2.286	2.263	2.238	2.303	2.301	2.295
PG 76-22 PM	12.5 mm	FT 3C	2.286	2.269	2.240	2.307	2.309	2.301
PG 76-22 PM	12.5 mm	DM 1	2.283	2.264	2.237	2.288	2.290	2.282
PG 76-22 PM	12.5 mm	DM 2	2.288	2.259	2.238	2.295	2.296	2.285
PG 76-22 PM	12.5 mm	DM 3	2.287	2.268	2.237	2.302	2.303	2.291

Dynamic Modulus Samples Voids in Total Mix (VTM)

Binder Type	NMAS	Sample Designation	SGC Before core and trimming			After Coring and Trimming		
			SSD	CoreLok	Dimensional	SSD	CoreLok	Dimensional
PG 70-22	9.5 mm	FT 1A	7.6%	8.2%	9.3%	6.5%	6.6%	6.8%
PG 70-22	9.5 mm	FT 1B	7.6%	8.2%	9.3%	6.5%	6.7%	6.7%
PG 70-22	9.5 mm	FT 1C	7.5%	8.4%	9.3%	6.4%	6.6%	6.6%
PG 70-22	9.5 mm	FT 2A	7.4%	8.3%	9.3%	6.7%	6.8%	7.3%
PG 70-22	9.5 mm	FT 2B	7.4%	8.1%	9.3%	6.6%	6.6%	7.0%
PG 70-22	9.5 mm	FT 2C	7.3%	8.1%	9.2%	6.6%	6.5%	6.9%
PG 70-22	9.5 mm	FT 3A	7.5%	8.2%	9.3%	6.3%	6.5%	6.7%
PG 70-22	9.5 mm	FT 3B	7.4%	8.5%	9.3%	6.5%	6.7%	6.8%
PG 70-22	9.5 mm	FT 3C	7.6%	8.2%	9.3%	6.5%	6.7%	6.9%
PG 70-22	9.5 mm	DM 1	7.6%	9.8%	9.3%	7.1%	7.2%	7.5%
PG 70-22	9.5 mm	DM 2	7.5%	8.2%	9.0%	6.8%	6.8%	7.4%
PG 70-22	9.5 mm	DM 3	7.4%	8.9%	9.2%	6.7%	6.7%	7.2%

Binder Type	NMAS	Sample Designation	Before			After		
			SSD	CoreLok	Dimensional	SSD	CoreLok	Dimensional
PG 70-22	12.5 mm	FT 1A	7.3%	7.9%	9.2%	6.5%	6.6%	6.7%
PG 70-22	12.5 mm	FT 1B	7.1%	8.1%	9.2%	6.1%	6.0%	6.4%
PG 70-22	12.5 mm	FT 1C	7.5%	8.0%	9.2%	6.4%	6.3%	6.7%
PG 70-22	12.5 mm	FT 2A	7.4%	8.0%	9.2%	6.4%	6.6%	6.6%
PG 70-22	12.5 mm	FT 2B	7.6%	8.1%	9.1%	6.4%	6.7%	6.8%
PG 70-22	12.5 mm	FT 2C	7.6%	8.1%	9.2%	6.5%	6.7%	6.8%
PG 70-22	12.5 mm	FT 3A	7.3%	8.0%	9.2%	6.6%	7.1%	7.0%
PG 70-22	12.5 mm	FT 3B	7.3%	8.0%	9.2%	6.3%	6.5%	6.6%
PG 70-22	12.5 mm	FT 3C	8.1%	8.7%	9.2%	7.2%	7.3%	7.5%
PG 70-22	12.5 mm	DM 1	7.6%	8.2%	9.3%	7.2%	7.2%	7.4%
PG 70-22	12.5 mm	DM 2	7.3%	8.1%	9.2%	6.7%	6.5%	7.1%
PG 70-22	12.5 mm	DM 3	7.2%	8.0%	9.2%	6.6%	6.6%	7.1%

Binder Type	NMAS	Sample Designation	Before			After		
			SSD	CoreLok	Dimensional	SSD	CoreLok	Dimensional
PG 70-22 PM	9.5 mm	FT 1A	7.5%	8.2%	9.2%	6.5%	6.6%	6.7%
PG 70-22 PM	9.5 mm	FT 1B	7.8%	8.4%	9.4%	6.7%	6.8%	6.9%
PG 70-22 PM	9.5 mm	FT 1C	7.8%	8.7%	9.4%	6.9%	7.2%	7.3%
PG 70-22 PM	9.5 mm	FT 2A	7.6%	8.2%	9.3%	6.6%	6.8%	6.9%
PG 70-22 PM	9.5 mm	FT 2B	7.5%	8.1%	9.2%	6.6%	6.6%	6.9%
PG 70-22 PM	9.5 mm	FT 2C	7.5%	8.2%	9.3%	6.4%	6.3%	6.6%
PG 70-22 PM	9.5 mm	FT 3A	7.8%	8.2%	9.3%	6.5%	6.7%	6.7%
PG 70-22 PM	9.5 mm	FT 3B	7.5%	8.1%	9.2%	6.6%	6.8%	6.9%
PG 70-22 PM	9.5 mm	FT 3C	7.7%	8.4%	9.4%	6.6%	6.8%	6.8%
PG 70-22 PM	9.5 mm	DM 1	7.4%	8.3%	9.3%	6.9%	6.8%	7.2%
PG 70-22 PM	9.5 mm	DM 2	7.7%	8.2%	9.6%	6.8%	6.8%	7.2%
PG 70-22 PM	9.5 mm	DM 3	7.5%	8.2%	9.3%	6.7%	6.7%	7.1%

Binder Type	NMAS	Sample Designation	Before			After		
			SSD	CoreLok	Dimensional	SSD	CoreLok	Dimensional
PG 70-22 PM	12.5 mm	FT 1A	7.3%	8.0%	9.2%	6.6%	6.6%	7.0%
PG 70-22 PM	12.5 mm	FT 1B	7.2%	8.1%	9.2%	6.2%	6.2%	6.6%
PG 70-22 PM	12.5 mm	FT 1C	7.6%	8.3%	9.3%	6.7%	6.6%	7.0%
PG 70-22 PM	12.5 mm	FT 2A	7.3%	8.0%	9.2%	6.6%	6.6%	7.0%
PG 70-22 PM	12.5 mm	FT 2B	7.4%	8.1%	9.3%	6.7%	6.7%	7.0%
PG 70-22 PM	12.5 mm	FT 2C	7.5%	8.3%	9.2%	7.1%	7.5%	7.5%
PG 70-22 PM	12.5 mm	FT 3A	7.4%	8.1%	9.2%	6.9%	6.7%	7.1%
PG 70-22 PM	12.5 mm	FT 3B	7.3%	8.0%	9.2%	6.7%	6.7%	7.0%
PG 70-22 PM	12.5 mm	FT 3C	7.4%	8.2%	9.2%	6.9%	7.3%	7.2%
PG 70-22 PM	12.5 mm	DM 1	7.4%	8.0%	9.2%	6.8%	6.8%	7.2%
PG 70-22 PM	12.5 mm	DM 2	7.4%	8.1%	9.2%	6.7%	6.6%	7.1%
PG 70-22 PM	12.5 mm	DM 3	7.3%	8.3%	9.1%	6.9%	6.7%	7.4%

Binder Type	NMAS	Sample Designation	Before			After		
			SSD	CoreLok	Dimensional	SSD	CoreLok	Dimensional
PG 76-22 PM	9.5 mm	FT 1A	7.4%	8.0%	9.3%	6.4%	6.5%	6.8%
PG 76-22 PM	9.5 mm	FT 1A2	7.4%	8.1%	9.3%	6.5%	6.8%	6.7%
PG 76-22 PM	9.5 mm	FT 1B	7.5%	8.4%	9.3%	6.3%	6.5%	6.7%
PG 76-22 PM	9.5 mm	FT 1B2	7.4%	8.2%	9.2%	6.4%	6.6%	6.7%
PG 76-22 PM	9.5 mm	FT 1C	7.4%	8.1%	9.2%	6.3%	6.6%	6.6%
PG 76-22 PM	9.5 mm	FT 2A	7.4%	8.2%	9.3%	6.2%	6.3%	6.5%
PG 76-22 PM	9.5 mm	FT 2B	7.4%	8.2%	9.3%	6.2%	6.2%	6.6%
PG 76-22 PM	9.5 mm	FT 2C	7.5%	8.2%	9.3%	6.4%	6.6%	6.7%
PG 76-22 PM	9.5 mm	FT 3A	7.4%	8.2%	9.2%	6.4%	6.5%	6.8%
PG 76-22 PM	9.5 mm	FT 3B	7.6%	8.2%	9.3%	6.5%	6.5%	7.3%
PG 76-22 PM	9.5 mm	FT 3C	7.6%	8.2%	9.3%	6.3%	6.5%	6.7%
PG 76-22 PM	9.5 mm	DM 1	8.0%	9.0%	10.0%	7.6%	7.5%	7.8%
PG 76-22 PM	9.5 mm	DM 2	7.4%	8.2%	9.3%	6.6%	6.7%	7.1%
PG 76-22 PM	9.5 mm	DM 3	7.5%	8.2%	9.3%	6.6%	6.6%	7.0%

Binder Type	NMAS	Sample Designation	Before			After		
			SSD	CoreLok	Dimensional	SSD	CoreLok	Dimensional
PG 76-22 PM	12.5 mm	FT 1A	7.2%	7.9%	9.2%	6.3%	6.3%	6.6%
PG 76-22 PM	12.5 mm	FT 1B	7.2%	7.9%	9.2%	6.5%	6.5%	6.8%
PG 76-22 PM	12.5 mm	FT 1C	7.3%	8.0%	9.1%	6.3%	6.3%	6.7%
PG 76-22 PM	12.5 mm	FT 2A	7.3%	7.9%	9.2%	6.2%	6.4%	6.4%
PG 76-22 PM	12.5 mm	FT 2B	7.4%	8.0%	9.2%	6.1%	6.2%	6.4%
PG 76-22 PM	12.5 mm	FT 2C	7.4%	8.0%	9.2%	6.2%	6.3%	6.4%
PG 76-22 PM	12.5 mm	FT 3A	7.4%	8.2%	9.3%	6.8%	6.9%	7.0%
PG 76-22 PM	12.5 mm	FT 3B	7.2%	8.2%	9.2%	6.6%	6.6%	6.9%
PG 76-22 PM	12.5 mm	FT 3C	7.2%	7.9%	9.1%	6.4%	6.3%	6.6%
PG 76-22 PM	12.5 mm	DM 1	7.3%	8.1%	9.2%	7.1%	7.1%	7.4%
PG 76-22 PM	12.5 mm	DM 2	7.1%	8.3%	9.2%	6.9%	6.8%	7.3%
PG 76-22 PM	12.5 mm	DM 3	7.2%	8.0%	9.2%	6.6%	6.5%	7.0%

Sample Geometry After Coring and Sawing

Binder Type	NMAS	Sample Designation	Diameter		Height	
			Average	Standard Deviation	Average	Standard Deviation
PG 70-22	9.5 mm	FT 1A	100.46	0.06	129.86	0.32
PG 70-22	9.5 mm	FT 1B	100.43	0.02	130.85	0.24
PG 70-22	9.5 mm	FT 1C	100.44	0.03	129.36	0.51
PG 70-22	9.5 mm	FT 2A	100.43	0.02	129.62	0.32
PG 70-22	9.5 mm	FT 2B	100.41	0.03	130.93	0.24
PG 70-22	9.5 mm	FT 2C	100.42	0.05	129.64	0.32
PG 70-22	9.5 mm	FT 3A	100.49	0.08	131.60	0.42
PG 70-22	9.5 mm	FT 3B	100.47	0.05	130.14	0.48
PG 70-22	9.5 mm	FT 3C	100.44	0.02	130.84	0.50
PG 70-22	9.5 mm	DM 1	100.48	0.02	150.10	0.47
PG 70-22	9.5 mm	DM 2	100.43	0.13	150.21	0.38
PG 70-22	9.5 mm	DM 3	100.46	0.02	150.90	0.08

Binder Type	NMAS	Sample Designation	Diameter		Height	
			Average	Standard Deviation	Average	Standard Deviation
PG 70-22	12.5 mm	FT 1A	100.42	0.03	129.97	0.21
PG 70-22	12.5 mm	FT 1B	100.43	0.02	129.13	0.59
PG 70-22	12.5 mm	FT 1C	100.42	0.03	130.02	0.29
PG 70-22	12.5 mm	FT 2A	100.42	0.03	129.58	0.67
PG 70-22	12.5 mm	FT 2B	100.43	0.04	129.70	0.47
PG 70-22	12.5 mm	FT 2C	100.45	0.03	129.63	0.67
PG 70-22	12.5 mm	FT 3A	100.43	0.02	129.36	0.63
PG 70-22	12.5 mm	FT 3B	100.43	0.03	130.32	0.43
PG 70-22	12.5 mm	FT 3C	100.44	0.02	130.39	0.33
PG 70-22	12.5 mm	DM 1	100.38	0.06	151.13	0.07
PG 70-22	12.5 mm	DM 2	100.45	0.06	150.17	0.09
PG 70-22	12.5 mm	DM 3	100.45	0.02	149.30	0.36

Binder Type	NMA S	Sample Designation	Diameter		Height	
			Average	Standard Deviation	Average	Standard Deviation
PG 70-22 PM	9.5 mm	FT 1A	100.44	0.01	130.50	0.43
PG 70-22 PM	9.5 mm	FT 1B	100.43	0.02	130.15	0.42
PG 70-22 PM	9.5 mm	FT 1C	100.43	0.04	130.13	0.36
PG 70-22 PM	9.5 mm	FT 2A	100.41	0.04	130.21	0.38
PG 70-22 PM	9.5 mm	FT 2B	100.41	0.03	130.27	0.37
PG 70-22 PM	9.5 mm	FT 2C	100.44	0.02	130.32	0.48
PG 70-22 PM	9.5 mm	FT 3A	100.41	0.02	131.02	0.50
PG 70-22 PM	9.5 mm	FT 3B	100.42	0.04	130.93	0.45
PG 70-22 PM	9.5 mm	FT 3C	100.43	0.03	129.93	0.52
PG 70-22 PM	9.5 mm	DM 1	100.46	0.05	150.39	0.24
PG 70-22 PM	9.5 mm	DM 2	100.47	0.05	148.50	0.08
PG 70-22 PM	9.5 mm	DM 3	100.46	0.04	149.87	0.31

