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Evaluating the protocol of the spectrum of hot mix asphalt mixes produced in West Virginia

Laura Dalton

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Evaluating the Protocol of the Spectrum of Hot Mix Asphalt Mixes Produced in West Virginia

Laura Dalton

**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 and Environmental Engineering**

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**Morgantown, West Virginia
2016**

**Keywords: Fatigue, Flow Number, Dynamic Modulus, AMPT, CoreLok
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ABSTRACT

Evaluating the Protocol of the Spectrum of Hot Mix Asphalt Mixes Produced in West Virginia

Laura Dalton

Reviewing asphalt concrete plant-produced mixes in a laboratory setting provides further insight into pavement characteristics. Nine mix designs provided from five hot mix asphalt plant producers were evaluated throughout this research. Five mixes were Wearing I and four mixes were Base II/19 mm each of which contained various aggregate sources. First, the determination of bulk specific gravity was performed using three methods: Saturated Surface-Dry, CoreLok, and Dimensional (volumetric mass density). Moreover, assessing a mix's inherent capability to be uniformly compacted is integral in both laboratory and field evaluations. The nine mix designs were assessed for uniformity following AASHTO PP 60 standard.

Furthermore, the Asphalt Mixture Performance Tester (AMPT) is a new performance testing machine that has dynamic modulus, flow number, and fatigue testing capabilities. This research focused on using the AMPT to determine dynamic modulus, fatigue characterization, and flow number values of the asphalt mixes. Master curves were developed using Mastersolver Version 2.2 to review the stiffness of the mixes. Asphalt Pavement Hierarchical Analysis Toolbox – Fatigue Program (Alpha-FatigueTM software) was utilized to determine fatigue coefficients used to model the traditional fatigue equation. Yang Huang's KENPAVE was used to develop a range of strain-modulus curves. Next, AMPT dynamic modulus values and fatigue K-value outputs were then compared using the KENPAVE strain outputs at a specified frequency level. Lastly, flow number was evaluated for rutting resistance and compared among mix designs using two methods: AMPT averaging method and the Francken Model.

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List of Abbreviations

Abs. = Absorption

AMPT = Asphalt Mixture Performance Tester

AVG = Average

B = Bottom

CL = CoreLok

CV = Coefficient of Variation

DM = Dynamic Modulus

Dim. = Dimensional

ESAL = Equivalent Single Axle Load

FN = Flow Number

FT = Fatigue Test

GYR = Gyration

H = High

L = Low

LVDT = Linear Variable Differential Transformer

M = Middle

NMAS = Nominal Maximum Aggregate Size

PG = Performance Grade

RAP = Reclaimed Asphalt Pavement

REP = Replicate

S = Sample

SD = Standard Deviation

SGC = Superpave Gyratory Compactor

SS = Sample (Bulk)

SSD = Saturated Surface-Dry

STAT = Statistic

T = Top

VFA = Voids Filled with Asphalt

VMA = Voids in the Mineral Aggregate

VTM = Void in the Total Mix

Chapter 1: Introduction

Background

Roadway infrastructure connects people to their destinations. Continuing to facilitate smooth transition from one place to another requires more extensive research of asphalt pavement distress, deterioration, and failure. Rutting and fatigue distress are common causes of premature failure of asphalt pavements. According to the 2015 West Virginia Blue Ribbon Commission on Highways (WVBRH), driving on rough roads costs West Virginia motorists a total of \$400 million annually in extra vehicle operating costs which include accelerated vehicle depreciation, additional repair costs, increased fuel consumption, and tire wear (WVBRCH, 2015). In West Virginia alone, there are approximately 36,000 miles of state-maintained highways. Economically, the state of West Virginia spent \$30 million on pavement preservation in 2012 and \$500 million for annual paving maintenance was passed in 2015 (WVBRH, 2015). Therefore, in situ pavements and maintenance of roads must meet design specifications as closely as possible.

There are numerous hot mix asphalt plants throughout the state of West Virginia. Each has its own asphalt mix designs used for construction and maintenance. Reviewing and analyzing asphalt mixes generated by various state asphalt plants allows a quantitative comparison of mix designs for the state. Meeting modern performance demands is essential to the continued success of pavement life. Fatigue and rutting damage are two primary forms of pavement deterioration which can be analyzed using the Asphalt Mixture Performance Tester (AMPT). Analyzing said distresses and dynamic modulus values of the asphalt concrete sources currently used throughout the state can provide insight for manufacturer's current mix designs and how the material properties contrast among WV state plants.

Problem Statement

This research was completed to compare and contrast a sample of mix designs currently used on WV roadways using the Asphalt Mixture Performance Tester (AMPT). Evaluating pavements subjected to existing traffic volumes throughout WV can provide insight to both the

WVDOH and supporting contractors on their product's material properties and performance. The AMPT has dynamic modulus, fatigue, flow time, and flow number testing capabilities. Expanding knowledge on how pavements should perform and withstand loading and environmental distress contributes to saving time and money over a pavement's lifespan. This research provides a quantitative analysis of how a sample of mix designs performed.

Objectives

There were two main objectives for this research: 1) test WV plant-produced mixes using the Asphalt Mixture Performance Tester (AMPT) and 2) provide a comparison of the mixes and their performance in uniformity, dynamic modulus, fatigue, and flow number testing.

Achieving these objectives is important because the studied asphalt concrete mixes are used throughout WV for past and current paving projects. Understanding what comprises each mix design compared to the aforementioned material performance properties, allows the state to better understand how the mixes compare to one another according to composition.

Scope and Limitations

The amount of HMA provided from each plant was limited to what was received. All mixes were plant-produced. There was no way to verify mix designs because correction factors and raw aggregate were not available to make laboratory replicate mixes. Once a mix had run out, an entire new batch would have had to have been acquired with all preliminary volumetric measurements and testing being rerun because the mix could have subtle changes in gradation between batches.

This research was performed on production samples collected from contractors during a limited time frame. There was no opportunity to designate mix types. As a result, there was no statistically designed experimental plan for this research. Thus, the results provide insight into the mixes produced in West Virginia, but there are limitations to the conclusions that can be drawn from the results.

Report Outline

There are five sections to this report starting with the first chapter being the introduction. Chapter two is a literature review covering HMA, Volumetric Properties, AMPT, Dynamic Modulus and Phase Angle, Fatigue, and Flow Number. Chapter three describes the research methodology for the project. The fourth chapter presents a summary of data, Mastersolver, Alpha-Fatigue, KENPAVE, and Flow Number results. Chapter five summarizes conclusions and provides recommendations for future work. Lastly, the appendices provide supplemental data.

Chapter 2: Literature Review

Asphalt Mixture Design

Hot mix asphalt (HMA) is a composite material comprised of aggregates, asphalt binder, and air voids. At various temperatures, asphalt mixtures behave differently. At low temperatures, HMA behaves similarly to elastic solids while at high temperatures the composite has the viscous properties of a liquid while maintaining some properties of plastic solids (Rodezno, 2010). There are three main mix design methods: Hveem, Marshall, and Superpave. Marshall and Superpave are explained in more detail below.

Marshall Design Method was developed by Bruce G. Marshall of the Mississippi Highway Department in 1939. During World War II, the U.S. Army Corp of Civil Engineers refined this mix design method to accommodate increased wheel loads and tire pressures of military aircrafts. Development was continued by U.S. Waterways Experiment Station (WES) through the 1950s looking at material tests, traffic loading, and weather influence. In Marshall Design Method, selecting a binder content that correlates to a desired density while maintaining minimum stability, flow range values, and volumetric properties is the primary goal (Cross, 1992 & Vasavi, 2002).

The Marshall method is still used in some states for its simplicity, compaction, and low cost. There are six steps in the design process: (1) Aggregate selection; (2) Asphalt binder selection; (3) Sample preparation; (4) Stability determination using Marshall stability and flow test; (5) Volumetric analysis; and (6) Optimum asphalt binder content selection. Marshall samples are compacted using the Marshall Hammer. The number of blows applied to each side of a sample is based on the traffic volume, Table 1 (Gillispie, 2011). The Marshall mix design method implemented in West Virginia is set forth in MP 401.02.22. In general it follows the recommendations of the Asphalt Institute with the exception that the compaction level of 50 blows per side is used for both light and medium traffic.

Table 1: Marshall Traffic

Marshall Traffic	Number of Blows	ESAL
Medium	50	10^4 to 10^6
Heavy	75	$10^6 <$

In 1987 Strategic Highway Research Program (SHRP) began the development of the Superior Performing Asphalt Paving (Superpave) mix design method which was subsequently implemented by the Federal Highway Administration (FHWA) in 1993 (Al-Mistarehi, 2014). The new mix design method was created to accommodate modern traffic patterns and heavier axle loads. Superpave contains five main steps: (1) Aggregate selection; (2) Asphalt binder selection; (3) Design aggregate structure; (4) Design binder content; and (5) Moisture sensitivity

The Superpave Gyratory Compactor (SGC) was designed to better simulate field compaction and make more consistent samples than the Marshall hammer. The SGC applies a 600 kPa load to a specimen cross section diameter of 150 mm at a 1.16° tilt and gyrates molds at a rate of 30 ± 0.5 gyrations per minute (AASHTO T 312). Advantages of this laboratory compaction method are transverse movement of asphalt mix particles; larger molds retain heat longer; and the tilted rotation better mimics that of a field compactor. Samples are compacted to the design number of gyrations, and then the volumetric properties are measured to determine if the samples meet design criteria. The SGC was designed to prepare samples measuring 150 mm in diameter by 115 ± 5 mm height to accommodate large stone mixes up to 37.5 mm. An image of an SGC and SGC mold can be seen in Figure 1.

Figure 1: *Superpave Gyratory Compactor and Molds*

Regardless of method, the main reason for constructing a mix design is to determine suitable combinations of aggregates and asphalt binder content to achieve optimum pavement performance. The job mix formula (JMF) is like a “recipe” for the design. A JMF is refined

within the asphalt mixture plant where the mix is proportioned, heated, and mix design components are combined (Mohammad et al., 2015).

Slag and Reclaimed Asphalt Pavement (RAP) are two materials found in literature to have both positive and negative impacts on asphalt concrete material properties. Some advantages of RAP include conservation of asphalt and aggregate resources, conservation of energy, and reduction in construction costs. It has been found that RAP can enhance mix stiffness properties (Smith, 2015). However, it has also been found that fatigue life can decrease when a high percentage of RAP is used (Vukosavljevic, 2006).

Slag is a stone-like, waste-matter byproduct separated from metals during the refining of iron ore. This material is incorporated in numerous WV mix designs because it is a readily available product in the southwestern part of the state. According to John Emry of the National Slag Association (1984), the incorporation of slag as an aggregate has both positive and negative features. Slag has shown to resist abrasion due to its high particle density adding to better skid resistance than natural aggregate (Emry, 1984 & Haifang et al., 2014). However, some drawbacks to slag include that it is inherently brittle, contains a high iron content which can lead to rust, has a porous exterior, and can be expansive. Within a mix plant, aggregates are not always completely coated with binder. Fine aggregates comprised of highly oxidative material can expand and disintegrate over time leading to weak points in an asphalt structure.

Volumetric Properties

According to Cornelison (2013), in-place volumetric properties are the number one contributing factor to asphalt pavement performance and durability. Determining the volumetric properties involves a combination of the aggregate properties, admixture type, and asphalt binder properties. Gradation, maximum specific gravity, bulk specific gravity, absorption, voids in the total mix (VTM) or air voids, voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA) are discussed in further detail.

Gradation

According to Cornelison (2013), minor deviations in gradation or asphalt binder is tolerable if volumetric properties still meet requirements. On the contrary, Mohammad et al.

(2015) found that slight differences in gradation, while within tolerances, might lead to significant differences in important volumetric properties, such as air voids and VFA.

Maximum Specific Gravity (Rice)

James M. Rice developed the maximum specific gravity (Rice) test method which became an ASTM standard in 1964. This allowed an indirect determination of mixture air voids when compared to bulk specific gravity of a compacted specimen while accounting for asphalt absorption to the aggregate (Cornelison, 2013). Specific gravity is the ratio of the mass of a solid or liquid to the mass of an equal volume of distilled water at a specified temperature. The maximum specific gravity of a mix is the specific gravity of the mix excluding air voids. In other words, G_{mm} is the case if all air was removed from a mix and only the aggregate and asphalt binder remained. This calculation is critical in determining the air void content in HMA. Equation 1 displays the calculation.

$$G_{mm} = \frac{M_s}{M_s + M_{bs} - M_{bms}} \quad (1)$$

Where:

M_s = Dry Mass of Sample, g

M_{bs} = Mass of Vacuum Bowl Submerged, g

M_{bms} = Mass of bowl and submerged sample in water, g

Bulk Specific Gravity

Bulk specific gravity of a mixture (G_{mb}) is used to determine the specific gravity of a compacted asphalt sample by relating the weight of a sample to the volume of water it displaces. While multiple bulk specific gravity measurement methods are available, AASHTO T 166 saturated-surface dry (SSD) is the standard recommendation. Figure 2 displays voids on the outer surface of an asphalt sample filled with water as opposed to Figure 3 showing all the places water can be lost when performing the SSD method. If these voids are not filled with water, then they are not accounted for in the calculation which leads to inaccurate measurements. However,

CoreLok method is becoming the preferred method of the WVDOH. Three methods are listed and explained below: SSD, CoreLok, and Dimensional.

Figure 2: *Compacted Asphalt with Water Filled Voids (Yan, 2012)*

Figure 3: *Potential Water Loss Areas (Yan, 2012)*

Saturated Surface-Dry (SSD)

From AASHTO T 166, SSD stands for saturated surface-dry and is defined as the specimen condition when the external air voids are filled with water and the surface is dry. Procedurally, this method involves weighing and recording the dry sample mass, submerging the specimen in 77°F (25°C) water for 3 to 5 minutes and recording the submerged weight. Lastly, the sample is removed from the water, rolled one full diameter on a damp towel, each face (top and bottom) of the sample is blotted on the towel, and the surface-dried sample weight is measured. Equation 2 shows the calculation for SSD.

$$G_{mb} = \frac{M_{DRY}}{M_{SSD} - M_{SUB}} \quad (2)$$

Where:

M_{DRY} = Mass of dry specimen, g

M_{SSD} = Mass of saturated surface dry specimen, g

M_{SUB} = Mass of specimen submerged in water, g

If the surface of the sample has large voids, then the drying process may remove too much water. Hence, the SSD method should not be used if the sample has more than two percent absorption.

CoreLok

The CoreLok G_{mb} method evolved from an increased use in coarse and open graded mixes (CoreLok[®] Operator's Guide, 2011). Determining accurate bulk specific gravity measurements for open graded mixes can be difficult due to their high absorption and drainage rates. AASHTO T 331 test specification requires vacuum sealing the sample. The Instro Tek[®] CoreLok machine can be used (Figure 4). This is a volumetric measurement made using a vacuum chamber to shrink wrap a plastic bag around the sample. This is a ten step process: 1) weigh sample, 2) weigh the bag, 3) place sample in the bag inside the vacuum sealing machine, 4) vacuum seal sample, 5) weigh vacuumed sample, 6) submerge vacuumed sample in water, 7) record submerged mass, 8) remove from water, 9) cut bag and remove sample, and 10) weigh sample once more. Step 10 is used to ensure no more than five grams of water permeated the bag. The calculation can be seen in Equation 3. CoreLok method involves a bag correction factor which is located in the CoreLok manual.

$$G_{mb} = \frac{M_s}{((M_b + M_{sa}) - M_{ss}) - \frac{M_b}{G_{ba}}} \quad (3)$$

Where:

M_b = bag mass, g

M_{sa} = dry sample mass after water submersion, g

M_{ss} = sealed sample mass in water, g

G_{ba} = bag apparent gravity

M_s = mass of dry core

Figure 4: Instron Tek® CoreLok Machine

Dimensional

The height-diameter method or dimensional method is based on the standard specified in AASHTO T 269. Procedurally, this G_{mb} method is most advantageous because it is simple, quick, and inexpensive. The height-diameter sample dimensions and mass of the sample are needed to calculate sample density. Equation 4 displays the calculation.

$$G_{mb} = 1000 \times \left(\frac{\rho_{sample}}{\rho_{water}} \right) \quad (4)$$

Where:

ρ_{sample} = density of the sample (mass of the sample divided by the volume)

ρ_{water} = density of water at 25 °C (0.99707g/cm³)

This method treats the voids on the surface of the sample as part of the volume of the sample. For samples compacted with either the Marshall hammer or SGC, these surface voids should not be considered as part of the sample. However, the external voids on cut faces produced by sawing and coring are part of the sample's volume and should be included when determining the bulk specific gravity.

Absorption

Absorption is defined as the amount of water “absorbed” by an asphalt specimen when submerged in water. This is an indication of a pavement’s ability to withstand water permeation. Equation 5 displays the calculation for water absorption of an asphalt concrete sample.

$$\text{Water Absorption (\%)} = \frac{M_{SSD} - M_{DRY}}{M_{DRY}} \quad (5)$$

Where:

M_{DRY} = Mass of dry specimen, g

M_{SSD} = Mass of saturated surface dry specimen, g

Note in Equation 5 that the amount of water “absorbed” is the difference between the mass at SSD and the dry mass. Hence, absorption is primarily based on the volume of the external voids and does not indicate the volume of the internal voids.