Binder Type	NMA S	Sample Designation	Diameter		Height	
			Average	Standard Deviation	Average	Standard Deviation
PG 70-22 PM	12.5 mm	FT 1A	100.43	0.05	130.07	0.18
PG 70-22 PM	12.5 mm	FT 1B	100.41	0.03	130.87	0.32
PG 70-22 PM	12.5 mm	FT 1C	100.41	0.02	131.26	0.22
PG 70-22 PM	12.5 mm	FT 2A	100.42	0.04	131.03	0.28
PG 70-22 PM	12.5 mm	FT 2B	100.42	0.03	129.31	0.25
PG 70-22 PM	12.5 mm	FT 2C	100.44	0.03	131.34	0.26
PG 70-22 PM	12.5 mm	FT 3A	100.41	0.04	130.21	0.35
PG 70-22 PM	12.5 mm	FT 3B	100.42	0.05	129.84	0.33
PG 70-22 PM	12.5 mm	FT 3C	100.43	0.03	130.18	0.52
PG 70-22 PM	12.5 mm	DM 1	100.47	0.02	151.16	0.16
PG 70-22 PM	12.5 mm	DM 2	100.47	0.05	150.22	0.49
PG 70-22 PM	12.5 mm	DM 3	100.50	0.05	150.95	0.57

Binder Type	NMAS	Sample Designation	Diameter		Height	
			Average	Standard Deviation	Average	Standard Deviation
PG 76-22 PM	9.5 mm	FT 1A	100.47	0.02	130.25	0.27
PG 76-22 PM	9.5 mm	FT 1A2	100.43	0.03	129.39	0.36
PG 76-22 PM	9.5 mm	FT 1B	100.45	0.05	130.91	0.36
PG 76-22 PM	9.5 mm	FT 1B2	100.47	0.04	129.89	0.48
PG 76-22 PM	9.5 mm	FT 1C	100.46	0.05	131.14	0.09
PG 76-22 PM	9.5 mm	FT 2A	100.45	0.03	130.08	0.38
PG 76-22 PM	9.5 mm	FT 2B	100.46	0.03	130.70	0.09
PG 76-22 PM	9.5 mm	FT 2C	100.45	0.01	130.23	0.37
PG 76-22 PM	9.5 mm	FT 3A	100.44	0.04	130.40	0.24
PG 76-22 PM	9.5 mm	FT 3B	100.45	0.01	131.40	0.17
PG 76-22 PM	9.5 mm	FT 3C	100.44	0.01	131.32	0.44
PG 76-22 PM	9.5 mm	DM 1	100.41	0.02	151.88	0.26
PG 76-22 PM	9.5 mm	DM 2	100.51	0.04	150.53	0.10
PG 76-22 PM	9.5 mm	DM 3	100.44	0.02	151.09	0.37

Binder Type	NMAS	Sample Designation	Diameter		Height	
			Average	Standard Deviation	Average	Standard Deviation
PG 76-22 PM	12.5 mm	FT 1A	100.43	0.03	130.57	0.17
PG 76-22 PM	12.5 mm	FT 1B	100.43	0.04	129.74	0.45
PG 76-22 PM	12.5 mm	FT 1C	100.46	0.02	130.40	0.22
PG 76-22 PM	12.5 mm	FT 2A	100.44	0.02	129.99	0.35
PG 76-22 PM	12.5 mm	FT 2B	100.44	0.01	131.20	0.26
PG 76-22 PM	12.5 mm	FT 2C	100.42	0.02	130.34	0.32
PG 76-22 PM	12.5 mm	FT 3A	100.43	0.02	130.04	0.52
PG 76-22 PM	12.5 mm	FT 3B	100.44	0.02	131.82	0.18
PG 76-22 PM	12.5 mm	FT 3C	100.42	0.01	130.18	0.44
PG 76-22 PM	12.5 mm	DM 1	100.42	0.04	152.04	0.20
PG 76-22 PM	12.5 mm	DM 2	100.46	0.03	150.11	0.23
PG 76-22 PM	12.5 mm	DM 3	100.46	0.02	150.31	0.53

Appendix C – Cut Sample Volumetrics

Bulk Specific Gravities (G_{mb}) for Sample Thirds

Binder Type	NMAS	Sample Designation	Section	SSD	CoreLok	Dimensional
PG 70-22	9.5 mm	DM 1	Top	2.301	2.295	2.280
PG 70-22	9.5 mm	DM 1	Middle	2.266	2.261	2.251
PG 70-22	9.5 mm	DM 1	Bottom	2.303	2.299	2.292
PG 70-22	9.5 mm	DM 2	Top	2.311	2.303	2.294
PG 70-22	9.5 mm	DM 2	Middle	2.276	2.272	2.258
PG 70-22	9.5 mm	DM 2	Bottom	2.302	2.293	2.286
PG 70-22	9.5 mm	DM 3	Top	2.315	2.306	2.304
PG 70-22	9.5 mm	DM 3	Middle	2.283	2.277	2.272
PG 70-22	9.5 mm	DM 3	Bottom	2.297	2.292	2.286

Binder Type	NMAS	Sample Designation	Section	SSD	CoreLok	Dimensional
PG 70-22	12.5 mm	DM 1	Top	2.300	2.299	2.287
PG 70-22	12.5 mm	DM 1	Middle	2.267	2.262	2.257
PG 70-22	12.5 mm	DM 1	Bottom	2.288	2.284	2.278
PG 70-22	12.5 mm	DM 2	Top	2.306	2.287	2.296
PG 70-22	12.5 mm	DM 2	Middle	2.281	2.274	2.269
PG 70-22	12.5 mm	DM 2	Bottom	2.298	2.286	2.287
PG 70-22	12.5 mm	DM 3	Top	2.308	2.301	2.291
PG 70-22	12.5 mm	DM 3	Middle	2.284	2.263	2.257
PG 70-22	12.5 mm	DM 3	Bottom	2.304	2.297	2.284

Binder Type	NMAS	Sample Designation	Section	SSD	CoreLok	Dimensional
PG 70-22 PM	9.5 mm	DM 1	Top	2.302	2.294	2.286
PG 70-22 PM	9.5 mm	DM 1	Middle	2.276	2.272	2.260
PG 70-22 PM	9.5 mm	DM 1	Bottom	2.312	2.309	2.291
PG 70-22 PM	9.5 mm	DM 2	Top	2.308	2.307	2.298
PG 70-22 PM	9.5 mm	DM 2	Middle	2.275	2.268	2.269
PG 70-22 PM	9.5 mm	DM 2	Bottom	2.308	2.303	2.307
PG 70-22 PM	9.5 mm	DM 3	Top	2.305	2.299	2.290
PG 70-22 PM	9.5 mm	DM 3	Middle	2.286	2.273	2.284
PG 70-22 PM	9.5 mm	DM 3	Bottom	2.312	2.309	2.306

Binder Type	NMAS	Sample Designation	Section	SSD	CoreLok	Dimensional
PG 70-22 PM	12.5 mm	DM 1	Top	2.297	2.288	2.286
PG 70-22 PM	12.5 mm	DM 1	Middle	2.280	2.276	2.269
PG 70-22 PM	12.5 mm	DM 1	Bottom	2.308	2.305	2.302
PG 70-22 PM	12.5 mm	DM 2	Top	2.313	2.314	2.299
PG 70-22 PM	12.5 mm	DM 2	Middle	2.283	2.276	2.270
PG 70-22 PM	12.5 mm	DM 2	Bottom	2.294	2.298	2.284
PG 70-22 PM	12.5 mm	DM 3	Top	2.304	2.292	2.299
PG 70-22 PM	12.5 mm	DM 3	Middle	2.284	2.222	2.274
PG 70-22 PM	12.5 mm	DM 3	Bottom	2.293	2.285	2.282

Binder Type	NMAS	Sample Designation	Section	SSD	CoreLok	Dimensional
PG 76-22 PM	9.5 mm	DM 1	Top	2.282	2.280	2.274
PG 76-22 PM	9.5 mm	DM 1	Middle	2.257	2.227	2.251
PG 76-22 PM	9.5 mm	DM 1	Bottom	2.287	2.281	2.280
PG 76-22 PM	9.5 mm	DM 2	Top	2.308	2.304	2.292
PG 76-22 PM	9.5 mm	DM 2	Middle	2.276	2.268	2.267
PG 76-22 PM	9.5 mm	DM 2	Bottom	2.323	2.317	2.312
PG 76-22 PM	9.5 mm	DM 3	Top	2.317	2.309	2.307
PG 76-22 PM	9.5 mm	DM 3	Middle	2.285	2.272	2.276
PG 76-22 PM	9.5 mm	DM 3	Bottom	2.308	2.300	2.301

Binder Type	NMAS	Sample Designation	Section	SSD	CoreLok	Dimensional
PG 76-22 PM	12.5 mm	DM 1	Top	2.297	2.293	2.277
PG 76-22 PM	12.5 mm	DM 1	Middle	2.274	2.271	2.272
PG 76-22 PM	12.5 mm	DM 1	Bottom	2.289	2.288	2.286
PG 76-22 PM	12.5 mm	DM 2	Top	2.296	2.284	2.292
PG 76-22 PM	12.5 mm	DM 2	Middle	2.278	2.269	2.264
PG 76-22 PM	12.5 mm	DM 2	Bottom	2.303	2.297	2.295
PG 76-22 PM	12.5 mm	DM 3	Top	2.304	2.167	2.294
PG 76-22 PM	12.5 mm	DM 3	Middle	2.287	2.286	2.265
PG 76-22 PM	12.5 mm	DM 3	Bottom	2.312	2.311	2.298

Sample Thirds Voids in Total Mix (VTM)

Binder Type	NMAS	Sample Designation	Section	SSD	CoreLok	Dimensional
PG 70-22	9.5 mm	DM 1	Top	6.7%	6.9%	7.5%
PG 70-22	9.5 mm	DM 1	Middle	8.1%	8.3%	8.7%
PG 70-22	9.5 mm	DM 1	Bottom	6.6%	6.8%	7.1%
PG 70-22	9.5 mm	DM 2	Top	6.3%	6.6%	7.0%
PG 70-22	9.5 mm	DM 2	Middle	7.7%	7.9%	8.4%
PG 70-22	9.5 mm	DM 2	Bottom	6.7%	7.0%	7.3%
PG 70-22	9.5 mm	DM 3	Top	6.1%	6.5%	6.6%
PG 70-22	9.5 mm	DM 3	Middle	7.4%	7.6%	7.9%
PG 70-22	9.5 mm	DM 3	Bottom	6.8%	7.1%	7.3%

Binder Type	NMAS	Sample Designation	Section	SSD	CoreLok	Dimensional
PG 70-22	12.5 mm	DM 1	Top	6.7%	6.7%	7.2%
PG 70-22	12.5 mm	DM 1	Middle	8.0%	8.2%	8.4%
PG 70-22	12.5 mm	DM 1	Bottom	7.1%	7.3%	7.5%
PG 70-22	12.5 mm	DM 2	Top	6.4%	7.2%	6.8%
PG 70-22	12.5 mm	DM 2	Middle	7.4%	7.7%	7.9%
PG 70-22	12.5 mm	DM 2	Bottom	6.7%	7.2%	7.2%
PG 70-22	12.5 mm	DM 3	Top	6.3%	6.6%	7.0%
PG 70-22	12.5 mm	DM 3	Middle	7.3%	8.2%	8.4%
PG 70-22	12.5 mm	DM 3	Bottom	6.5%	6.8%	7.3%

Binder Type	NMAS	Sample Designation	Section	SSD	CoreLok	Dimensional
PG 70-22 PM	9.5 mm	DM 1	Top	6.7%	7.0%	7.3%
PG 70-22 PM	9.5 mm	DM 1	Middle	7.7%	7.9%	8.4%
PG 70-22 PM	9.5 mm	DM 1	Bottom	6.2%	6.4%	7.1%
PG 70-22 PM	9.5 mm	DM 2	Top	6.4%	6.5%	6.8%
PG 70-22 PM	9.5 mm	DM 2	Middle	7.8%	8.0%	8.0%
PG 70-22 PM	9.5 mm	DM 2	Bottom	6.4%	6.6%	6.4%
PG 70-22 PM	9.5 mm	DM 3	Top	6.5%	6.8%	7.1%
PG 70-22 PM	9.5 mm	DM 3	Middle	7.3%	7.8%	7.4%
PG 70-22 PM	9.5 mm	DM 3	Bottom	6.2%	6.4%	6.5%

Binder Type	NMAS	Sample Designation	Section	SSD	CoreLok	Dimensional
PG 70-22 PM	12.5 mm	DM 1	Top	6.8%	7.1%	7.2%
PG 70-22 PM	12.5 mm	DM 1	Middle	7.5%	7.6%	7.9%
PG 70-22 PM	12.5 mm	DM 1	Bottom	6.3%	6.5%	6.6%
PG 70-22 PM	12.5 mm	DM 2	Top	6.1%	6.1%	6.7%
PG 70-22 PM	12.5 mm	DM 2	Middle	7.3%	7.6%	7.9%
PG 70-22 PM	12.5 mm	DM 2	Bottom	6.9%	6.8%	7.3%
PG 70-22 PM	12.5 mm	DM 3	Top	6.5%	7.0%	6.7%
PG 70-22 PM	12.5 mm	DM 3	Middle	7.3%	9.8%	7.7%
PG 70-22 PM	12.5 mm	DM 3	Bottom	6.9%	7.3%	7.4%