Research Comparing Bulk Specific Gravity Methods

According to AASHTO T 166 SSD may be used for fine graded mixes when water absorption is less than 2.0 percent. SSD is also considered adequate for determining the G_{mb} of conventionally designed fine-graded mixes, but can give erroneous results for coarse-graded mixes. Moreover, Griffith (2009) claims G_{mb} values from SSD and CoreLok testing methods were significantly different when specimens have low air void contents, and the CoreLok method results in lower bulk specific gravity measurements than the SSD method. However, as the air void content increased the differences between the two methods diverged (Griffith, 2009).

Voids in the Total Mix (VTM)

Air void distribution is key to continued integrity of pavement life and directly related to the bulk specific gravity of an asphalt mixture. Air void distribution is related to numerous pavement factors such as mix gradation, compaction effort, and compaction method. The higher the air void content, the increased likelihood of interconnected air voids throughout a pavement.

Interconnected air voids create areas for water to become trapped which can cause thermal cracking when subjected to cold weather and freeze-thaw cycles.

Once bulk specific gravity value is determined, the main air void calculation among the three methods is the same. Equation 6 displays the VTM calculation.

$$VTM = 100 \times \left(1 - \frac{G_{mb}}{G_{mm}}\right) \quad (6)$$

Where:

G_{mb} = bulk specific of the compacted mix

G_{mm} = theoretical maximum specific gravity of the mix

Cornelison (2013) claims a reduction in air voids below 8.0 percent will result in significant fatigue life improvement, moisture resistance, and raveling resistance. Field target air void content ranges from 5 to 8 percent with anything over 8 percent considered unacceptable. Table 2 summarizes target air void values used in literature. In Table 2 DM, FN, and FT stand for dynamic modulus, flow number, and fatigue. As can be seen, 7.0 ± 0.5 percent has been well documented in literature as a target air void content for testing with 10.0 ± 0.5 percent being the higher end of the range. Witczak (2013) found that the percent air voids for fatigue testing “was insignificant, especially at lower asphalt contents.”

Table 2: Literature Review Target Air Void Contents for Performance Testing

Reference Article	Target Air Void Content	Testing
Bonaquist, 2010	$7.0 \pm 0.5\%$	DM and FN
Bonaquist, 2011b	$7.0 \pm 0.5\%$	DM and FN
Vukosavljevic, 2006	$4.0 \pm 0.5\%$ and $6.0 \pm 1.0\%$	FT
Rodezno, 2010	$4.0 \pm 0.5\%$, $7.0 \pm 0.5\%$, and $10.0 \pm 0.5\%$	FN
Witczak et al., 2013	$4.0 \pm 0.5\%$, $7.0 \pm 0.5\%$, and $9.0 \pm 0.5\%$ (PG 64-22)	FT
Hou, 2009	$5.5 \pm 0.5\%$	FT

Chen et al. (2013) found that air voids close to the mold boundary were much higher than other regions, coarse aggregate (CA) ratio influenced vertical air void distribution (gradations with higher CA ratio resulted in more uniform air voids), and the height of an asphalt mixture specimen had a significant effect on vertical air void distributions.

Assessing Test Specimen Uniformity

For AMPT testing the air void uniformity is critical. AASHTO PP 60 specifies the method for testing the uniformity of air voids. After compaction, the samples are cored and trimmed to the dimensions used for AMPT testing. AASHTO PP 60 requires testing three replicate samples. Each replicate is cut into thirds. The G_{mb} of each slice is measured and a t-test is used to determine if the G_{mb} of the middle slice is statistically different from the top or bottom slices using equations 7 and 8. The test statistic must be less than 2.78 to conclude that top and middle or bottom and middle slices possess equal G_{mb} values. The test does not require a comparison between top and bottom thirds.

$$s = \sqrt{\frac{s_{t,b}^2 + s_m^2}{2}} \quad (7)$$

Where:

s = computed standard deviation

$s_{t,b}^2$ = computed variance for the top or bottom slices

s_m^2 = computed variance for the middle slices

$$t = \frac{(\bar{y}_{t,b} - \bar{y}_m)}{0.8165(s)} \quad (8)$$

Where:

t = test statistic

$y_{t,b}$ = computed mean for the top or bottom slices

y_m = computed mean for the middle slices

According to AASHTO PP 60, significant differences in G_{mb} of the top and bottom slices relative to the middle indicate a systematic variation in density within the specimen; specimen with differences in the G_{mb} for the top or bottom slices relative to the middle slices on the order of 0.025 have performed satisfactorily in the dynamic modulus, flow number, flow time, and continuum damage fatigue tests; and altering the height of the SGC specimen can improve the

uniformity of the density in the test specimen. This result justifies coring and trimming laboratory compacted samples prior to performance testing.

Voids in the Mineral Aggregate (VMA)

Voids in the mineral aggregate indicate the film thickness on the surface of the aggregate. This is the limiting criteria for the minimum amount of binder needed to coat the aggregate. The calculation is shown in Equation 9.

$$VMA = \frac{G_{mb}P_s}{G_{sb}} \quad (9)$$

Where:

G_{mb} =bulk specific of the compacted mix

P_s =percent of aggregate in the mix

G_{sb} =specific gravity of the bulk aggregate

Voids Filled with Asphalt (VFA)

Voids Filled with Asphalt is the amount of VMA that is filled with asphalt. This determines the maximum amount of asphalt needed for a mix design. Researchers have reported good correlations between VFA and rutting susceptibility (Cross, 1992). Equation 10 displays the VFA calculation.

$$VFA = 100 \times \frac{VMA - VTM}{VMA} \quad (10)$$

Where:

VMA = voids in the mineral aggregate

VTM = volume of air voids

Asphalt Mixture Performance Tester (AMPT)

Formerly known as the Simple Performance Tester (SPT), the Asphalt Mixture Performance Tester (AMPT) is a servo-hydraulic testing machine engineered as a result of

NCHRP Project 9-19, *Superpave Support and Performance Models Management* and NCHRP Project 9-29, *Simple Performance Tester for Superpave Mix Design* (OPT, 2013). The AMPT has flow time, flow number, dynamic modulus, and fatigue testing capabilities. The output of the AMPT can be used in AASHTOWare® Pavement ME Design.

Dynamic Modulus and Phase Angle

Dynamic modulus is a material property indicative of a mix's stiffness and is used to calculate other distresses such as rutting and fatigue cracking. Mathematically, the dynamic modulus is defined as the maximum (peak) dynamic stress divided by the recoverable axial strain (Equation 11). Dynamic modulus of an asphalt mixture is known to be dependent on variables such as temperature and loading rate in addition to mixture characteristics such as binder stiffness, gradation, and air voids. Binder stiffness is needed to withstand distress at low temperatures and indirectly influences pavement fatigue failure. Figure 5 displays an idealized stress-strain relationship of a dynamic modulus test on a viscoelastic material.

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \quad (11)$$

Where:

E^* = absolute value of the complex modulus (dynamic modulus)

σ_0 = stress

ε_0 = strain

Phase angle is the lag between applied shear stress and the resultant shear strain. The phase angle ranges from 0 to 90° where $\delta = 0^\circ$ for an elastic material and $\delta = 90^\circ$ represents a purely viscous material. With an increase in temperature or a decrease in loading frequency, asphalt binder becomes soft allowing the asphalt mix behavior to be dominated by the aggregate (Witczak et al., 2013). At this point the phase angle will increase. It has been found that the phase angle increases with decreasing reduced frequency at a constant reduced frequency until a certain point where it starts to decrease (Witczak et al., 2013). Equation 12 displays the equation for phase angle.

Figure 5: Typical Dynamic Modulus Test Data (Bonaquist et al., 2003)

$$\delta = \frac{T_l}{T_p} \times 360 \quad (12)$$

Where:

δ = phase angle in degrees

T_l = time lag (sec.)

T_p = time period of applied stress (sec.)

Dynamic modulus testing is a nondestructive test performed at multiple temperatures to determine viscoelastic properties of asphalt mixes over a wide range of temperatures and frequencies (Tran et al., 2013). Table 3 displays the recommended testing temperatures and frequencies according to performance grade following AASHTO PP 61.