Binder Type	NMAS	Sample Designation	Section	SSD	CoreLok	Dimensional
PG 76-22 PM	9.5 mm	DM 1	Top	7.5%	7.5%	7.8%
PG 76-22 PM	9.5 mm	DM 1	Middle	8.5%	9.7%	8.7%
PG 76-22 PM	9.5 mm	DM 1	Bottom	7.2%	7.5%	7.5%
PG 76-22 PM	9.5 mm	DM 2	Top	6.4%	6.6%	7.1%
PG 76-22 PM	9.5 mm	DM 2	Middle	7.7%	8.0%	8.1%
PG 76-22 PM	9.5 mm	DM 2	Bottom	5.8%	6.0%	6.2%
PG 76-22 PM	9.5 mm	DM 3	Top	6.0%	6.4%	6.5%
PG 76-22 PM	9.5 mm	DM 3	Middle	7.4%	7.9%	7.7%
PG 76-22 PM	9.5 mm	DM 3	Bottom	6.4%	6.7%	6.7%

Binder Type	NMAS	Sample Designation	Section	SSD	CoreLok	Dimensional
PG 76-22 PM	12.5 mm	DM 1	Top	6.8%	6.9%	7.6%
PG 76-22 PM	12.5 mm	DM 1	Middle	7.7%	7.8%	7.8%
PG 76-22 PM	12.5 mm	DM 1	Bottom	7.1%	7.1%	7.2%
PG 76-22 PM	12.5 mm	DM 2	Top	6.8%	7.3%	7.0%
PG 76-22 PM	12.5 mm	DM 2	Middle	7.5%	7.9%	8.1%
PG 76-22 PM	12.5 mm	DM 2	Bottom	6.5%	6.8%	6.9%
PG 76-22 PM	12.5 mm	DM 3	Top	6.5%	12.0%	6.9%
PG 76-22 PM	12.5 mm	DM 3	Middle	7.2%	7.2%	8.1%
PG 76-22 PM	12.5 mm	DM 3	Bottom	6.2%	6.2%	6.7%

Sample Thirds Geometry

Binder Type	NMAS	Sample Designation	Section	Diameter	Height
PG 70-22	9.5 mm	DM 1	Top	100.46	51.93
PG 70-22	9.5 mm	DM 1	Middle	100.56	45.62
PG 70-22	9.5 mm	DM 1	Bottom	100.55	45.02
PG 70-22	9.5 mm	DM 2	Top	100.44	47.64
PG 70-22	9.5 mm	DM 2	Middle	100.41	45.79
PG 70-22	9.5 mm	DM 2	Bottom	100.52	49.11
PG 70-22	9.5 mm	DM 3	Top	100.45	46.99
PG 70-22	9.5 mm	DM 3	Middle	100.53	46.74
PG 70-22	9.5 mm	DM 3	Bottom	100.53	49.24

Binder Type	NMAS	Sample Designation	Section	Diameter	Height
PG 70-22	12.5 mm	DM 1	Top	100.38	49.37
PG 70-22	12.5 mm	DM 1	Middle	100.48	44.30
PG 70-22	12.5 mm	DM 1	Bottom	100.55	49.70
PG 70-22	12.5 mm	DM 2	Top	100.44	47.65
PG 70-22	12.5 mm	DM 2	Middle	100.58	46.99
PG 70-22	12.5 mm	DM 2	Bottom	100.57	47.79
PG 70-22	12.5 mm	DM 3	Top	100.41	46.15
PG 70-22	12.5 mm	DM 3	Middle	100.51	47.89
PG 70-22	12.5 mm	DM 3	Bottom	100.58	48.07

Binder Type	NMAS	Sample Designation	Section	Diameter	Height
PG 70-22 PM	9.5 mm	DM 1	Top	100.49	49.43
PG 70-22 PM	9.5 mm	DM 1	Middle	100.51	48.87
PG 70-22 PM	9.5 mm	DM 1	Bottom	100.62	44.66
PG 70-22 PM	9.5 mm	DM 2	Top	100.42	48.24
PG 70-22 PM	9.5 mm	DM 2	Middle	100.42	48.22
PG 70-22 PM	9.5 mm	DM 2	Bottom	100.45	44.13
PG 70-22 PM	9.5 mm	DM 3	Top	100.42	47.70
PG 70-22 PM	9.5 mm	DM 3	Middle	100.45	47.15
PG 70-22 PM	9.5 mm	DM 3	Bottom	100.48	47.24

Binder Type	NMAS	Sample Designation	Section	Diameter	Height
PG 70-22 PM	12.5 mm	DM 1	Top	100.46	47.08
PG 70-22 PM	12.5 mm	DM 1	Middle	100.55	49.66
PG 70-22 PM	12.5 mm	DM 1	Bottom	100.53	46.63
PG 70-22 PM	12.5 mm	DM 2	Top	100.42	46.93
PG 70-22 PM	12.5 mm	DM 2	Middle	100.51	47.30
PG 70-22 PM	12.5 mm	DM 2	Bottom	100.55	48.32
PG 70-22 PM	12.5 mm	DM 3	Top	100.43	47.73
PG 70-22 PM	12.5 mm	DM 3	Middle	100.50	47.21
PG 70-22 PM	12.5 mm	DM 3	Bottom	100.55	48.17

Binder Type	NMAS	Sample Designation	Section	Diameter	Height
PG 76-22 PM	9.5 mm	DM 1	Top	100.39	50.77
PG 76-22 PM	9.5 mm	DM 1	Middle	100.42	45.23
PG 76-22 PM	9.5 mm	DM 1	Bottom	100.48	48.18
PG 76-22 PM	9.5 mm	DM 2	Top	100.42	49.95
PG 76-22 PM	9.5 mm	DM 2	Middle	100.51	45.47
PG 76-22 PM	9.5 mm	DM 2	Bottom	100.45	47.50
PG 76-22 PM	9.5 mm	DM 3	Top	100.35	46.64
PG 76-22 PM	9.5 mm	DM 3	Middle	100.50	48.64
PG 76-22 PM	9.5 mm	DM 3	Bottom	100.47	47.98

Binder Type	NMAS	Sample Designation	Section	Diameter	Height
PG 76-22 PM	12.5 mm	DM 1	Top	100.38	47.51
PG 76-22 PM	12.5 mm	DM 1	Middle	100.38	48.09
PG 76-22 PM	12.5 mm	DM 1	Bottom	100.46	48.66
PG 76-22 PM	12.5 mm	DM 2	Top	100.43	47.90
PG 76-22 PM	12.5 mm	DM 2	Middle	100.45	46.48
PG 76-22 PM	12.5 mm	DM 2	Bottom	100.45	48.07
PG 76-22 PM	12.5 mm	DM 3	Top	100.49	44.67
PG 76-22 PM	12.5 mm	DM 3	Middle	100.45	49.62
PG 76-22 PM	12.5 mm	DM 3	Bottom	100.43	48.61

Appendix D – JMP Output

Air Void Distribution Analysis by Section and Method

Fit Group

Oneway Analysis of SSD Gmb By Section

Practical Equivalence between T and B

Specified Practical Difference Threshold 0.05
Actual Difference in Means 0.001833
Std Error of Difference 0.002895

Test	t Ratio	p-Value
Lower Threshold	-16.6368	<.0001*
Upper Threshold	17.90327	<.0001*
Max over both		<.0001*

Practical Equivalence between T and M

Specified Practical Difference Threshold 0.05
Actual Difference in Means 0.026444
Std Error of Difference 0.002895

Test	t Ratio	p-Value
Lower Threshold	-8.13611	<.0001*
Upper Threshold	26.40397	<.0001*
Max over both		<.0001*

Robust Fit

Sigma	ChiSquare	PValue	LogWorth
0.00855	124.923	<.0001*	27.1268

Level	Robust Mean	Std Error
B	2.30206	0.00228
M	2.27788	0.00185
T	2.30441	0.00184

Oneway Analysis of CoreLok Gmb By Section

Fit Group

Oneway Analysis of CoreLok Gmb By Section

Practical Equivalence between M and B

Specified Practical Difference Threshold 0.05
Actual Difference in Means -0.03139
Std Error of Difference 0.007195

Test	t Ratio	p-Value
Lower Threshold	-11.3124	<.0001*
Upper Threshold	2.586801	0.0063*
Max over both		0.0063*

Practical Equivalence between T and B

Specified Practical Difference Threshold 0.05
Actual Difference in Means -0.00733
Std Error of Difference 0.007195

Test	t Ratio	p-Value
Lower Threshold	-7.96889	<.0001*
Upper Threshold	5.930338	<.0001*
Max over both		<.0001*

Practical Equivalence between T and M

Specified Practical Difference Threshold 0.05
Actual Difference in Means 0.024056
Std Error of Difference 0.007195

Test	t Ratio	p-Value
Lower Threshold	-3.60608	0.0004*
Upper Threshold	10.29315	<.0001*
Max over both		0.0004*

Robust Fit

Sigma	ChiSquare	PValue	LogWorth
0.01083	79.7409	<.0001*	17.3155

Level	Robust Mean	Std Error
B	2.29744	0.00236
M	2.26849	0.00281
T	2.29606	0.00271

Oneway Analysis of Dimensional Gmb By Section

Fit Group

Oneway Analysis of Dimensional Gmb By Section

Practical Equivalence between M and B

Specified Practical Difference Threshold 0.05
 Actual Difference in Means -0.02622
 Std Error of Difference 0.003091

Test	t Ratio	p-Value
Lower Threshold	-24.6581	<.0001*
Upper Threshold	7.692169	<.0001*
Max over both		<.0001*

Practical Equivalence between T and B

Specified Practical Difference Threshold 0.05
 Actual Difference in Means -0.00061
 Std Error of Difference 0.003091

Test	t Ratio	p-Value
Lower Threshold	-16.3728	<.0001*
Upper Threshold	15.97742	<.0001*
Max over both		<.0001*

Practical Equivalence between T and M

Specified Practical Difference Threshold 0.05
 Actual Difference in Means 0.025611
 Std Error of Difference 0.003091

Test	t Ratio	p-Value
Lower Threshold	-7.88986	<.0001*
Upper Threshold	24.46038	<.0001*
Max over both		<.0001*

Robust Fit

Sigma	ChiSquare	PValue	LogWorth
0.00975	102.392	<.0001*	22.2341

Level	Robust Mean	Std Error
B	2.29202	0.00249
M	2.26583	0.00202
T	2.29144	0.00202

Robust Fit of Dynamic Modulus versus CoreLok® VTM After

Bivariate Fit of Dynamic Modulus (ksi) By CoreLok VTM After

Robust Fit

Sigma	ChiSquare	PValue	LogWorth
71.3142	0.97472	0.3235	0.49012

Parameter	Robust Estimate	Std Error
Intercept	284.868	159.279
CoreLok VTM After	2424.57	2455.81

Linear Fit

Dynamic Modulus (ksi) = 286.0512 + 2471.8482*CoreLok VTM After

Summary of Fit

RSquare	0.008728
RSquare Adj	-0.00504
Root Mean Square Error	77.14016
Mean of Response	450.7297
Observations (or Sum Wgts)	74

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	3772.37	3772.37	0.6339
Error	72	428443.47	5950.60	Prob > F
C. Total	73	432215.83		0.4285

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	286.0512	207.0229	1.38	0.1713
CoreLok VTM After	2471.8482	3104.526	0.80	0.4285

Appendix E – Compaction Data

PG 70-22 9.5 mm

Gyrations	FT 1A	FT 1B	FT 1C	FT 2A	FT 2B	FT 2C	FT 3A	FT 3B	FT 3C	DM 1	DM 2	DM 3	EXTRA
0	224.2	223.8	225.8	226.8	223	223.3	224.4	225	224.6	225.6	223.4	223.4	223.4
1	216.3	216.1	218	218.8	215.1	215.5	216.3	216.9	216.7	217.7	215.7	215.6	215.8
2	211.7	211.6	213.3	214.1	210.4	211	211.6	212.3	212.2	213	211.1	210.9	211.3
3	208.2	208.2	209.8	210.6	207	207.5	208.2	208.8	208.7	209.5	207.6	207.4	207.9
4	205.5	205.5	207.1	207.7	204.3	204.9	205.4	206	205.9	206.8	204.9	204.7	205.3
5	203.3	203.3	204.8	205.4	202.1	202.7	203.2	203.7	203.7	204.5	202.7	202.4	203
Break													
50	180.3	180.6	181.6	181.9	179.7	180.2	180.5	180.4	180.9	181.3	180.1	179.8	180.2
51	180.2	180.4	181.4	181.7		180	180.3	180.2	180.7	181.1	179.9	179.7	180
52	180	180.3	181.2	181.5		179.8	180.2	180	180.6	181	179.8		179.8
53	179.9	180.1	181.1	181.4		179.7	180	179.9	180.4	180.8			
54	179.7	179.9	180.9	181.2			179.9	179.8	180.2	180.6			
55		179.8	180.7	181					180.1	180.5			
56			180.6	180.9					179.9	180.3			
57			180.4	180.7					179.8	180.2			
58			180.3	180.6						180			
59			180.1	180.5						179.9			
60			180	180.3						179.8			
61			179.9	180.2									
62			179.8	180									
63				179.9									
64				179.8									

PG 70-22 PM 9.5 mm

Gyrations	FT 1A	FT 1B	FT 1C	FT 2A	FT 2B	FT 2C	FT 3A	FT 3B	FT 3C	DM 1	DM 2	DM 3	EXTRA
0	223.3	222.8	222.8	223.7	223.5	224.4	226	224	224	224.4	223.4	225	222.5
1	215.4	214.8	215	216	215.7	216.4	218.1	216.1	216.2	216.4	215.6	217	214.8
2	210.8	210.2	210.4	211.5	211.1	211.8	213.4	211.5	211.6	211.8	211	212.4	210.2
3	207.3	206.8	206.9	208.1	207.6	208.4	209.9	207.9	208.1	208.3	207.6	208.8	206.8
4	204.6	204.1	204.2	205.3	204.9	205.6	207.2	205.2	205.3	205.6	204.8	206.1	204.1
5	202.4	201.9	202	203.1	202.7	203.4	204.9	202.9	203.2	203.3	202.6	203.8	201.9
Break													
48	180.1	179.9	179.8	180.7	180.5	181	182	180.4	180.9	180.8	180.3	181.2	179.7
49	180	179.8		180.5	180.4	180.8	181.8	180.3	180.7	180.7	180.1	181.1	
50	179.8			180.4	180.2	180.6	181.7	180.1	180.5	180.5	179.9	180.9	
51				180.2	180	180.4	181.5	179.9	180.4	180.3	179.8	180.7	
52				180.1	179.9	180.3	181.3	179.8	180.2	180.2		180.6	
53				179.9	179.7	180.1	181.2		180.1	180		180.4	
54				179.8		180	181		179.9	179.9		180.2	
55						179.8	180.9		179.8	179.7		180.1	
56							180.7					179.9	
57							180.6					179.8	
58							180.4						
59							180.3						
60							180.2						
61							180						
62							179.9						
63							179.8						

PG 76-22 PM 9.5 mm

Gyrations	FT 1A	FT 1A2	FT 1B	FT 1B2	FT 1C	FT 2A	FT 2B	FT 2C	FT 3A	FT 3B	FT 3C	DM 1	DM 2	DM 3
0	224.2	222.9	223.3	223	225.2	222.9	223.9	223.8	221.3	222.7	222.8	222.6	222.8	225.2
1	216	214.9	215.4	214.8	217.1	214.7	216	216	213.5	214.8	214.9	214.5	215	217.2
2	211.3	210.2	210.8	210.3	212.4	210.2	211.3	211.3	208.8	210.1	210.4	209.9	210.3	212.4
3	207.7	206.7	207.3	206.8	208.9	206.7	207.9	207.8	205.3	206.6	206.9	206.3	206.8	208.9
4	205	204.1	204.6	204	206.1	204.1	205.1	205.1	202.6	203.9	204.1	203.5	204.1	206.1
5	202.7	201.8	202.4	201.8	203.9	201.9	202.8	202.8	200.4	201.7	201.9	201.3	201.8	203.8
Break														
42	181.2	181	181.6	180.7	182.3	181	181.4	181.4	179.7	180.7	180.8	180	180.4	182.1
43	181	180.8	181.4	180.5	182.1	180.8	181.2	181.2		180.5	180.6	179.8	180.2	181.9
44	180.8	180.6	181.2	180.3	181.9	180.6	181	181		180.3	180.4		180	181.7
45	180.6	180.5	181	180.1	181.7	180.4	180.8	180.8		180.1	180.2		179.8	181.5
46	180.4	180.3	180.9	179.9	181.6	180.2	180.6	180.6		179.9	180			181.3
47	180.3	180.1	180.7	179.8	181.4	180	180.4	180.4		179.7	179.9			181.1
48	180.1	179.9	180.5		181.2	179.9	180.3	180.3			179.7			181
49	179.9	179.8	180.3		181	179.7	180.1	180.1						180.8
50	179.8		180.2		180.9		179.9	179.9						180.6
51			180		180.7		179.8	179.8						180.4
52			179.9		180.5									180.3
53			179.8		180.4									180.1
54					180.2									180
55					180.1									179.8
56					179.9									
57					179.8									

PG 70-22 12.5 mm

Gyrations	FT 1A	FT 1B	FT 1C	FT 2A	FT 2B	FT 2C	FT 3A	FT 3B	FT 3C	DM 1	DM 2	DM 3	EXTRA
0	220.3	221.5	220.8	221	224.3	223.4	222	222	221.1	222.4	221.6	223.3	222.8
1	212.6	213.6	213.1	213.2	216.6	215.7	214.1	214	213	214.4	213.7	215.5	214.9
2	208.1	209.1	208.4	208.8	212	211.1	209.5	209.4	208.4	209.9	209.1	210.9	210.1
3	204.8	205.7	205	205.5	208.6	207.7	206.1	206.1	204.9	206.6	205.6	207.4	206.8
4	202.2	203	202.3	202.8	205.9	205.1	203.4	203.4	202.2	204	203	204.6	204.1
5	200	200.9	200.2	200.7	203.7	203	201.2	201.2	199.9	201.8	200.8	202.4	201.9
Break													
41	179.7	180.4	180	180.4	183.6	182.9	180.8	180.6	179.6	181.5	180.4	181.6	181.9
42		180.2	179.8	180.2	183.4	182.7	180.6	180.4		181.3	180.2	181.4	181.7
43		180		180	183.2	182.5	180.4	180.2		181.1	180	181.2	181.5
44		179.8		179.8	183	182.3	180.3	180		180.9	179.8	181.1	181.3
45				179.7	182.9	182.1	180.1	179.9		180.7	179.7	180.9	181.2
46					182.7	181.9	179.9	179.7		180.6		180.7	181
47					182.5	181.8	179.7			180.4		180.5	180.8
48					182.3	181.6				180.2		180.3	180.7
49					182.2	181.4				180		180.2	180.5
50					182	181.3				179.9		180	180.3
51					181.9	181.1				179.7		179.8	180.2
52					181.7	181						179.7	180
53					181.6	180.8							179.9
Break													
61					180.5	179.8							
Break													
67					179.8								

PG 70-22 PM 12.5 mm

Gyrations	FT 1A	FT 1B	FT 1C	FT 2A	FT 2B	FT 2C	FT 3A	FT 3B	FT 3C	DM 1	DM 2	DM 3	EXTRA
0	220.3	220.4	223.4	220.4	220.7	223.7	223.6	220.2	220.3	221	220.8	220.2	221
1	212.7	212.7	215.6	212.7	213.1	215.9	215.7	212.5	212.6	213.1	212.8	212.5	213.2
2	208.2	208.2	211.2	208.1	208.5	211.3	211.2	208	208.1	208.6	208.3	207.9	208.7
3	204.9	204.9	207.8	204.8	205.1	207.9	207.7	204.6	204.8	205.2	204.9	204.6	205.3
4	202.2	202.3	205.2	202	202.5	205.3	205.1	202	202.2	202.6	202.3	202	202.6
5	200	200.2	203	199.9	200.3	203.2	202.9	199.8	200	200.4	200.1	199.8	200.4
Break													
40	180.1	180.4	183.4	179.9	180.2	183.5	183	179.8	180.4	180.6	180.3	180	180.3
41	179.9	180.2	183.2	179.7	180	183.3	182.8		180.2	180.4	180.1	179.8	180.1
42	179.7	180	183		179.8	183.1	182.6		180	180.2	179.9	179.6	179.9
43		179.8	182.9			182.9	182.4		179.8	180	179.7		179.7
44			182.7			182.7	182.2		179.7	179.9			
45			182.5			182.5	182			179.7			
Break													
55			181			181	180.5						
56			180.8			180.8	180.3						
57			180.7			180.7	180.2						
58			180.6			180.6	180.1						
59			180.4			180.4	179.9						
60			180.3			180.3	179.8						
61			180.2			180.2							
62			180.1			180.1							
63			179.9			179.9							
64			179.9			179.8							

PG 76-22 PM 12.5 mm

Gyrations	FT 1A	FT 1B	FT 1C	FT 2A	FT 2B	FT 2C	FT 3A	FT 3B	FT 3C	DM 1	DM 2	DM 3	EXTRA
0	219.9	219.6	219.3	221.7	220.4	219.5	221.9	220.5	220.3	220.8	220.4	219.6	220.1
1	212.2	211.8	211.5	213.9	212.4	211.6	214	212.6	212.4	212.9	212.5	211.7	212.3
2	207.6	207.3	206.9	209.2	207.9	206.9	209.4	208	208	208.4	208	207.1	207.9
3	204.2	204	203.6	205.8	204.4	203.6	206.2	204.5	204.6	205.1	204.5	203.7	204.5
4	201.6	201.4	201	203.1	201.8	201	203.6	201.8	201.9	202.5	201.9	201.1	201.9
5	199.5	199.3	198.8	200.9	199.6	198.8	201.4	199.7	199.7	200.3	199.7	198.9	199.7
Break													
37	180.6	180.1	179.6	181.4	180.3	179.8	182.7	180.3	180.2	181.2	180.5	179.8	180.6
38	180.3	179.9		181.2	180.1		182.5	180.1	180	181	180.3	179.6	180.3
39	180.1	179.7		181	179.9		182.2	179.9	179.8	180.8	180.1		180.1
40	179.9			180.7	179.7		182	179.7	179.6	180.6	179.9		179.9
41	179.8			180.5			181.8			180.4	179.7		179.7
42				180.3			181.6			180.2			
43				180.1			181.5			180			
44				180			181.3			179.8			
45				179.8			181.1			179.7			
46							180.9						
47							180.8						
48							180.6						
49							180.4						
50							180.3						
51							180.1						
52							180						
53							179.9						

Appendix F – Dynamic Modulus

MEPDG Outputs

PG 70-22 9.5 mm

Temp (°C)	Temp (°F)	Frequency (Hz)	Shift Factor	Reduced Frequency	E* (ksi)	E* (MPa)
-10.0	14	25	3.786929	153062.6	2618.8	18061.7
-10.0	14	10	3.786929	61225.04	2522.7	17399.3
-10.0	14	5	3.786929	30612.52	2440.0	16828.8
-10.0	14	1	3.786929	6122.504	2212.1	15257.0
-10.0	14	0.5	3.786929	3061.252	2098.2	14471.1
-10.0	14	0.1	3.786929	612.2504	1799.3	12410.0
4.4	40	25	1.861437	1817.092	2006.3	13837.7
4.4	40	10	1.861437	726.8369	1833.3	12644.0
4.4	40	5	1.861437	363.4185	1693.7	11681.3
4.4	40	1	1.861437	72.68369	1350.9	9317.5
4.4	40	0.5	1.861437	36.34185	1200.7	8281.4
4.4	40	0.1	1.861437	7.268369	865.5	5969.3
21.1	70	25	-0.12543	18.72879	1059.2	7305.0
21.1	70	10	-0.12543	7.491515	871.5	6010.5
21.1	70	5	-0.12543	3.745757	739.0	5097.1
21.1	70	1	-0.12543	0.749151	475.7	3281.0
21.1	70	0.5	-0.12543	0.374576	384.3	2650.2
21.1	70	0.1	-0.12543	0.074915	223.4	1540.7
37.8	100	25	-1.89933	0.315219	363.6	2507.9
37.8	100	10	-1.89933	0.126088	267.9	1847.7
37.8	100	5	-1.89933	0.063044	210.1	1449.1
37.8	100	1	-1.89933	0.012609	116.5	803.5
37.8	100	0.5	-1.89933	0.006304	90.0	620.7
37.8	100	0.1	-1.89933	0.001261	50.0	344.6
54.4	130	25	-3.49276	0.008039	98.5	679.5
54.4	130	10	-3.49276	0.003215	70.1	483.7
54.4	130	5	-3.49276	0.001608	54.5	375.9
54.4	130	1	-3.49276	0.000322	31.3	216.0
54.4	130	0.5	-3.49276	0.000161	25.1	173.4
54.4	130	0.1	-3.49276	3.22E-05	15.9	109.8

PG 70-22 12.5 mm

Temp (°C)	Temp (°F)	Frequency (Hz)	Shift Factor	Reduced Frequency	E* (ksi)	E* (MPa)
-10.0	14	25	3.936123	215805.6	2560.3	17658.6
-10.0	14	10	3.936123	86322.26	2452.3	16913.4
-10.0	14	5	3.936123	43161.13	2359.7	16275.2
-10.0	14	1	3.936123	8632.226	2107.6	14535.8
-10.0	14	0.5	3.936123	4316.113	1983.1	13677.6
-10.0	14	0.1	3.936123	863.2226	1662.7	11467.7
4.4	40	25	1.934772	2151.355	1849.4	12755.3
4.4	40	10	1.934772	860.542	1662.1	11463.2
4.4	40	5	1.934772	430.271	1513.9	10441.4
4.4	40	1	1.934772	86.0542	1162.2	8015.9
4.4	40	0.5	1.934772	43.0271	1014.0	6993.4
4.4	40	0.1	1.934772	8.60542	697.7	4811.8
21.1	70	25	-0.13037	18.51689	842.1	5807.9
21.1	70	10	-0.13037	7.406757	671.0	4627.7
21.1	70	5	-0.13037	3.703378	555.2	3829.6
21.1	70	1	-0.13037	0.740676	338.8	2336.4
21.1	70	0.5	-0.13037	0.370338	268.3	1850.1
21.1	70	0.1	-0.13037	0.074068	150.9	1040.9
37.8	100	25	-1.97416	0.265329	238.9	1647.7
37.8	100	10	-1.97416	0.106132	172.1	1187.2
37.8	100	5	-1.97416	0.053066	133.5	920.6
37.8	100	1	-1.97416	0.010613	73.7	508.3
37.8	100	0.5	-1.97416	0.005307	57.4	395.8
37.8	100	0.1	-1.97416	0.001061	33.2	228.6
54.4	130	25	-3.63036	0.005856	59.4	409.9
54.4	130	10	-3.63036	0.002342	43.1	297.4
54.4	130	5	-3.63036	0.001171	34.2	236.1
54.4	130	1	-3.63036	0.000234	21.0	144.9
54.4	130	0.5	-3.63036	0.000117	17.4	120.3
54.4	130	0.1	-3.63036	2.34E-05	12.0	82.7