Table 3: AASHTO PP 61 Recommended Testing Temperatures and Loading Frequencies

PG 58 - XX and softer		PG 64 - XX and PG 70 - XX		PG 76- XX and stiffer	
Temp. °C	Loading Frequencies, Hz	Temp. °C	Loading Frequencies, Hz	Temp. °C	Loading Frequencies, Hz
4	10, 1, 0.1	4	10, 1, 0.1	4	10, 1, 0.1
20	10, 1, 0.1	20	10, 1, 0.1	20	10, 1, 0.1
35	10, 1, 0.1, and 0.01	40	10, 1, 0.1, and 0.01	45	10, 1, 0.1, and 0.01

Mastersolver

Dr. Ramon Bonaquist, the principal investigator for NCHRP Project 9-29, developed an Excel macro worksheet that computes dynamic modulus master curves from AMPT data. This workbook is now known as Mastersolver. It utilizes a modified version of the Mechanistic-Empirical Pavement Design Guide (MEPDG) master curve equation along with the Arrhenius equation and Hirsch model (Bonaquist, 2011a). The modified equation used in Mastersolver is as follows in Equation 13:

$$\log|E^*| = \log(\text{Min}) + \frac{\log(\text{Max}) - \log(\text{Min})}{1 + e^{\beta + \gamma \log(\omega_r)}} \quad (13)$$

Where:

$|E^*|$ = dynamic modulus

Min = limiting minimum modulus, ksi

Max = limiting maximum modulus, ksi

ω_r = reduced frequency, Hz

β and γ = fitting parameters

However, to accommodate the dynamic modulus values tested at various temperatures and frequencies, the master curve must be fitted to a reduced frequency curve. An arbitrary reference temperature of 70°F is usually used (Rodezno, 2010). Reduced frequency can be determined using Arrhenius equation shown in Equation 14. Substituting Equation 14 into Equation 13 forms the master curve equation fitted in the Mastersolver workbook.

$$\log \omega_r = \log \omega + \frac{\Delta E_\alpha}{19.14714} \left(\frac{1}{T} - \frac{1}{T_r} \right) \quad (14)$$

Where:

ω_r = reduced frequency at the reference temperature, Hz

ω = loading frequency at the test temperature, Hz

T_r = reference temperature, °K

T = test temperature, Hz

ΔE_a = activation energy, J/mol

The shape of the master curve is characterized by five parameters: β , γ , E_{min} , E_{max} , and ΔE_a . The parameter E_{max} is calculated directly from the volumetrics of the mix so this is not considered a fitted parameter and requires no evaluation. Relationships can be determined by comparing the remaining four parameters and a mixture's components (Roberts et al., 2012). Additionally, Witczak et al. (2013) observed that binder type influences the dynamic modulus master curve.

Fatigue Damage and Testing

Fatigue damage is a leading cause for pavement failure. Fatigue cracking is defined as a series of longitudinal cracks that can become interconnected overtime. Structural stability is eventually lost at critical locations. In thin pavements subjected to traffic loading, the pavement bottom section is placed in tension and this is where cracking initiates. There are two types of fatigue cracking: bottom-up cracking and a newer acknowledged phenomenon of top-down cracking (Witczak et al., 2013). Bottom-up cracking is considered in a three-step process: crack initiation, propagation, and final fracture failure. Microscopic cracks originally form until reaching a critical size of 7.5 mm (Little et al., 2001). Location evolves from critical stress and strain point development within the pavement structure. According to Witczak et al. (2013), top-down cracking initiates at the top of thick pavements in areas of high tensile stress as a result of tire-pavement interaction and aging binder.

Numerous fatigue test methodologies have been developed over the past several decades to characterize fatigue behavior in asphalt concrete. A cyclic direct tension-compression test has been developed by Kim et al. at North Carolina State University. This methodology has evolved

into an AASHTO test method PP 107 for use with the AMPT. Since this was the methodology available for the current research, it is the only method reviewed herein.

Over the years, Kim et al. have developed a simplified-viscoelastic continuum damage (S-VECD) theory for the evaluation of asphalt materials. The details of the process are complex and are well documented elsewhere (Hou, 2009, Underwood et al. 2009, Zhang, 2012, Underwood et al., 2012, LaCroix., 2013, Witczak et al., 2013, and Sabouri, 2014). The analysis used in this methodology is implemented in the Alpha-Fatigue software. This program uses output files from the AMPT dynamic modulus and fatigue tests to compute the fatigue parameters. There are only two user-interactions in the Alpha-Fatigue software: 1) selecting the “failure” point that corresponds to a specific number of cycles to failure, Figure 6 and 2) selecting either the exponential or power-law model for the normalized pseudo secant modulus (C) versus cumulative damage (S), Figure 7.

Figure 6: Alpha-Fatigue Phase Angle Drop

For the first user-interaction, the phase angle versus load cycle curve is used for selecting the failure point. The user can allow the software to determine the failure point automatically or can specify a point. Recent studies recommend selecting the point where there is a rapid decrease in the phase angle (Reese, 1997, Hou, 2009, Zhang, 2012, and LaCroix, 2013). For the second user-interaction, the user selects the model with the lower mean square error.

Figure 7: Alpha Fatigue Simple Model Characterization Interface

The Alpha-Fatigue software output provides several alternative formats for fatigue models. For constructing historical fatigue evaluations, the conventional model, Equation 15, was implemented in the current research. The three K-values are constants determined from damage models produced from regression analyses. Once determined, these values can be correlated to field performance.

$$N_f = K_1 \left(\frac{1}{\varepsilon_t} \right)^{K_2} \left(\frac{1}{E} \right)^{K_3} \quad (15)$$

Where:

$K_1, K_2, K_3 = \text{constants}$

$\varepsilon_t = \text{strain}$

$E = \text{dynamic modulus}$

The Asphalt Institute has reported K_1 , K_2 , and K_3 values of 0.0796, 3.291, and 0.854 while Shell has used 0.0685, 2.363, and 5.571 (Huang, 2004). Moreover, Hou (2009) completed fatigue testing on a range of mixes. A summary of regression coefficients are displayed in Table 4. K-values vary from the aforementioned constants.

Furthermore, the endurance limit is defined as the allowable tensile strain below which fatigue cracking does not occur. For strain levels above the endurance limit, considerably more damage is induced. A pavement's endurance limit is believed to vary depending on the mixture properties, gradation, paving temperature, and traffic conditions. Monismith and Nunn recommend a limiting criteria of less than 70 micro strains for tensile strain at the bottom of a composite HMA layer (Lenz, 2011).

Table 4: Regression Coefficients from Hou (2009) and Witczak et al. (2013)

Reference Article	Mix	K ₁	K ₂	K ₃
Hou, 2009	S9.5C	2.40E+10	8.253	4.821
	S9.5B	4.89E+04	8.253	4.099
	I19C	8.86E-06	7.275	2.327
	B25B	4.75E-09	7.510	1.951
	R9.5C	1.02E+02	7.547	3.262
	S12.5C	1.51E-01	7.902	3.180
	I19B	7.21E-09	8.090	2.329
	RS12.5C	5.83E-09	8.000	2.191
	RI19B	5.07E-15	7.391	1.135
	RI19C	9.16E-09	7.609	2.056
	RB25B	1.34E-18	7.762	0.913
Witczak et al., 2013	9.5% VTM/ 5.2% Binder Content	1.42E-05	4.942	1.681
	4.5% VTM/ 5.2% Binder Content	9.95E-03	3.464	1.112
	All Mixtures	3.28E-06	5.281	1.825

Rutting and Flow Number Test

Rutting is defined as permanent deformation of the surface of a pavement in the wheel path which is caused by progressive movement of materials, under repeated loads, either in asphalt pavement or underlying layers (Cross, 1992). Permanent deformation occurs primarily when a pavement is subjected to high temperatures where the structure becomes more viscoelastic-plastic. Any damage that occurs in the viscous state is irreparable. Traffic volume, magnitude of wheel load and tire pressure, environmental conditions, mix properties including

aggregate characteristics, binder content, and air void levels can all influence rutting in a pavement structure (Rodezno, 2010).

The AMPT flow number test applies a dynamic load for several thousand repetitions and records the accumulation of permanent deformation as a function of the number of cycles. Haversine loading for 0.1 second is applied to the sample followed by a 0.9 second rest period. Typical results between measured permanent strain and load cycle can be divided into three major zones: primary, secondary, and tertiary, Figure 8. It should be noted that Figure 8 was remade to represent the relationship of permanent strain and number of cycles in a flow number test as found in Rodezno (2010). During the primary phase, the strain rate or slope of the curve decreases; in the secondary phase the permanent strain rate becomes constant; and in the tertiary phase the strain rate increases until rupture. Classical rutting evaluation involved the concept of creep where the secondary phase was defined as linear. The flow number can be defined as the load repetition value where shear deformation under constant volume starts or can be defined as the minimum point in the rate of change of permanent strain versus loading time relationship (Rodezno, 2010). Figure 9 displays a completed flow number test where the flow number was determined using the minimum point of change in permanent strain (Bonaquist et al., 2003). The flow number appears to fall somewhere in the secondary phase as opposed to the beginning of tertiary flow as shown in Figure 8. Bonaquist et al. (2003) determined the secondary phase was not linear because the behavior of permanent deformation per cycle of asphalt concrete decreases until it reaches inflection point and then increases.

Figure 8: Classical Flow Number Test Relationship between Permanent Strain and Loading Cycles

Figure 9: Typical Repeated Load Test and Flow Number (Bonaquist et al., 2003)

The AMPT flow number test has been adopted to evaluate asphalt mixture resistance to permanent deformation. Software provided with the AMPT for running flow number tests uses a data-smoothing model to determine a flow number. Equation 16 is used to find the rate of change of permanent strain using a data-smoothing model.

$$\frac{d(\varepsilon_p)_i}{dN} \cong \frac{(\varepsilon_p)_{i+\Delta N} - (\varepsilon_p)_{i-\Delta N}}{2\Delta N} \quad (16)$$

Where:

$\frac{d(\varepsilon_p)_i}{dN}$ = the rate of change of permanent axial strain at cycle i

ΔN = sampling interval

$$(\varepsilon_p)_{i+\Delta N} = \text{permanent strain at cycle } i+\Delta N$$

$$(\varepsilon_p)_{i-\Delta N} = \text{permanent strain at cycle } i-\Delta N$$

Some researchers have identified issues with the data averaging method used in the AMPT and have proposed using the Francken model (Von Quintos et al., 2012 & Biligiri et al., 2007). The Francken model is a combination of a power model and an exponential, Equation 17. The fitting coefficients are determined using numerical optimization. Once fitted the second derivative of the Francken model (Equation 18) is determined and the flow number is the cycle where the second derivative changes from negative to positive. Using the Francken model with a sampling interval of one standardizes the flow number computation and leads to reduced variability in flow number tests on replicate specimens (AASHTO TP 79).

$$\varepsilon_p = An^B + C(e^{Dn} - 1) \quad (17)$$

$$\frac{d^2\varepsilon_p}{dn^2} = AB(B-1)n^{B-2} + CD^2e^{Dn} \quad (18)$$

Where:

ε_p = permanent axial strain

n = number of cycles

$A, B, C,$ and D = fitting coefficients

AASHTO TP 79 flow number test parameters are presented in Table 5 and flow number rutting criteria is located in Table 6. The test method does not specify if the criteria in Table 6 are applicable to both the data-smoothing and Francken methods for determining flow number.

Table 5: Flow Number Test Parameters

Test Parameter	Value
Test Temperature	Adjusted PG temperature
Repeated axial stress	600kPa
Contact stress	30 kPa
Confining stress	0 kPa (unconfined)

Table 6: Flow Number Rutting Criteria

Traffic Level, million ESALs	HMA Minimum Average Flow Number
< 3	-
3 to < 10	50
10 to < 30	190
30 ≤	740

Research Using the AMPT

Hou (2009) expressed the need to develop a model that could characterize fatigue performance quickly using cyclic data for the AMPT. S-VECD developed at North Carolina State University was applied to various asphalt mixtures used throughout North Carolina and the results of this study concluded that VECD model can predict fatigue tests fairly accurately under various temperature conditions and strain levels (Hou, 2009). Additionally, Hou (2009) looked at where fatigue samples fractured when pulled apart. He concluded that both middle-failure (within LVDT gauge points) and end-failure (outside LVDT gauge points) results do not affect damage characterization. However, Witczak et al. (2013) excluded end-failure test results in fatigue failure analysis, claiming it is crucial that failure occurs within the LVDT gauge length.

NCHRP Report 702 documents the results of Phase IV of the NCHRP Report 9-29. This phase involved an interlaboratory study to prepare precision statements for dynamic modulus and phase angle, unconfined flow number, and permanent strain in confined flow number testing. The precision statements for this study were developed using specimens with an air void tolerance range ± 1.0 percent. No air void effect was detected using this tolerance. Variability within the AMPT tests was found to increase with decreasing specimen stiffness (Bonaquist, 2011b). To further reduce variability of low stiffness dynamic modulus measurements, a potential improvement for the AMPT equipment suggested was using lower spring rate sensors for mounted specimens. Average flow number values from the eight laboratories testing the same 9.5 mm mix ranged from 50 to 290. However, the variability of unconfined flow number tests was considered unacceptable.

From 2012 to 2014, the pooled-fund interlaboratory study (ISL) was conducted to determine variability of the dynamic modulus and flow number test conducted on loose plant-produced mix and how results compared to the NCHRP Project 09-29 ISL; and another objective was to examine if the tolerance fabrication could be enlarged from ± 0.5 percent to ± 1.0 percent.

Taylor and Tran (2014) found within-lab variability values to be at or above that of the NCHRP Project 09-29 for dynamic modulus and phase angle while reproducibility was at or below. For flow number both repeatability and reproducibility significantly improved over the Bonaquist (2011b) report. Average flow number values for 12.5 mm NMAS samples made at 6, 7, and 8 percent air voids were 340, 211, and 145. It was concluded that the fabrication tolerance for air voids should remain at the narrow ± 0.5 percent.

Roberts et al. (2012) conducted a five year evaluation of the AMPT in Utah. Spring loaded LVDTs were used which creates a spring force on the studs. This force is counteracted by compensating springs on either side of the LVDT. This study explored the difference between the two forces and determined the springs were not providing enough force to counteract the LVDT force (Roberts et al., 2012). Moreover, investigators found that coefficient of variation increased with both a decrease in frequency and increase in temperature during dynamic modulus testing. Most of the coefficient of variation values were below 15 percent when looking at tests run at 20°C and a frequency of 1 Hz with the average coefficient of variation being 10.2 percent. The AMPT was determined to be repeatable and generate precise data.

Salient Points

- There are numerous methods to determine G_{mb} . However, which method is best and how methods compare is not fully known.
- Sample uniformity varies with numerous factors: specimen height, mix composition, etc. Sample uniformity must be met to ensure subsequent testing is acceptable.
- A target air void content of 7.0 ± 0.5 percent is well documented in literature for dynamic modulus and flow number testing while fatigue is not as well specified (Table 2). However, Witczack et al. (2013) found fatigue parameters are not sensitive to percent air voids.
- Fatigue failure has been extensively studied using a variety of test methods. Kim et al. have determined that the S-VECD analysis method can be used to model any test mode.
- Two methods for determining flow number are suggested in AASHTO TP 79. The flow number computation using the Francken model leads to reduced variability in flow number test replicates.

- LVDT errors have been problematic in past AMPT use.
- AMPT dynamic modulus and flow number testing repeatability has been quantified in past research.

Chapter 3: Methodology

Materials

As previously mentioned, there were two main objectives for this research: 1) test WV plant-produced mixes using the Asphalt Mixture Performance Tester (AMPT) and 2) provide a comparison of the mixes and their performance in uniformity, dynamic modulus, fatigue, and flow number testing. These objectives were completed following the methodologies explained herein. Both Marshall and Superpave asphalt mixes were provided for this research through the West Virginia Division of Highways (WVDOT). The mixes are from various HMA plants located throughout West Virginia. Five paving companies provided samples. Nominal maximum aggregate sizes (NMAS) of 9.5 and 19 mm were provided. Mixes are listed in Table 7.

Table 7: Mixes Provided from Asphalt Plants throughout West Virginia

Company	Plant Location	Mix NMAS	Binder Content (%)	Mix Type	Design Traffic	HMA Type
American Asphalt of WV	St. Albans	9.5 mm ($\frac{3}{8}$ ")	5.6	Marshall	Heavy	Wearing I RAP
Greer Industries	Morgantown	9.5 mm ($\frac{3}{8}$ ")	5.7	Marshall	Heavy	Wearing I
Jefferson Asphalt Paving	Millville	19 mm ($\frac{3}{4}$ ")	4.9	Marshall	Medium	Base II
J. F. Allen Co.	Saltwell	19 mm ($\frac{3}{4}$ ")	4.9	Marshall	Heavy	Base II
J. F. Allen Co.	Saltwell	9.5 mm ($\frac{3}{8}$ ")	5.8	Marshall	Medium	Wearing I
J. F. Allen Co.	Saltwell	19 mm ($\frac{3}{4}$ ")	4.9	Superpave	3 to <30 million	19 mm
Kelly Paving	Benwood	9.5 mm ($\frac{3}{8}$ ")	5.6	Marshall	Heavy	Wearing I Skid w/RAP
West Virginia Paving, Inc.	Dunbar	19 mm ($\frac{3}{4}$ ")	4.6	Marshall	Heavy	Base II w/RAP
West Virginia Paving, Inc.	Parkersburg	9.5 mm ($\frac{3}{8}$ ")	5.9	Marshall	Heavy	Wearing I RAP
West Virginia Paving, Inc.	Dunbar	9.5 mm ($\frac{3}{8}$ ")	6.1	Marshall	Heavy	Wearing I Skid-RAP

Due to limited mix quantities only nine of the ten mixes were used for the full gamut of testing. Throughout the rest of this report, mixes are identified by a company acronym followed by the last three digits of the mix design number. Each mix was designed with PG 64-22 binder. Below are the mixture descriptions:

American Asphalt of WV (AA)

- AA937 is a fine-graded Wearing I mix containing 35 percent #8 limestone, 16 percent limestone, 34 percent natural sand, and 15 percent RAP.