PG 70-22 PM 9.5 mm

Temp (°C)	Temp (°F)	Frequency (Hz)	Shift Factor	Reduced Frequency	E* (ksi)	E* (MPa)
-10.0	14	25	4.193196	390064.5	2535.2	17485.6
-10.0	14	10	4.193196	156025.8	2428.9	16752.3
-10.0	14	5	4.193196	78012.89	2338.6	16129.4
-10.0	14	1	4.193196	15602.58	2095.0	14449.4
-10.0	14	0.5	4.193196	7801.289	1975.9	13627.6
-10.0	14	0.1	4.193196	1560.258	1670.9	11524.1
4.4	40	25	2.061135	2877.893	1791.0	12352.6
4.4	40	10	2.061135	1151.157	1609.7	11102.2
4.4	40	5	2.061135	575.5787	1467.6	10121.7
4.4	40	1	2.061135	115.1157	1133.2	7816.0
4.4	40	0.5	2.061135	57.55787	993.2	6850.0
4.4	40	0.1	2.061135	11.51157	694.6	4790.4
21.1	70	25	-0.13889	18.15739	774.3	5340.2
21.1	70	10	-0.13889	7.262954	618.7	4266.9
21.1	70	5	-0.13889	3.631477	514.1	3545.6
21.1	70	1	-0.13889	0.726295	319.1	2200.8
21.1	70	0.5	-0.13889	0.363148	255.4	1761.4
21.1	70	0.1	-0.13889	0.07263	148.3	1022.5
37.8	100	25	-2.10309	0.197174	208.5	1438.1
37.8	100	10	-2.10309	0.07887	152.5	1052.0
37.8	100	5	-2.10309	0.039435	120.0	827.4
37.8	100	1	-2.10309	0.007887	68.9	475.3
37.8	100	0.5	-2.10309	0.003943	54.7	377.0
37.8	100	0.1	-2.10309	0.000789	33.0	227.5
54.4	130	25	-3.86746	0.003392	52.0	358.9
54.4	130	10	-3.86746	0.001357	38.9	268.1
54.4	130	5	-3.86746	0.000678	31.6	217.6
54.4	130	1	-3.86746	0.000136	20.4	140.5
54.4	130	0.5	-3.86746	6.78E-05	17.2	118.9
54.4	130	0.1	-3.86746	1.36E-05	12.3	85.1

PG 70-22 PM 12.5 mm

Temp (°C)	Temp (°F)	Frequency (Hz)	Shift Factor	Reduced Frequency	E* (ksi)	E* (MPa)
-10.0	14	25	4.058589	286107.2	2501.3	17251.5
-10.0	14	10	4.058589	114442.9	2388.0	16469.9
-10.0	14	5	4.058589	57221.44	2291.9	15807.4
-10.0	14	1	4.058589	11444.29	2034.2	14029.8
-10.0	14	0.5	4.058589	5722.144	1909.0	13166.2
-10.0	14	0.1	4.058589	1144.429	1591.6	10977.6
4.4	40	25	1.994969	2471.208	1747.4	12051.9
4.4	40	10	1.994969	988.4833	1561.4	10768.8
4.4	40	5	1.994969	494.2416	1416.4	9768.7
4.4	40	1	1.994969	98.84833	1079.0	7441.7
4.4	40	0.5	1.994969	49.42416	939.4	6479.2
4.4	40	0.1	1.994969	9.884833	646.4	4458.5
21.1	70	25	-0.13443	18.34475	752.8	5191.9
21.1	70	10	-0.13443	7.3379	598.4	4127.2
21.1	70	5	-0.13443	3.66895	495.4	3416.7
21.1	70	1	-0.13443	0.73379	305.2	2105.0
21.1	70	0.5	-0.13443	0.366895	243.8	1681.2
21.1	70	0.1	-0.13443	0.073379	141.3	974.6
37.8	100	25	-2.03558	0.230336	208.7	1439.6
37.8	100	10	-2.03558	0.092134	152.8	1054.0
37.8	100	5	-2.03558	0.046067	120.4	830.1
37.8	100	1	-2.03558	0.009213	69.6	479.7
37.8	100	0.5	-2.03558	0.004607	55.4	382.0
37.8	100	0.1	-2.03558	0.000921	33.8	233.3
54.4	130	25	-3.74331	0.004515	55.0	379.6
54.4	130	10	-3.74331	0.001806	41.3	284.7
54.4	130	5	-3.74331	0.000903	33.6	231.9
54.4	130	1	-3.74331	0.000181	21.9	151.1
54.4	130	0.5	-3.74331	9.03E-05	18.6	128.5
54.4	130	0.1	-3.74331	1.81E-05	13.5	92.8

PG 76-22 PM 9.5 mm

Temp (°C)	Temp (°F)	Frequency (Hz)	Shift Factor	Reduced Frequency	E* (ksi)	E* (MPa)
-10.0	14	25	3.747481	139772.3	2490.8	17179.0
-10.0	14	10	3.747481	55908.92	2370.7	16350.8
-10.0	14	5	3.747481	27954.46	2268.4	15644.9
-10.0	14	1	3.747481	5590.892	1992.3	13741.1
-10.0	14	0.5	3.747481	2795.446	1858.1	12815.3
-10.0	14	0.1	3.747481	559.0892	1519.7	10481.1
4.4	40	25	1.842047	1737.747	1761.5	12148.9
4.4	40	10	1.842047	695.0989	1567.0	10807.9
4.4	40	5	1.842047	347.5495	1415.3	9761.3
4.4	40	1	1.842047	69.50989	1063.4	7334.2
4.4	40	0.5	1.842047	34.75495	919.1	6338.9
4.4	40	0.1	1.842047	6.950989	620.6	4280.2
21.1	70	25	-0.12412	18.78522	798.0	5503.8
21.1	70	10	-0.12412	7.514087	633.6	4369.8
21.1	70	5	-0.12412	3.757044	524.0	3613.7
21.1	70	1	-0.12412	0.751409	322.5	2224.5
21.1	70	0.5	-0.12412	0.375704	257.9	1779.0
21.1	70	0.1	-0.12412	0.075141	151.1	1042.0
37.8	100	25	-1.87954	0.329911	247.2	1704.8
37.8	100	10	-1.87954	0.131965	182.4	1257.9
37.8	100	5	-1.87954	0.065982	144.7	997.8
37.8	100	1	-1.87954	0.013196	85.5	589.4
37.8	100	0.5	-1.87954	0.006598	68.9	475.2
37.8	100	0.1	-1.87954	0.00132	43.5	300.3
54.4	130	25	-3.45637	0.008741	75.1	518.0
54.4	130	10	-3.45637	0.003496	57.1	393.5
54.4	130	5	-3.45637	0.001748	47.0	323.9
54.4	130	1	-3.45637	0.00035	31.4	216.8
54.4	130	0.5	-3.45637	0.000175	27.1	186.7
54.4	130	0.1	-3.45637	3.5E-05	20.2	139.1

PG 76-22 PM 12.5 mm

Temp (°C)	Temp (°F)	Frequency (Hz)	Shift Factor	Reduced Frequency	E* (ksi)	E* (MPa)
-10.0	14	25	3.784247	152120.1	2460.0	16966.3
-10.0	14	10	3.784247	60848.04	2333.6	16094.5
-10.0	14	5	3.784247	30424.02	2226.2	15354.3
-10.0	14	1	3.784247	6084.804	1938.9	13372.9
-10.0	14	0.5	3.784247	3042.402	1800.4	12417.6
-10.0	14	0.1	3.784247	608.4804	1455.1	10035.6
4.4	40	25	1.860118	1811.584	1692.1	11670.7
4.4	40	10	1.860118	724.6336	1493.6	10301.4
4.4	40	5	1.860118	362.3168	1340.2	9243.4
4.4	40	1	1.860118	72.46336	990.3	6830.0
4.4	40	0.5	1.860118	36.23168	849.4	5858.3
4.4	40	0.1	1.860118	7.246336	563.6	3887.0
21.1	70	25	-0.12534	18.73262	724.4	4996.1
21.1	70	10	-0.12534	7.493048	568.8	3923.2
21.1	70	5	-0.12534	3.746524	466.8	3219.3
21.1	70	1	-0.12534	0.749305	283.2	1953.0
21.1	70	0.5	-0.12534	0.374652	225.5	1555.3
21.1	70	0.1	-0.12534	0.07493	131.6	907.7
37.8	100	25	-1.89798	0.316197	213.1	1470.0
37.8	100	10	-1.89798	0.126479	156.8	1081.6
37.8	100	5	-1.89798	0.063239	124.4	857.9
37.8	100	1	-1.89798	0.012648	74.0	510.2
37.8	100	0.5	-1.89798	0.006324	60.0	413.6
37.8	100	0.1	-1.89798	0.001265	38.5	265.8
54.4	130	25	-3.49028	0.008085	64.5	445.0
54.4	130	10	-3.49028	0.003234	49.5	341.1
54.4	130	5	-3.49028	0.001617	41.0	283.1
54.4	130	1	-3.49028	0.000323	28.1	193.5
54.4	130	0.5	-3.49028	0.000162	24.4	168.2
54.4	130	0.1	-3.49028	3.23E-05	18.5	127.9

Appendix G – ALPHA Fatigue Outputs

PG 70-22 9.5 mm Default Output

North Carolina
State University

ALPHA-Fatigue Dynamic Modulus Report

Instron, Inc.
Raleigh, North Carolina
(919) 875-0071

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 07/02/17
Testing Performed by: Elizabeth Bashiti
Default Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_9.5

Output Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_9.5\Default Output

Comments:

Test Protocol: PP-51/TP-79
Number of $|E^*|$ Tests: 3
Maximum Limiting Modulus: Fixed (Hirsch)
Shift Factor Function: Arrhenius

Shift Factor Coefficients		
T_r	21.1	deg. C
E_a	186.46	kJ/mol
a_1	N/A	
a_2	N/A	
A	N/A	
VTS	N/A	
C	N/A	

Mastercurve Function	
κ	1.38E+00
β	2.95E+00
δ	-5.60E-01
γ	-5.05E-01

$$\log |E^*| = \kappa + \frac{\beta}{1 + e^{\delta + \gamma \log \omega}}$$

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	$ E^* $ (Mpa)	Phase Angle (deg)	Cov. $ E^* $ (%)	Cov. Phase Angle (deg.)
4	10	1.10E+03	13199	10.89	5.61	2.63
4	1	1.10E+02	9714	14.53	5.39	2.87
4	0.1	1.10E+01	6521.67	19.36	5.33	2.37
20	10	1.33E+01	5998.67	21.59	5.65	3.86
20	1	1.33E+00	3363	27.2	6.61	3.49
20	0.1	1.33E-01	1675.67	31.1	8.09	2.51
40	10	1.01E-01	1605.33	33.88	10.92	5.15
40	1	1.01E-02	679	32.79	11.45	4.18
40	0.1	1.01E-03	285.33	29.29	10.01	2.96
40	0.01	1.01E-04	138.03	24.7	6.93	2.02

Project Name: Elizabeth Bashiti Graduate Project
 Analysis Performed by: Elizabeth Bashiti
 Analysis Date: 07/02/17
 Testing Performed by: Elizabeth Bashiti
 Default Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_9.5
 Output Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_9.5\Default Output
 Comments:

Number of Fatigue Tests: 9
 Damage Model Function: Exponential

Damage Model Coefficients	
a	-1.29E-04
b	7.68E-01
y	N/A
z	N/A
alpha	3.701
Parameter r in Failure Cnt.	1.01E+05
Parameter s in Failure Cnt.	-5.26E-01

$$C = e^{aS^b}$$

$$C = 1 - yS^z$$

$$N_f = r(G^s)^{1/\alpha}$$

Test Name	Temperature (deg. C)	Frequency (Hz)	E'_{Live} (MPa)	E'_{Eng} (MPa)	N_f	G^R
PG70-22_9.5_FT1A	15	10	8063.4	8538	6435	1.38E+02
PG70-22_9.5_FT1B	15	10	8048	5976	3515	5.42E+02
PG70-22_9.5_FT1C	14.9	10	8068.8	6415	5835	2.79E+02
PG70-22_9.5_FT2A	15	10	8048	7415	7095	1.36E+02
PG70-22_9.5_FT2B	15	10	8059.4	6948	4095	7.27E+02
PG70-22_9.5_FT2C	15	10	8046.4	8110	5155	3.33E+02
PG70-22_9.5_FT3A	15	10	8040.9	6549	7635	1.13E+02
PG70-22_9.5_FT3B	15.1	10	8020.8	9199	1415	2.01E+03
PG70-22_9.5_FT3C	15	10	8047.9	6719	5495	3.53E+02

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 07/02/17
Testing Performed by: Elizabeth Bashiti
Default Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_9.5
Output Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_9.5\Default Output
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	2.45E+08
K2	3.058
K3	-2.245

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	3.65E-02
K2	-3.956
K3	2.597

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	3.65E-02
K2	3.956
K3	-1.359

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Strain Fatigue Relationship (psi units)	
K1	3.21E+06
K2	3.058
K3	-2.245

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	2.64E-03
K2	-3.956
K3	2.597

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	2.64E-03
K2	3.956
K3	-1.359

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	16
10	17
15	20
20	23
25	29

PG 70-22 9.5 mm Peak Output

**North Carolina
State University**

ALPHA-Fatigue Dynamic Modulus Report

Intronix, Inc.
Raleigh, North Carolina
(919) 875-8377

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 07/02/17
Testing Performed by: Elizabeth Bashiti
Default Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_9.5

Output Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_9.5\Peak Output

Comments:

Test Protocol: PP-61/TP-79
Number of |E*| Tests: 3
Maximum Limiting Modulus: Fixed (Hirsch)
Shift Factor Function: Arrhenius

Shift Factor Coefficients		
Tr	21.1	deg. C
Ea	186.46	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTs	N/A	
C	N/A	

Mastercurve Function	
κ	1.38E+00
β	2.95E+00
δ	-5.60E-01
γ	-5.05E-01

$$\log |E^*| = \kappa + \frac{\beta}{1 + e^{\delta + \gamma \log a}}$$

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E* (Mpa)	Phase Angle (deg)	Cov. E* (%)	Cov. Phase Angle (deg.)
4	10	1.10E+03	13199	10.89	5.61	2.63
4	1	1.10E+02	9714	14.53	5.39	2.87
4	0.1	1.10E+01	6521.67	19.36	5.33	2.37
20	10	1.33E+01	5998.67	21.59	5.65	3.86
20	1	1.33E+00	3363	27.2	6.61	3.49
20	0.1	1.33E-01	1675.67	31.1	8.09	2.51
40	10	1.01E-01	1605.33	33.88	10.92	5.15
40	1	1.01E-02	679	32.79	11.45	4.18
40	0.1	1.01E-03	285.33	29.29	10.01	2.96
40	0.01	1.01E-04	138.03	24.7	6.93	2.02

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 07/02/17
Testing Performed by: Elizabeth Bashiti
Default Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_9.5
Output Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_9.5\Peak Output
Comments:

Number of Fatigue Tests: 9
Damage Model Function: Exponential

Damage Model Coefficients	
a	-1.05E-04
b	7.87E-01
y	N/A
z	N/A
alpha	3.701
Parameter r in Failure Crit.	7.58E+05
Parameter s in Failure Crit.	-7.25E-01

$$C = e^{aS^b}$$

$$C = 1 - yS^z$$

$$N_f = r'(G^R)^s$$

Test Name	Temperature (deg. C)	Frequency (Hz)	$ E _{Live}$ (MPa)	$ E _{Ramp}$ (MPa)	Nf	G ^R
PG70-22_9.5_FT1A	15	10	8063.4	8538	25808	7.41E+01
PG70-22_9.5_FT1B	15	10	8048	5976	7695	3.68E+02
PG70-22_9.5_FT1C	14.9	10	8068.8	6415	19575	1.90E+02
PG70-22_9.5_FT2A	15	10	8048	7415	35078	7.68E+01
PG70-22_9.5_FT2B	15	10	8059.4	6948	8895	5.90E+02
PG70-22_9.5_FT2C	15	10	8046.4	8110	13136	2.38E+02
PG70-22_9.5_FT3A	15	10	8040.9	6549	46481	5.09E+01
PG70-22_9.5_FT3B	15.1	10	8020.8	9199	3455	1.46E+03
PG70-22_9.5_FT3C	15	10	8047.9	6719	16284	2.98E+02

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 07/02/17
Testing Performed by: Elizabeth Bashiti
Default Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_9.5
Output Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_9.5\Peak Output
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	7.43E+18
K2	5.579
K3	-4.899

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	8.39E-15
K2	-5.254
K3	5.062

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	8.39E-15
K2	5.254
K3	-0.191

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Strain Fatigue Relationship (psi units)	
K1	5.79E+14
K2	5.579
K3	-4.899

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	5.80E-15
K2	-5.254
K3	5.062

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	5.80E-15
K2	5.254
K3	-0.191

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	66
10	73
15	89
20	107
25	146

PG 70-22 12.5 mm Default Output

**North Carolina
State University**

ALPHA-Fatigue Dynamic Modulus Report

Instron, Inc.
Raleigh, North Carolina
(919) 877-0871

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 06/20/17
Testing Performed by: Elizabeth Bashiti
Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_12.5

Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_12.5\Default Output

Comments:

Test Protocol: PP-61/TP-79
Number of $|E^*|$ Tests: 3
Maximum Limiting Modulus: Fixed (Hirsch)
Shift Factor Function: Arrhenius

Shift Factor Coefficients		
Tr	21.1	deg. C
Ea	193.8	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTs	N/A	
C	N/A	

Mastercurve Function	
κ	1.43E+00
β	2.91E+00
δ	-2.92E-01
γ	-5.10E-01

$$\log |E^*| = \kappa + \frac{\beta}{1 + e^{\delta + \gamma \log a}}$$

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	$ E^* $ (Mpa)	Phase Angle (deg)	Cov. $ E^* $ (%)	Cov. Phase Angle (deg.)
4	10	1.33E+03	12043.33	11.88	5.13	4.82
4	1	1.33E+02	8590.67	15.75	6.18	5.54
4	0.1	1.33E+01	5589.67	20.73	7.98	5.05
20	10	1.35E+01	4441.67	25.35	15.63	6.97
20	1	1.35E+00	2316.33	30.31	18.9	5.43
20	0.1	1.35E-01	1113.6	32.41	20.98	3.48
40	10	8.39E-02	1059.33	35.51	11.24	1.8
40	1	8.39E-03	437.7	32.92	14.15	0.58
40	0.1	8.39E-04	189.57	28.46	14.86	2.11
40	0.01	8.39E-05	102	23.31	9.25	5.21

Project Name: Elizabeth Bashitt Graduate Project
Analysis Performed by: Elizabeth Bashitt
Analysis Date: 06/20/17
Testing Performed by: Elizabeth Bashitt
Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_12.5

Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_12.5\Default Output

Comments:

Number of Fatigue Tests: 9
Damage Model Function: Exponential

Damage Model Coefficients	
a	-3.43E-04
b	6.94E-01
y	N/A
z	N/A
alpha	3.694
Parameter r in Failure Crt.	9.99E+04
Parameter s in Failure Crt.	-5.79E-01

$$C = e^{a/y^b}$$

$$C = 1 - yS^z$$

$$N_f = r(G^R)^s$$

Test Name	Temperature (deg. C)	Frequency (Hz)	$ E' _{LVR}$ (MPa)	$ E' _{HVR}$ (MPa)	NR	G^R
PG70-22_12.5_FT1A	14.9	10	6674.9	8378	6175	8.84E+01
PG70-22_9.5_FT1B	14.9	10	6677.3	8439	2395	6.62E+02
PG70-22_12.5_FT1C	14.9	10	6679.5	8445	5215	2.28E+02
PG70-22_12.5_FT2A	14.9	10	6682.1	7175	6755	9.09E+01
PG70-22_12.5_FT2B	14.9	10	6684.4	8446	1095	1.88E+03
PG70-22_12.5_FT2C	15	10	6663.8	7959	4635	2.64E+02
PG70-22_12.5_FT3A	14.9	10	6697.6	6887	7055	8.60E+01
PG70-22_12.5_FT3B	15	10	6636.8	8316	1915	8.81E+02
PG70-22_12.5_FT3C	14.9	10	6681.8	6656	5555	1.86E+02

Project Name: Elizabeth Bashitt Graduate Project
 Analysis Performed by: Elizabeth Bashitt
 Analysis Date: 06/20/17
 Testing Performed by: Elizabeth Bashitt
 Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_12.5
 Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_12.5\Default Output
 Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	4.46E+10
K2	3.591
K3	-2.886

$$N_f = K_1 \left(\frac{1}{\varepsilon_i} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	1.20E+01
K2	-4.28
K3	2.361

$$N_f = K_1 (\sigma_i)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	1.20E+01
K2	4.28
K3	-1.919

$$N_f = K_1 \left(\frac{1}{\varepsilon_{i,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Strain Fatigue Relationship (psi units)	
K1	1.69E+08
K2	3.591
K3	-2.886

$$N_f = K_1 \left(\frac{1}{\varepsilon_i} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	2.95E-01
K2	-4.28
K3	2.361

$$N_f = K_1 (\sigma_i)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	2.95E-01
K2	4.28
K3	-1.919

$$N_f = K_1 \left(\frac{1}{\varepsilon_{i,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	19
10	21
15	26
20	31
25	43

PG 70-22 12.5 mm Peak Output

North Carolina
State University

ALPHA-Fatigue Dynamic Modulus Report

Project Name: Elizabeth Bashiti Graduate Project
 Analysis Performed by: Elizabeth Bashiti
 Analysis Date: 06/20/17
 Testing Performed by: Elizabeth Bashiti
 Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_12.5
 Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_12.5\Peak Output
 Comments:

Test Protocol: PP-61/TP-79
 Number of |E*| Tests: 3
 Maximum Limiting Modulus: Fixed (Hirsch)
 Shift Factor Function: Arrhenius

Shift Factor Coefficients		
Tr	21.1	deg. C
Ea	193.8	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTS	N/A	
C	N/A	

Mastercurve Function	
κ	1.43E+00
β	2.91E+00
δ	-2.92E-01
γ	-5.10E-01

$$\log |E^*| = \kappa + \frac{\beta}{1 + e^{\delta + \gamma \log \omega}}$$

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E* (Mpa)	Phase Angle (deg)	Cov. E* (%)	Cov. Phase Angle (deg.)
4	10	1.33E+03	12043.33	11.88	5.13	4.82
4	1	1.33E+02	8590.67	15.75	6.18	5.54
4	0.1	1.33E+01	5589.67	20.73	7.98	5.05
20	10	1.35E+01	4441.67	25.35	15.63	6.97
20	1	1.35E+00	2316.33	30.31	18.9	5.43
20	0.1	1.35E-01	1113.6	32.41	20.98	3.48
40	10	8.39E-02	1059.33	35.51	11.24	1.8
40	1	8.39E-03	437.7	32.92	14.15	0.58
40	0.1	8.39E-04	189.57	28.46	14.86	2.11
40	0.01	8.39E-05	102	23.31	9.25	5.21

Project Name: Elizabeth Bashitt Graduate Project
Analysis Performed by: Elizabeth Bashitt
Analysis Date: 06/20/17
Testing Performed by: Elizabeth Bashitt
Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_12.5
Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_12.5\Peak Output
Comments:

Number of Fatigue Tests: 9
Damage Model Function: Exponential

Damage Model Coefficients	
a	-2.28E-04
b	7.35E-01
y	N/A
z	N/A
alpha	3.694
Parameter r in Failure Cnt.	5.65E+05
Parameter s in Failure Cnt.	-7.49E-01

$$C = e^{aS^b}$$

$$C = 1 - yS^z$$

$$N_f = r(G^R)^s$$

Test Name	Temperature (deg. C)	Frequency (Hz)	$ E' _{Lve}$ (MPa)	$ E' _{Rger}$ (MPa)	NI	G^R
PG70-22_12.5_FT1A	14.9	10	6674.9	8378	23902	4.72E+01
PG70-22_9.5_FT1B	14.9	10	6677.3	8439	5475	4.67E+02
PG70-22_12.5_FT1C	14.9	10	6679.5	8445	13407	1.61E+02
PG70-22_12.5_FT2A	14.9	10	6682.1	7175	31827	5.19E+01
PG70-22_12.5_FT2B	14.9	10	6684.4	8446	2855	1.24E+03
PG70-22_12.5_FT2C	15	10	6663.8	7959	9976	2.04E+02
PG70-22_12.5_FT3A	14.9	10	6697.6	6887	36733	4.73E+01
PG70-22_12.5_FT3B	15	10	6636.8	8316	4275	6.26E+02
PG70-22_12.5_FT3C	14.9	10	6681.8	6656	16285	1.26E+02

Project Name: Elizabeth Bashitt Graduate Project
Analysis Performed by: Elizabeth Bashitt
Analysis Date: 06/20/17
Testing Performed by: Elizabeth Bashitt
Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_12.5
Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22_12.5\Peak Output
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	7.81E+20
K2	6.196
K3	-5.588

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	1.64E-08
K2	-5.433
K3	4.227

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	1.64E-08
K2	5.433
K3	-1.206

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Strain Fatigue Relationship (psi units)	
K1	1.61E+16
K2	6.196
K3	-5.588

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	1.60E-09
K2	-5.433
K3	4.227

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	1.60E-09
K2	5.433
K3	-1.206

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	65
10	77
15	96
20	123
25	179

PG 70-22 PM 9.5 mm Default Output

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 06/20/17
Testing Performed by: Elizabeth Bashiti
Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_9.5

Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_9.5\Default Output

Comments:

Test Protocol: PP-61/TP-79
Number of |E'| Tests: 3
Maximum Limiting Modulus: Fixed (Hirsch)
Shift Factor Function: Arrhenius

Shift Factor Coefficients		
T _r	21.1	deg. C
E _a	206.46	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTS	N/A	
C	N/A	

Mastercurve Function	
κ	1.47E+00
β	2.66E+00
δ	-2.47E-01
γ	-4.86E-01

$$\log |E^*| = \kappa + \frac{\beta}{1 + e^{\delta + \gamma \log \omega}}$$

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E' (Mpa)	Phase Angle (deg)	Cov. E' (%)	Cov. Phase Angle (deg.)
4	10	1.82E+03	11187.33	12.28	9.26	1.65
4	1	1.82E+02	7988	16.07	8.4	1.2
4	0.1	1.82E+01	5200.33	20.85	7.59	1.18
20	10	1.37E+01	4462	24.58	5.74	0.51
20	1	1.37E+00	2363.33	29.15	5.52	0.34
20	0.1	1.37E-01	1138.67	31.14	5.99	0.5
40	10	6.14E-02	915.63	34.78	4.17	0.36
40	1	6.14E-03	388.03	31.52	5.4	0.65
40	0.1	6.14E-04	184.03	26.79	6.29	0.66
40	0.01	6.14E-05	111.47	22.31	8.04	2.1

Project Name: Elizabeth Bashiti Graduate Project
 Analysis Performed by: Elizabeth Bashiti
 Analysis Date: 06/20/17
 Testing Performed by: Elizabeth Bashiti
 Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_9.5
 Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_9.5\Default Output
 Comments:

Number of Fatigue Tests: 9
 Damage Model Function: Exponential

Damage Model Coefficients	
a	-1.19E-04
b	7.89E-01
y	N/A
z	N/A
alpha	3.866
Parameter r in Failure Crr.	2.83E+04
Parameter s in Failure Crr.	-2.76E-01

$$C = e^{a/y^b}$$

$$C = 1 - y^z$$

$$N_f = r(G^s)^{1/\alpha}$$

Test Name	Temperature (deg. C)	Frequency (Hz)	E'_{LVR} (MPa)	E'_{HIGW} (MPa)	N_f	G^R
PG70-22PM_9.5_FT1A	14.9	10	6311	6315	8975	6.77E+01
PG70-22PM_9.5_FT1B	15	10	6301.4	6272	5735	3.19E+02
PG70-22PM_9.5_FT1C	14.9	10	6308.7	6282	7135	1.50E+02
PG70-22PM_9.5_FT2A	14.9	10	6312.5	6256	8875	6.41E+01
PG70-22PM_9.5_FT2B	15	10	6304	6139	5575	3.89E+02
PG70-22PM_9.5_FT2C	14.9	10	6305	6725	6335	2.09E+02
PG70-22PM_9.5_FT3A	15	10	6292.3	6555	8775	6.96E+01
PG70-22PM_9.5_FT3B	15	10	6297.4	6541	5475	3.79E+02
PG70-22PM_9.5_FT3C	14.9	10	6316.8	6841	6375	2.04E+02

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 06/20/17
Testing Performed by: Elizabeth Bashiti
Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_9.5
Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_9.5\Default Output
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	7.07E+05
K2	1.306
K3	-0.971

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	5.07E+01
K2	-2.486
K3	1.453

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	5.07E+01
K2	2.486
K3	-1.033

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Strain Fatigue Relationship (psi units)	
K1	1.09E+05
K2	1.306
K3	-0.971

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	6.91E+00
K2	-2.486
K3	1.453