Greer Industries (GR)

- GR465 is a course-graded Wearing I mix comprised of 48 percent #8 limestone, 32 percent limestone, and 20 percent limestone.

Jefferson Asphalt Paving (JAP)

- JAP909 is a fine-graded Base II mix comprised of 50 percent #67 and 50 percent #10 limestone only.

JF Allen (JFA)

- JFA060 is a fine/coarse graded Base II mix comprised of 30 percent #67 limestone, 36 percent #8 limestone, 33 percent limestone sand, and 1 percent BHF.
- JFA115 is a coarse-graded Wearing I mix comprised of 40 percent #67 limestone, 50 percent limestone sand, 9 percent #9 limestone, and 1 percent BHF.
- JFA429 is the only 19 mm mix. It is a fine gradation design comprised of 33 percent #67 limestone, 20 percent #8 limestone, 14 percent #9 limestone, 32 percent limestone, and 1 percent BHF.

Kelly Paving (KP)

- KP483 is a coarse-graded Wearing I mix comprised of 44 percent #8 limestone, 19 percent natural sand, 22 percent limestone, and 15 percent RAP.

West Virginia Paving (WVP)

- WVP523 is a fine-graded Base II mix that contains 40 percent #67 limestone, 9 percent limestone, 25 percent natural sand, 10 percent slag, 1 percent baghouse fines (BHF), and 15 percent RAP.
- WVP766 is a coarse-graded Wearing I mix consisting of 40 percent #8 limestone, 9 percent limestone, 25 percent natural sand, 10 percent slag, 1 percent BHF, and 15 percent RAP.
- WVP882 is a coarse-graded Wearing I mix containing 30 percent #8 slag, 29 percent limestone, 25 percent natural sand, 1 percent BHF, and 15 percent RAP.

The American Asphalt, Kelly Paving, and WV Paving mixes contained natural sands and 15 percent RAP. All other mixes contained 100 percent crushed limestone aggregate. The three West Virginia Paving mixes included slag.

Table 8 displays the gradations of each Wearing I mix and Table 9 displays the Base II/19 mm mix details. All JMFs and power 0.45 gradation charts are available in Appendix A.

Table 8: Wearing I Mixes Gradations

Mix	Sieve (mm)							
	12.5	9.5	4.75	2.36	1.18	600	300	75
AA937	100	96	66	48	37	28	11	5.3
JFA115	100	98	66	44	28	19	13	4.9
KP482	100	98	58	38	23	13	9	5.4
WVP766	100	95	62	41	30	22	11	4.8
WVP882	100	94	66	43	30	23	13	6.2

Table 9: Base II and 19 mm Mixes Gradations

Mix	Sieve (mm)									
	25	19	12.5	9.5	4.75	2.36	1.18	600	300	75
JAP909	100	93	-	67	52	35	-	14	10	5
JFA060	100	97	83	75	47	30	18	12	9	4.9
JFA429	100	100	81	70	49	30	19	13	9	4.3
WVP523	100	97	81	72	57	43	33	25	13	5.7

Randomizing Sample Mix Procedure

Each sample set was weighed and inventoried on the day of delivery. The first step in the experimental plan was to randomize each batch of asphalt provided. This was completed to minimize the effect of variability. The following 23 steps were taken to randomize the asphalt mixtures:

1. Clean work tables with WD-40 and grease lighting.
2. Cover table in release paper for a clean, stick-free work surface as seen in Figure 10.
3. Remove asphalt mixture from boxes and place in pans.
4. Place in ovens.
5. Heat all mix.

Figure 10: Table Covered in Release Paper

6. Once HMA reaches 105°F (41°C) remove from oven and break apart into two smaller sections to quicken the heating process.
7. Place back in oven.
8. Wait until 150°F (65°C) is reached.
9. Remove three pans randomly.
10. Thoroughly mix contents together on table.
11. Break mix into eight sections as seen in Figure 11.

Figure 11: Separated Eight Sections

12. Generate random numbers using Excel command RANDBETWEEN(1,8) and label as seen in Figure 12. These batched quantities are pre-samples.

Figure 12: Separated Mix in Randomized Order

13. Pre-sample one is then placed in a new pan according to the random number generated and weighed to 3,875 grams (half a full sample size).
14. Continue through pre-sample eight.
15. If sample is overweight, place in a pan as extra to be remixed later.
16. If weight is under, grab mix from the next mix pile.
17. All left over mix is remixed together to form more half samples until the mix remaining cannot constitute an entire half sample. This is done by mixing the leftovers together, separating into four quarters as seen in Figure 13 and combining opposite quarters.

Figure 13: Quartering Process

18. Place extra in a pan and set aside.
19. Repeat steps 9-14 for remaining mix.
20. Generate random numbers using Excel command: RANDBETWEEN(1, number of half the samples being produced).
21. Combine pre-sample halves to create whole samples.
22. Place in labeled boxes or plastic bags for storage.
23. Repeat for additional nine mix sets.

Throughout the entire process steps were taken to eliminate bias. When mix had to be removed from a pan, mix was removed from different pan locations.

Sample Preparation and Fabrication

Maximum specific gravity (G_{mm}) values were determined following AASHTO T 209. For plant-produced mixes the samples were heated to 105°C, broken apart, allowed to cool to room temperature, and were tested. This step was completed for the ten mixes to compare to the Job Mix Formulas (JMF) values.

All but one mix was Marshall which required experimenting to see how Marshall mixes would compact in the SGC. GR465 was the first mix set evaluated as a starting point. Samples were made with the assumption that each mix set reached absorption and aging when mixed at

the mixing plants. Following past WVU laboratory experience (Smith, 2015 & Turner, 2015) the GR465 samples were made to be 180 mm tall by 150 mm diameter with a target air void content of 7.0 ± 0.5 percent. Literature supported this target air void value as described in Table 2 in Chapter 2.

Initial mix mass was calculated using AASHTO PP 60 (Equation 19). The mass calculated was 7,209 grams which translated to a mix amount exceeding mold capacity. Approximately 7,130 grams of mix were placed in the mold, but the SGC was unable to compact to the specified 180 mm height, instead reaching 185 mm. This sample was excluded for air void testing and further adjustments were estimated for subsequent samples resulting in a final mass of 6620 grams.

$$Mass = \left[\frac{100 - (V_{at} + F)100}{100} \right] G_{mm} \times 176.7147 \times H \quad (19)$$

Where:

V_{at} = target air void content

F = air void adjustment factor (1.0 for fine-graded and 1.5 for coarse-graded mixtures)

G_{mm} = theoretical maximum specific gravity of the mix

H = sample height, cm

A second sample was generated to 180 mm height using the aforementioned adjusted mix mass and successfully compressed to 180 mm. Having become a trial and error process, two subsequent samples were made using a slightly lowered mass of 6,600 grams. The following day air voids were determined by running both CoreLok and SSD bulk specific gravity tests. All four samples were a VTM of approximately 12 percent which was significantly higher than the target air void content of 7.0 ± 0.5 percent. Also, the absorption was 5.5 percent which was also exceedingly high.

To verify these values, one bulk pill was made using the remaining GR465 material. The VTM was 10 percent as opposed to the target 4 ± 0.5 percent and had a high absorption of 3.0 percent. Marshall verification pills were compacted to verify the mixes. The appropriate traffic counts (50 or 75 hammer drops) were found in the JMFs for each of the remaining eight Marshall mixes. Three verification pills for each were made using the Marshall hammer. Figure

14 displays the eight Marshall sets made following ASTM D6929. Next, VTM for each Marshall sample was determined using three methods: CoreLok, SSD, and Dimensional. None of the mixes showed cause for concern.

Figure 14: Marshall Pills made at the WVDOH site in Charleston, WV

To verify the sole Superpave mix (JFA429), two bulk verification samples were made. They came out to be reasonable so no further investigation was needed. All verification data are found in Appendix B.

From this information, it was decided to move forward using the SGC for compaction. Sample height was lowered to 170 mm from 180 mm to negate the prior issue of fitting required mix mass in the mold. As previously mentioned, pills were made with the assumption that each mix set reached absorption and aging when mixed at the mixing plants. Mixes were heated to uniform temperature using JMF compaction temperatures, removed, weighed to required mix mass, placed in the SGC mold, compacted using the SGC, and cooled in the mold for 30 minutes to one hour. Next, the sample was removed and set to cool for approximately 16 hours.