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	6.91E+00
K2	2.486
K3	-1.033

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	5
10	5
15	6
20	7
25	9

PG 70-22 PM 9.5 mm Peak Output

**North Carolina
State University**

ALPHA-Fatigue Dynamic Modulus Report

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 06/20/17
Testing Performed by: Elizabeth Bashiti
Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_9.5

Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_9.5\Peak Output

Comments:

Test Protocol: PP-61/TP-79
Number of |E*| Tests: 3
Maximum Limiting Modulus: Fixed (Hirsch)
Shift Factor Function: Arrhenius

Shift Factor Coefficients		
Tr	21.1	deg. C
Ea	206.46	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTS	N/A	
C	N/A	

Mastercurve Function	
κ	1.47E+00
β	2.86E+00
δ	-2.47E-01
γ	-4.86E-01

$$\log |E^*| = \kappa + \frac{\beta}{1 + e^{\delta + \gamma \log \omega}}$$

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E* (Mpa)	Phase Angle (deg)	Cov. E* (%)	Cov. Phase Angle (deg.)
4	10	1.82E+03	11187.33	12.28	9.26	1.65
4	1	1.82E+02	7988	16.07	8.4	1.2
4	0.1	1.82E+01	5200.33	20.85	7.59	1.18
20	10	1.37E+01	4462	24.58	5.74	0.51
20	1	1.37E+00	2363.33	29.15	5.52	0.34
20	0.1	1.37E-01	1138.67	31.14	5.99	0.5
40	10	6.14E-02	915.63	34.78	4.17	0.36
40	1	6.14E-03	368.03	31.52	5.4	0.65
40	0.1	6.14E-04	184.03	26.79	6.29	0.66
40	0.01	6.14E-05	111.47	22.31	8.04	2.1

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 06/20/17
Testing Performed by: Elizabeth Bashiti
Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_9.5
Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_9.5\Peak Output
Comments:

Number of Fatigue Tests: 9
Damage Model Function: Exponential

Damage Model Coefficients	
a	-1.45E-04
b	7.71E-01
y	N/A
z	N/A
alpha	3.866
Parameter r in Failure Crit.	1.03E+06
Parameter s in Failure Crit.	-7.32E-01

$$C = e^{a/y^b}$$

$$C = 1 - y^b S^z$$

$$N_f = r(G^R)^s$$

Test Name	Temperature (deg. C)	Frequency (Hz)	$[E']_{LVE}$ (MPa)	$[E']_{HVE}$ (MPa)	Nf	G ^R
PG70-22PM_9.5_FT1A	14.9	10	6311	6315	98107	2.54E+01
PG70-22PM_9.5_FT1B	15	10	6301.4	6272	17495	2.55E+02
PG70-22PM_9.5_FT1C	14.9	10	6308.7	6282	36544	1.01E+02
PG70-22PM_9.5_FT2A	14.9	10	6312.5	6256	98610	2.54E+01
PG70-22PM_9.5_FT2B	15	10	6304	6139	16263	3.26E+02
PG70-22PM_9.5_FT2C	14.9	10	6305	6725	23780	1.47E+02
PG70-22PM_9.5_FT3A	15	10	6292.3	6555	82438	3.06E+01
PG70-22PM_9.5_FT3B	15	10	6297.4	6541	15393	3.15E+02
PG70-22PM_9.5_FT3C	14.9	10	6316.8	6841	24894	1.48E+02

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 06/20/17
Testing Performed by: Elizabeth Bashiti
Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_9.5

Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_9.5\Peak Output

Comments:

Number of Fatigue Tests: 9
Damage Model Function: Exponential

Damage Model Coefficients	
a	-1.45E-04
b	7.71E-01
y	N/A
z	N/A
alpha	3.866
Parameter r in Failure Crit.	1.03E+05
Parameter s in Failure Crit.	-7.32E-01

$$C = e^{a S^b}$$

$$C = 1 - y S^z$$

$$N_f = r' (G^H)^s$$

Test Name	Temperature (deg. C)	Frequency (Hz)	$ E^* _{Live}$ (MPa)	$ E^* _{Range}$ (MPa)	Nf	G*
PG70-22PM_9.5_FT1A	14.9	10	6311	6315	96107	2.54E+01
PG70-22PM_9.5_FT1B	15	10	6301.4	6272	17495	2.55E+02
PG70-22PM_9.5_FT1C	14.9	10	6308.7	6282	36544	1.01E+02
PG70-22PM_9.5_FT2A	14.9	10	6312.5	6256	96610	2.54E+01
PG70-22PM_9.5_FT2B	15	10	6304	6139	16263	3.26E+02
PG70-22PM_9.5_FT2C	14.9	10	6305	6725	23780	1.47E+02
PG70-22PM_9.5_FT3A	15	10	6292.3	6555	82438	3.06E+01
PG70-22PM_9.5_FT3B	15	10	6297.4	6541	15393	3.15E+02
PG70-22PM_9.5_FT3C	14.9	10	6316.8	6841	24894	1.48E+02

PG 70-22 PM 12.5 mm Default Output

North Carolina
State University

ALPHA-Fatigue Dynamic Modulus Report

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 06/20/17
Testing Performed by: Elizabeth Bashiti
Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_12.5

Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_12.5\Default Output

Comments:

Test Protocol: PP-61/TP-79
Number of |E*| Tests: 3
Maximum Limiting Modulus: Fixed (Hirsch)
Shift Factor Function: Arrhenius

Shift Factor Coefficients		
Tr	21.1	deg. C
Ea	199.83	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTs	N/A	
C	N/A	

Mastercurve Function	
κ	1.54E+00
β	2.80E+00
δ	-1.77E-01
γ	-4.93E-01

$$\log |E^*| = \kappa + \frac{\beta}{1 + e^{\delta + \gamma \log a}}$$

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E* (Mpa)	Phase Angle (deg)	Cov. E* (%)	Cov. Phase Angle (deg.)
4	10	1.54E+03	10847.33	12.68	5.64	1.32
4	1	1.54E+02	7688.67	16.61	5.08	0.83
4	0.1	1.54E+01	4962	21.41	4.89	0.99
20	10	1.36E+01	4235.67	25.13	8.39	2.4
20	1	1.36E+00	2220.67	29.56	9.68	2.05
20	0.1	1.36E-01	1062.03	31.37	11	1.79
40	10	7.23E-02	935.83	34.89	6.82	0.94
40	1	7.23E-03	398.37	31.41	8.12	1.07
40	0.1	7.23E-04	192.17	26.5	9.56	0.82
40	0.01	7.23E-05	116.93	21.78	9.45	2.46

Project Name:	Elizabeth Bashiti Graduate Project
Analysis Performed by:	Elizabeth Bashiti
Analysis Date:	06/20/17
Testing Performed by:	Elizabeth Bashiti
Default Directory:	D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_12.5
Output Directory:	D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_12.5\Default Output
Comments:	

Number of Fatigue Tests: 9
Damage Model Function: Exponential

Damage Model Coefficients	
a	-1.62E-04
b	7.62E-01
y	N/A
z	N/A
alpha	3.883
Parameter r in Failure Cnt.	2.80E+04
Parameter s in Failure Cnt.	-2.77E-01

$$C = e^{a/S^b}$$

$$C = 1 - y/S^z$$

$$N_f = r \left(G^R \right)^s$$

Test Name	Temperature (deg. C)	Frequency (Hz)	$ E^* _{Live}$ (MPa)	$ E^* _{Super}$ (MPa)	NT	G^R
PG70-22PM_12.5_FT1A	15	10	6069.6	6127	8975	6.20E+01
PG70-22PM_12.5_FT1B	15	10	6066.1	6276	5775	2.87E+02
PG70-22PM_12.5_FT1C	14.9	10	6072.7	6513	6735	1.68E+02
PG70-22PM_12.5_FT2A	15	10	6056.8	5998	8735	6.53E+01
PG70-22PM_12.5_FT2B	15	10	6063.9	6434	5775	2.82E+02
PG70-22PM_12.5_FT2C	15	10	6068.9	5489	8175	1.02E+02
PG70-22PM_12.5_FT3A	15	10	6036.1	6025	8715	6.22E+01
PG70-22PM_12.5_FT3B	14.9	10	6072.9	6491	5475	3.86E+02
PG70-22PM_12.5_FT3C	14.9	10	6079	6053	6755	1.55E+02

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 06/20/17
Testing Performed by: Elizabeth Bashiti
Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_12.5
Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_12.5\Default Output
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	8.93E+05
K2	1.291
K3	-0.978

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	2.21E+02
K2	-2.36
K3	1.302

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	2.21E+02
K2	2.36
K3	-1.058

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Strain Fatigue Relationship (psi units)	
K1	1.35E+05
K2	1.291
K3	-0.978

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	2.87E+01
K2	-2.36
K3	1.302

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	2.87E+01
K2	2.36
K3	-1.058

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	5
10	5
15	6
20	6
25	8

PG 70-22 PM 12.5 mm Peak Output

North Carolina
State University

ALPHA-Fatigue Dynamic Modulus Report

Project Name: Elizabeth Bashiti Graduate Project
 Analysis Performed by: Elizabeth Bashiti
 Analysis Date: 06/20/17
 Testing Performed by: Elizabeth Bashiti
 Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_12.5
 Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_12.5\Peak Output
 Comments:

Test Protocol: PP-61/TP-79
 Number of $|E^*|$ Tests: 3
 Maximum Limiting Modulus: Fixed (Hirsch)
 Shift Factor Function: Arrhenius

Shift Factor Coefficients		
T_r	21.1	deg. C
E_a	199.83	kJ/mol
a_1	N/A	
a_2	N/A	
A	N/A	
VTS	N/A	
C	N/A	

Mastercurve Function	
κ	1.54E+00
β	2.80E+00
δ	-1.77E-01
γ	-4.93E-01

$$\log |E^*| = \kappa + \frac{\beta}{1 + e^{\delta + \gamma \log a_r}}$$

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	$ E^* $ (Mpa)	Phase Angle (deg)	Cov. $ E^* $ (%)	Cov. Phase Angle (deg.)
4	10	1.54E+03	10847.33	12.68	5.64	1.32
4	1	1.54E+02	7688.67	16.61	5.08	0.83
4	0.1	1.54E+01	4962	21.41	4.89	0.99
20	10	1.36E+01	4235.67	25.13	8.39	2.4
20	1	1.36E+00	2220.67	29.56	9.68	2.05
20	0.1	1.36E-01	1062.03	31.37	11	1.79
40	10	7.23E-02	935.83	34.89	6.82	0.94
40	1	7.23E-03	398.37	31.41	8.12	1.07
40	0.1	7.23E-04	192.17	26.5	9.56	0.82
40	0.01	7.23E-05	116.93	21.78	9.45	2.46

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 06/20/17
Testing Performed by: Elizabeth Bashiti
Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_12.5
Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_12.5\Peak Output
Comments:

Number of Fatigue Tests: 9
Damage Model Function: Exponential

Damage Model Coefficients	
a	-1.55E-04
b	7.68E-01
y	N/A
z	N/A
alpha	3.883
Parameter r in Failure Crit.	9.30E+05
Parameter s in Failure Crit.	-7.19E-01

$$C = e^{a/S^b}$$

$$C = 1 - y/S^z$$

$$N_f = r(G^R)^s$$

Test Name	Temperature (deg. C)	Frequency (Hz)	$ E^* _{Lve}$ (MPa)	$ E^* _{Hgar}$ (MPa)	Nf	G ^R
PG70-22PM_12.5_FT1A	15	10	6069.6	6127	91793	2.61E+01
PG70-22PM_12.5_FT1B	15	10	6066.1	6276	17675	2.23E+02
PG70-22PM_12.5_FT1C	14.9	10	6072.7	6513	29025	1.17E+02
PG70-22PM_12.5_FT2A	15	10	6056.8	5996	85446	2.48E+01
PG70-22PM_12.5_FT2B	15	10	6063.9	6434	17856	2.38E+02
PG70-22PM_12.5_FT2C	15	10	6068.9	5489	60642	6.09E+01
PG70-22PM_12.5_FT3A	15	10	6036.1	6025	93213	2.38E+01
PG70-22PM_12.5_FT3B	14.9	10	6072.9	6491	15550	3.29E+02
PG70-22PM_12.5_FT3C	14.9	10	6079	6053	30712	9.98E+01

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 06/20/17
Testing Performed by: Elizabeth Bashiti
Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_12.5
Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG70-22PM_12.5\Peak Output
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	2.09E+20
K2	5.428
K3	-4.99

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	8.91E-13
K2	-5.718
K3	4.984

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	8.91E-13
K2	5.718
K3	-0.734

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Strain Fatigue Relationship (psi units)	
K1	1.36E+16
K2	5.428
K3	-4.99

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	2.16E-13
K2	-5.718
K3	4.984

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	2.16E-13
K2	5.718
K3	-0.734

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	80
10	97
15	125
20	163
25	242

PG 76-22 PM 9.5 mm Default Output

North Carolina
State University

ALPHA-Fatigue Dynamic Modulus Report

Instron, Inc.
Raleigh, North Carolina
(919) 876-4071

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 07/02/17
Testing Performed by: Elizabeth Bashiti
Default Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_9.5
Output Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_9.5\Default Output
Comments:

Test Protocol: PP-61/TP-79
Number of $|E^*|$ Tests: 3
Maximum Limiting Modulus: Fixed (Hirsch)
Shift Factor Function: Arrhenius

Shift Factor Coefficients		
T_r	21.1	deg. C
E_a	184.51	kJ/mol
a_1	N/A	
a_2	N/A	
A	N/A	
VTS	N/A	
C	N/A	

Mastercurve Function	
κ	1.79E+00
β	2.54E+00
δ	-4.03E-02
γ	-5.26E-01

$$\log |E^*| = \kappa + \frac{\beta}{1 + e^{\delta + \gamma \log \omega}}$$

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	$ E^* $ (Mpa)	Phase Angle (deg)	Cov. $ E^* $ (%)	Cov. Phase Angle (deg.)
4	10	1.05E+03	11120.67	12.39	10.4	3.75
4	1	1.05E+02	7891.67	16.26	11.51	4.19
4	0.1	1.05E+01	5111.33	20.9	12.61	3.93
20	10	1.33E+01	4201.67	25.15	21.15	7.63
20	1	1.33E+00	2195	29.29	25.76	5.58
20	0.1	1.33E-01	1058.5	30.67	28.16	2.88
45	10	3.47E-02	817.83	34.09	24.02	1.78
45	1	3.47E-03	368.77	30.06	24.89	0.92
45	0.1	3.47E-04	200.67	25.11	22.8	1.21
45	0.01	3.47E-05	131.13	20.7	16.86	2.39

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 07/02/17
Testing Performed by: Elizabeth Bashiti
Default Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_9.5
Output Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_9.5\Default Output
Comments:

Number of Fatigue Tests: 6
Damage Model Function: Exponential

Damage Model Coefficients	
a	-2.69E-04
b	7.05E-01
y	N/A
z	N/A
alpha	3.947
Parameter r in Failure Crit.	3.19E+04
Parameter s in Failure Crit.	-3.02E-01

$$C = e^{a/S^b}$$

$$C = 1 - yS^z$$

$$N_f = r(G^t)^s$$

Test Name	Temperature (deg. C)	Frequency (Hz)	$ E' _{\text{live}}$ (MPa)	$ E' _{\text{dmg}}$ (MPa)	Nf	G ⁿ
PG76-22PM_9.5_FT1A2	15	10	6238.9	6921	8915	6.64E+01
PG76-22PM_9.5_FT1B	15.1	10	6198.1	7041	3415	9.63E+02
PG76-22PM_9.5_FT1C	15	10	6221.4	6573	6095	3.06E+02
PG76-22PM_9.5_3A	15	10	6248.6	6388	9055	5.29E+01
PG76-22PM_9.5_FT3B	15	10	6223.6	6175	5095	5.71E+02
PG76-22PM_9.5_FT3C	15	10	6231.4	6656	5895	3.50E+02

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 07/02/17
Testing Performed by: Elizabeth Bashiti
Default Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_9.5
Output Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_9.5\Default Output
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	2.15E+06
K2	1.391
K3	-1.083

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	1.59E+03
K2	-2.264
K3	1.139

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	1.59E+03
K2	2.264
K3	-1.125

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Strain Fatigue Relationship (psi units)	
K1	2.66E+05
K2	1.391
K3	-1.083

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	1.81E+02
K2	-2.264
K3	1.139

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	1.81E+02
K2	2.264
K3	-1.125

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	4
10	4
15	4
20	5
25	6

PG 76-22 PM 9.5 mm Peak Output

**North Carolina
State University**

ALPHA-Fatigue Dynamic Modulus Report

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 07/02/17
Testing Performed by: Elizabeth Bashiti
Default Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_9.5

Output Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_9.5\Peak Output

Comments:

Test Protocol: PP-61/TP-79
Number of |E*| Tests: 3
Maximum Limiting Modulus: Fixed (Hirsch)
Shift Factor Function: Arrhenius

Shift Factor Coefficients		
Tr	21.1	deg. C
Ea	184.51	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTs	N/A	
C	N/A	

Mastercurve Function	
κ	1.79E+00
β	2.54E+00
δ	-4.03E-02
γ	-5.26E-01

$$\log |E^*| = \kappa + \frac{\beta}{1 + e^{\delta + \gamma \log a}}$$

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E* (Mpa)	Phase Angle (deg)	Cov. E* (%)	Cov. Phase Angle (deg.)
4	10	1.05E+03	11120.67	12.39	10.4	3.75
4	1	1.05E+02	7891.67	16.26	11.51	4.19
4	0.1	1.05E+01	5111.33	20.9	12.61	3.93
20	10	1.33E+01	4201.67	25.15	21.15	7.63
20	1	1.33E+00	2195	29.29	25.76	5.58
20	0.1	1.33E-01	1068.5	30.67	28.16	2.88
45	10	3.47E-02	817.83	34.09	24.02	1.78
45	1	3.47E-03	368.77	30.06	24.89	0.92
45	0.1	3.47E-04	200.67	25.11	22.8	1.21
45	0.01	3.47E-05	131.13	20.7	16.86	2.39

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 07/02/17
Testing Performed by: Elizabeth Bashiti
Default Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_9.5
Output Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_9.5\Peak Output
Comments:

Number of Fatigue Tests: 6
Damage Model Function: Exponential

Damage Model Coefficients	
a	-2.36E-04
b	7.19E-01
y	N/A
z	N/A
alpha	3.947
Parameter r in Failure Crit.	6.79E+05
Parameter s in Failure Crit.	-6.43E-01

$$C = e^{aS^b}$$

$$C = 1 - yS^z$$

$$N_f = r(G^R)^s$$

Test Name	Temperature (deg. C)	Frequency (Hz)	E* _{Live} (MPa)	E* _{Age} (MPa)	Nf	G ^R
PG76-22PM_9.5_FT1A2	15	10	6238.9	6921	98610	2.37E+01
PG76-22PM_9.5_FT1B	15.1	10	6198.1	7041	7535	8.56E+02
PG76-22PM_9.5_FT1C	15	10	6221.4	6573	21139	2.50E+02
PG76-22PM_9.5_3A	15	10	6248.6	6388	98610	1.61E+01
PG76-22PM_9.5_FT3B	15	10	6223.6	6175	12673	5.36E+02
PG76-22PM_9.5_FT3C	15	10	6231.4	6656	18888	2.89E+02

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 07/02/17
Testing Performed by: Elizabeth Bashiti
Default Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_9.5

Output Directory: E:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_9.5\Peak Output

Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	4.27E+15
K2	4.179
K3	-3.681

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	1.30E-05
K2	-5.72
K3	3.963

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	1.30E-05
K2	5.72
K3	-1.757

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Strain Fatigue Relationship (psi units)	
K1	3.49E+12
K2	4.179
K3	-3.681

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	4.36E-07
K2	-5.72
K3	3.963

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	4.36E-07
K2	5.72
K3	-1.757

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	58
10	67
15	85
20	106
25	149

PG 76-22 PM 12.5 mm Default Output

**North Carolina
State University**

ALPHA-Fatigue Dynamic Modulus Report

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 06/21/17
Testing Performed by: Elizabeth Bashiti
Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_12.5

Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_12.5\Default Output

Comments:

Test Protocol: PP-61/TP-79
Number of |E*| Tests: 3
Maximum Limiting Modulus: Fixed (Hirsch)
Shift Factor Function: Arrhenius

Shift Factor Coefficients		
Tr	21.1	deg. C
Ea	186.32	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTs	N/A	
C	N/A	

Mastercurve Function	
κ	1.76E+00
β	2.55E+00
δ	5.10E-02
γ	-5.27E-01

$$\log |E^*| = \kappa + \frac{\beta}{1 + e^{\delta + \gamma \log a_r}}$$

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E* (Mpa)	Phase Angle (deg)	Cov. E* (%)	Cov. Phase Angle (deg.)
4	10	1.10E+03	10499	12.87	4.76	1.33
4	1	1.10E+02	7396	16.84	4.44	1.13
4	0.1	1.10E+01	4763.33	21.58	4.18	1.5
20	10	1.33E+01	3765.33	26.35	5.01	2.13
20	1	1.33E+00	1905	30.41	6.57	1.93
20	0.1	1.33E-01	915.97	31.3	7.17	1.44
45	10	3.28E-02	716.17	33.85	9.32	3.27
45	1	3.28E-03	322.97	29.89	9.43	4.05
45	0.1	3.28E-04	180.47	24.97	9.96	3.16
45	0.01	3.28E-05	120.87	20.42	8.23	3.79

Project Name:	Elizabeth Bashiti Graduate Project
Analysis Performed by:	Elizabeth Bashiti
Analysis Date:	06/21/17
Testing Performed by:	Elizabeth Bashiti
Default Directory:	D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_12.5
Output Directory:	D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_12.5\Default Output
Comments:	

Number of Fatigue Tests: 9
Damage Model Function: Exponential

Damage Model Coefficients	
a	-2.31E-04
b	7.23E-01
y	N/A
z	N/A
alpha	3.929
Parameter r in Failure Cnt.	2.29E+04
Parameter s in Failure Cnt.	-2.36E-01

$$C = e^{aS^b}$$

$$C = 1 - yS^z$$

$$N_f = r(G^R)^s$$

Test Name	Temperature (deg. C)	Frequency (Hz)	E* _{Live} (MPa)	E* _{Range} (MPa)	Nf	G ^R
PG76-22PM_12.5_FT1A	15	10	5746.4	6154	8875	4.96E+01
PG76-22PM_12.5_FT1B	15	10	5731.4	6429	4855	6.93E+02
PG76-22PM_12.5_FT1C	15	10	5753.8	6771	5995	3.16E+02
PG76-22PM_12.5_FT2A	15	10	5745.1	6917	9115	6.00E+01
PG76-22PM_12.5_FT2B	14.9	10	5761.6	5759	5915	3.21E+02
PG76-22PM_12.5_FT2C	14.9	10	5767.2	6521	6155	2.44E+02
PG76-22PM_12.5_FT3A	15	10	5744.1	5911	9075	4.34E+01
PG76-22PM_12.5_FT3B	15	10	5743.5	6428	4895	5.75E+02
PG76-22PM_12.5_FT3C	15	10	5738.6	6014	6495	2.44E+02

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 06/21/17
Testing Performed by: Elizabeth Bashiti
Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_12.5
Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_12.5\Default Output
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	4.92E+05
K2	1.054
K3	-0.816

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	1.87E+03
K2	-1.901
K3	0.96

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	1.87E+03
K2	1.901
K3	-0.941

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Strain Fatigue Relationship (psi units)	
K1	1.02E+05
K2	1.054
K3	-0.816

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	3.03E+02
K2	-1.901
K3	0.96

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	3.03E+02
K2	1.901
K3	-0.941

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	4
10	4
15	5
20	6
25	7

PG 76-22 PM 12.5 mm Peak Output

**North Carolina
State University**

ALPHA-Fatigue Dynamic Modulus Report

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 06/21/17
Testing Performed by: Elizabeth Bashiti
Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_12.5

Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_12.5\Peak Output

Comments:

Test Protocol: PP-61/TP-79
Number of |E'| Tests: 3
Maximum Limiting Modulus: Fixed (Hirsch)
Shift Factor Function: Arrhenius

Shift Factor Coefficients		
Tr	21.1	deg. C
Ea	186.32	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTs	N/A	
C	N/A	

Mastercurve Function	
κ	1.78E+00
β	2.55E+00
δ	5.10E-02
γ	-5.27E-01

$$\log |E'| = \kappa + \frac{\beta}{1 + e^{\delta + \gamma \log \omega}}$$

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E' (Mpa)	Phase Angle (deg)	Cov. E' (%)	Cov. Phase Angle (deg.)
4	10	1.10E+03	10499	12.87	4.76	1.33
4	1	1.10E+02	7396	16.84	4.44	1.13
4	0.1	1.10E+01	4763.33	21.58	4.18	1.5
20	10	1.33E+01	3765.33	26.35	5.01	2.13
20	1	1.33E+00	1905	30.41	6.57	1.93
20	0.1	1.33E-01	915.97	31.3	7.17	1.44
45	10	3.28E-02	716.17	33.85	9.32	3.27
45	1	3.28E-03	322.97	29.89	9.43	4.05
45	0.1	3.28E-04	180.47	24.97	9.96	3.16
45	0.01	3.28E-05	120.87	20.42	8.23	3.79

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 06/21/17
Testing Performed by: Elizabeth Bashiti
Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_12.5
Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_12.5\Peak Output
Comments:

Number of Fatigue Tests: 9
Damage Model Function: Exponential

Damage Model Coefficients	
a	-2.25E-04
b	7.28E-01
y	N/A
z	N/A
alpha	3.929
Parameter r in Failure Crit.	4.52E+05
Parameter s in Failure Crit.	-5.65E-01

$$C = e^{a.S^b}$$

$$C = 1 - y.S^z$$

$$N_f = r(G^H)^s$$

Test Name	Temperature (deg. C)	Frequency (Hz)	$ E' _{LVE}$ (MPa)	$ E' _{Higer}$ (MPa)	Nf	G [#]
PG76-22PM_12.5_FT1A	15	10	5746.4	6154	98610	1.40E+01
PG76-22PM_12.5_FT1B	15	10	5731.4	6429	11152	6.56E+02
PG76-22PM_12.5_FT1C	15	10	5753.8	6771	20086	2.93E+02
PG76-22PM_12.5_FT2A	15	10	5745.1	6917	98610	2.41E+01
PG76-22PM_12.5_FT2B	14.9	10	5761.6	5759	19377	2.49E+02
PG76-22PM_12.5_FT2C	14.9	10	5767.2	6521	22244	1.83E+02
PG76-22PM_12.5_FT3A	15	10	5744.1	5911	97606	1.02E+01
PG76-22PM_12.5_FT3B	15	10	5743.5	6428	11383	5.28E+02
PG76-22PM_12.5_FT3C	15	10	5738.6	6014	26887	1.94E+02

Project Name: Elizabeth Bashiti Graduate Project
Analysis Performed by: Elizabeth Bashiti
Analysis Date: 06/21/17
Testing Performed by: Elizabeth Bashiti
Default Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_12.5
Output Directory: D:\Graduate\Research\ALPHA-Fatigue\Exponential\PG76-22PM_12.5\Peak Output
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	4.58E+12
K2	3.287
K3	-2.821

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	9.67E-04
K2	-5.632
K3	3.646

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	9.67E-04
K2	5.632
K3	-1.986

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Strain Fatigue Relationship (psi units)	
K1	1.97E+10
K2	3.287
K3	-2.821

$$N_f = K_1 \left(\frac{1}{\varepsilon_f} \right)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	2.09E-05
K2	-5.632
K3	3.646

$$N_f = K_1 (\sigma_f)^{K_2} (|E^*|)^{K_3}$$

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	2.09E-05
K2	5.632
K3	-1.986

$$N_f = K_1 \left(\frac{1}{\varepsilon_{f,ini}} \right)^{K_2} (|E^*|)^{K_3}$$

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	39
10	45
15	57
20	71
25	99