The following day, G_{mb} and VTM measurements were obtained using CoreLok, SSD, and Dimensional. The CoreLok machine had not been used on full sized (170 mm) compacted specimen in the WVU laboratory. To make this feasible, some adjustments were made to get

VTM measurements using CoreLok (Appendix F). An image of a CoreLok vacuum-sealed gyratory sample can be seen in Figure 15.

Figure 15: *CoreLok Vacuum-Sealed Gyratory Sample*

Equation 19 was not accurate for the first Marshall mix evaluated. Instead, high and low mix masses were estimated and compacted for each mix. From here air voids were calculated for the gyratory samples. The correlation between a compacted specimen and a cored and sawed specimen VTM was determined for each mix type. Using the laboratory core drill and wet saw, specimens were cut to the AASHTO PP 60 required tolerances displayed in Table 10. Linear interpolation using the CoreLok gyratory VTMs was used to determine mass correlations. The CoreLok measurement was used because it is the WVDOH preferred method. Occasionally, high and low samples fell within the 7.0 ± 0.5 percent range requiring only minor adjustments while some required extrapolation.

Table 10: Test Specimen Tolerances

Item	Specification
Average Diameter	98 to 104 mm
Standard Deviation of Diameter	≤ 1.0 mm
Height	147.5 to 152.5 mm
End Flatness	≤ 0.5 mm
End Perpendicularity	≤ 1.0 mm

The mix masses and air voids used for dynamic modulus, flow number, and fatigue testing are summarized in Table 11. The dynamic modulus and flow number samples were cut to 150 mm while the fatigue samples were trimmed to 130 mm. It was found the shorter fatigue samples had lower air voids than the taller samples. It is hypothesized this was the result of removing more of the lower density material from the ends of the fatigue samples. This is discussed further in the Fatigue Procedure section.

Table 11: Mix Masses Placed in Mold Used for Each Sample Set

Mix	DM/FN Mass (g)	FT Mass (g)	AVG VTM (%)
AA937	6,650	6,650	7.0
JAP909	7,115	7,115	6.6
JFA060	6,750	6,727	7.0
JFA115	6,735	6,720	6.8
JFA429	6,800	6,745	6.7
KP483	6,675	6,675	6.7
WVP523	6,735	6,720	6.7
WVP766	6,705	6,680	6.8
WVP882	6,585	6,560	6.8

Dynamic Modulus and Specimen Uniformity

Sample specifications for dynamic modulus and flow number samples per AASHTO PP 60 are listed in Table 10. End flatness and perpendicularity were checked along with height prior to running all three VTM methods on cored and sawed samples. Additionally, to avoid unnecessary exposure to light and excess oxygenation, samples were stored in plastic bags and placed in a dark cabinet as seen in Figure 16. All samples were tested within two weeks of being cored and sawed.

Figure 16: Specimen Storage

As previously mentioned, all mix designs contain PG 64-22 binder so every sample was run using the same temperatures and frequencies listed in Table 3. Prior to testing, the samples were temperature conditioned to the test temperatures. A dummy sample containing a thermometer drilled into its core was used to monitor conditioning temperatures. Images of the equipment are available in Appendix F. Devcon 5-minute Epoxy Gel was used to adhere gauge points to samples.

Although dynamic modulus testing is considered nondestructive, testing at the lower temperatures and higher frequencies could cause the least damage while the higher would theoretically cause the most. Therefore, specimens were first tested at 4°C, then 20°C, and lastly at 40°C to avoid any discrepancies in the material property evaluation. After testing was completed, the dynamic modulus samples were cut into thirds and used to assess specimen uniformity per AASHTO PP 60. Figure 17 summarizes the steps taken to identify mix masses and verify specimen uniformity.

Figure 17: Flow Diagram of Air Void Uniformity Evaluation

Fatigue Procedure

The first fatigue set contained one sample from each mix type. Following AASHTO TP 107, samples were cut down to 130 mm height. The most compactive effort occurs toward the center of a SGC sample so there was concern that some samples would fall out of the VTM range. While the target air void thirds showed no indication for concern, this step was still deemed necessary.

As anticipated, there were issues with samples falling out of the VTM specifications. Minor adjustments were made to the mix masses throughout fatigue testing to avoid subsequent samples from falling out of range (Table 11). For most mix sets, there was not enough mix to repeat the high and low air void procedure to pinpoint the mix mass required for the shorter samples. Six of the 27 fatigue samples fell below 6.5 percent. These samples are bolded in Table 14. Since Witczack et al. (2013) found that fatigue results were not sensitive to air voids, the samples that were out of the target range were tested for fatigue.

The test specification calls for a minimum of three samples so three replicates for each mix were made. A combination of Devcon 10110 and resin was used to adhere samples to the end platens per the test specification protocol. An additional step of heating end platens to 40°C facilitated better adhesion of the steel putty to sample interface. Testing temperature was determined using LTPPBind 98 percent reliability climatic Performance Grade (PG) for Morgantown, WV. The high temperature was 58°C and the low was -22°C. Using Equation 20, the final testing temperature for all fatigue testing was determined to be 15°C.

$$T(^{\circ}C) = \frac{\text{High temperature binder PG grade} - \text{Low temperature binder PG grade}}{2} - 3 \quad (20)$$

From AASHTO TP 107, the second and third fatigue replicate micro strain values are adjusted according to number of cycles to failure (N_f) from the first completed test as seen in Table 12. Fatigue tests were performed for one of the three replicates for all of the mixes in order to determine the initial N_f for each mix. Two samples from the first round of testing did not meet an ending criteria: AA937 and WVP882. AA937 sample 5 reached 4,620 cycles before the AMPT encountered an LVDT error. When the error occurred, the sample had reached 15 percent

of its dynamic modulus. Reviewing the data confirmed that the number of cycles to failure would not have exceeded the 5,000 cycle limit. Therefore, the N_f range 1,000 to 5,000 was used for replicate micro strain adjustments. WVP882 S7 failed at 30,710 cycles at approximately 30 percent of the dynamic modulus criteria. The next threshold value cutoff is 100,000 cycles. Therefore, N_f range 20,000 to 100,000 micro strain adjustments were used. Three replicates from each mix type were tested per the test protocol with subsequent replicates tested at the appropriate adjusted micro strain values which can be seen in Table 13.

Table 12: On-specimen Strain Adjustments for Second and Third Fatigue Specimen

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

Table 13: Cycles to Failure Micro Strain Adjustments for Replicates

Mix	Nr	$\epsilon_{os1} = 300$	ϵ_{os2}	ϵ_{os3}	Nr Range
AA937	4,620	300	250	200	$1,000 < N_{fl} < 5,000$
JAP 909	7,190	300	350	250	$5,000 < N_{fl} < 20,000$
JFA060	7,350	300	350	250	$5,000 < N_{fl} < 20,000$
JFA115	22,640	300	400	350	$20,000 < N_{fl} < 100,000$
JFA429	3,670	300	250	200	$1,000 < N_{fl} < 5,000$
KP483	13,150	300	350	250	$5,000 < N_{fl} < 20,000$
WVP523	2,950	300	250	200	$1,000 < N_{fl} < 5,000$
WVP766	15,840	300	350	250	$5,000 < N_{fl} < 20,000$
WVP882	30,710	300	400	350	$20,000 < N_{fl} < 100,000$

For the third round of testing, upon test completion samples were pulled apart using the AMPT hydraulics. This step was added to identify where the sample failed. In all but two cases, the samples separated within the 70 mm gauge length.

Table 14 summarizes all fatigue samples including: the VTM of each sample; dynamic modulus from the fingerprint test; dynamic modulus ratios (DMR); if an LVDT error occurred during the test; if there was a phase angle drop; and where the sample fractured with respect to the gauge points. In the Error column, Completed indicates no LVDT error occurred. For

fracture location, Middle means the failure fell within all three gauge point sets, Figure 18, and End means the sample broke outside the gauge points. One sample (JFA429 S8) cracked below two gauge point sets and within one set (Middle/End). Also, dynamic modulus ratio (DMR) and fingerprint dynamic modulus values are reported. A DMR value between 0.9 and 1.1 guarantees the linear viscoelastic properties obtained from the dynamic modulus tests can be used effectively in S-VECD analysis (Kim, 2015). Two samples fell outside of this range (AA937 S5 and JFA429 S6). However, the rationale for this recommendation is not documented and there is no discussion of the consequences of having a DMR outside this range. It should be noted that all samples that fell outside the air void range remained within the aforementioned DMR range except JFA429 sample 6.

Figure 18: KP483 Sample 8 Middle Failure

Table 14: Fatigue Testing Compilation

Mix	REP	VTM (%)	E* _{finger} (MPa)	DMR	Error	Phase Angle Drop	Failure Location
AA937	1 (S5)	7.0	11,379	1.2	LVDT 1	No	-
	2 (S6)	6.4	11,140	1.1	LVDT 3	Yes	Middle
	3 (S7)	6.3	11,349	1.1	LVDT 1	Yes	Middle
JAP909	1 (S6)	6.4	11,859	1.1	Completed	No	-
	2 (S7)	6.7	11,921	1.1	Completed	Yes	-
	3 (S8)	6.7	11,803	1.1	LVDT 3	Yes	Middle
JFA060	1 (S5)	6.9	9,502	1.0	LVDT 1	Yes	-
	2 (S6)	6.3	10,447	1.1	Completed	No	-
	3 (S7)	7.0	10,028	1.0	Completed	No	Middle
JFA115	1 (S6)	7.0	8,686	1.0	Completed	No	-
	2 (S7)	6.5	8,697	1.0	LVDT 1	Yes	-
	3 (S8)	6.9	9,405	1.0	Completed	Yes	Middle
JFA429	1 (S6)	6.3	11,478	1.2	Completed	Yes	-
	2 (S7)	6.5	10,234	1.1	LVDT 1	Yes	-
	3 (S8)	6.9	10,244	1.1	LVDT 3	Yes	Middle/End
KP483	1 (S6)	6.5	8,161	0.9	Completed	Yes	-
	2 (S7)	6.8	8,995	1.0	LVDT 2	Yes	-
	3 (S8)	6.7	9,688	1.1	LVDT 2	No	Middle
WVP523	1 (S6)	7.2	10,763	1.1	LVDT 2	Yes	-
	2 (S7)	6.8	10,720	1.1	LVDT 2	Yes	End
	3 (S8)	6.7	10,555	1.0	LVDT 3	No	Middle
WVP766	1 (S6)	6.7	9,757	1.1	LVDT 2	Yes	-
	2 (S7)	6.7	9,678	1.1	LVDT 3	Yes	-
	3 (S8)	7.0	9,231	1.0	LVDT 3	Yes	Middle
WVP882	1 (S7)	6.3	9,420	1.1	LVDT 2	No	-
	2 (S8)	6.7	9,680	1.1	Completed	Yes	-
	3 (S9)	6.7	8,980	1.0	Completed	Yes	Middle

Flow Number Procedure

The flow number specimen conditioning procedure was not performed in the laboratory for the plant-produced mixes, it was assumed that mixes met full absorption and aging at the HMA plants. This is the accepted procedure specified by the WVDOT for testing plant produced quality control samples. Four flow number replicates were made at 7.0 ± 0.5 percent air voids to evaluate the rutting resistance. All samples used for flow number testing met AASHTO PP 60 precision standards and air void content of 7.0 ± 0.5 percent except one, WVP523 S9, which fell out of air void range. Two mixes, JFA115 and JFA429, have only three and two replicates because not enough mix was available to make four samples.

Temperatures for the two mix types analyzed (Wearing I and Base II/19mm) were determined using LTPPBind Version 3.1 Beta software. The equation provided in the software for LTPP High Pavement Temperature Model was used to determine an initial temperature in the Morgantown, WV, area from the two locations provided within the software. The locations were Morgantown Municipal AP (WV6202) and Morgantown L & D (WV6212). The equation and variables are listed in Equation 21 and values used are displayed in Table 15.

$$T_{pav} = 54.32 + 0.78 T_{air} - 0.0025 Lat^2 - 15.1 \log_{10}(H + 25) + z \sqrt{9 + 0.61 S_{air}^2} \quad (21)$$

Where:

T_{pav} = the high asphalt cement pavement temperature below surface, °C

T_{air} = the high air temperature, °C

Lat = the latitude of the section, °

H = the depth to surface, mm

S_{air} = the standard deviation of the 7 day mean air temperature, °C

z = the standard normal distribution table

Table 15: LTPPBind Equation Values Used

T_{air}	Latitude	H(mm)	z at 50% reliability	S_{air}
32.4	39.6428	25/50	0	1.7

First, the program averaged the two Morgantown stations to be 49.9°C at 50 mm depth. However, the calculated value using Equation 21 at the two locations resulted in an average value of 47.2°C (47.1 and 47.3°C). The results from the equation varied slightly from the values provided in the software so 0.4 was added to the average value of the two for a final value of 47.6°C. From here the program value and the adjusted calculated value were averaged. For 19 mm mixes, the test temperature used was 49°C.

The same procedure was conducted for the Wearing I (9.5 mm) mixes evaluated, but at a depth of 25 mm below the ground surface. The program average from the two Morgantown stations was 51.9°C. However, the calculated value using Equation 21 resulted in an average

value of 49.9°C (49.9 and 49.8°C) so 0.4 was added resulting in a final value of 50.3°C. The final averaged value was calculated to 51°C. Similar to dynamic modulus testing, a dummy sample containing a thermometer placed in its center was placed in the conditioning oven with the samples prior to testing.

All flow number testing was completed following and using the aforementioned information. Once testing was completed, two methods were used to find the flow number: the AMPT averaging method and the Francken model. The Francken model fitting coefficients were found using nonlinear regression in MATLAB. The code can be seen below:

```
n = table(Cycle, Microstrain);

modelfun = @(x,n) (x(1)*(n(:,1).^(x(2))))+(x(3)*(exp(x(4)*n(:,1))-1));

beta0 = [600 0.5 100 0.001];

mdl = fitnlm(n,modelfun,beta0)
```

Figure 19 displays the Francken model fitted equation and corresponding AMPT permanent axial strain data from AA937 sample 8 flow number test. All Francken model fitting coefficients are located in Appendix E.

Figure 19: AA937 S8 AMPT Permanent Axial Strain and Francken Model

Chapter 4: Results and Discussion

This section presents testing results and all additional analyses performed. Since this is an evaluation of numerous mixes provided from contractors throughout WV, multiple comparisons are made ranging from similar mix types to mix types provided from a manufacturer to all mixes. In the data tables, samples are identified by the producer mix identifications in one column and if needed a second column shows the replicate number. For example, S4 is the fourth replicate of a mix.

Maximum Specific Gravity

Laboratory G_{mm} values varied from JMF values. All but one mix had a higher G_{mm} value as seen in Table 16. Only two of the samples fell within the acceptable range of 0.024 for AASHTO T 209 multilaboratory precision. There can be multiple reasons why the G_{mm} from mix design does not match the G_{mm} from plant produced mixes such as variations in percent binder, stockpile gradations, etc. The complete laboratory test data are available in Appendix B. These data demonstrate the single-operator precision of the tests done during this research are within variability allowed in AASHTO T 209. Proceeding forward, the laboratory G_{mm} values were used for all subsequent calculations.

Table 16: Variation in G_{mm} between JMF and Laboratory

Mix	JMF G_{mm}	AVG Lab G_{mm}	Difference
AA937	2.447	2.489	0.042
JAP909	2.613	2.644	0.031
JFA060	2.500	2.528	0.028
JFA115	2.459	2.494	0.035
JFA429	2.500	2.530	0.030
KP483	2.440	2.471	0.031
WVP523	2.473	2.493	0.020
WVP766	2.476	2.475	-0.001
WVP882	2.408	2.447	0.039

Assessing Sample Uniformity

To preserve materials, air void uniformity was evaluated using the samples tested for dynamic modulus. Air void uniformity was conducted using AASHTO PP 60 with the exception that sample uniformity was conducted at 7.0 ± 0.5 percent and not 5.0 ± 0.5 percent air voids as the test specifies. It was more beneficial to investigate uniformity at 7.0 ± 0.5 percent given all test samples were made at this target. Each of the three 150 mm replicates was cut into equal thirds (approximately 50 mm). Next, the samples were measured using the SSD, CoreLok, and Dimensional methods and the averaged G_{mb} was computed.

As previously mentioned, the AASHTO PP 60 test statistic must be less than 2.78 to reject the null hypothesis that the sample means are equal. All mixes except WVP523 and WVP882 met air void uniformity test. WVP523 did not meet requirements for three of the four G_{mb} methods evaluated (SSD, CoreLok, and average) in the top-middle comparison while WVP882 did not meet requirements in SSD for middle-bottom thirds. The t-statistics for each method can be seen in Table 17.

Figure 20 displays images of one WVP523 sample at four angles rotated approximately ninety degrees. Visually there appears to be segregation with irregular heterogeneity between the bottom and top sample halves and from one side to the other. In the bottom portion of the rightmost image, no large aggregates can be seen. This irregularity may have led to the top-middle third not meeting acceptable air void uniformity.

Figure 20: WVP523 Sample

Table 17: T-statistic for the Three G_{mb} Methods and Averaged Values

Mix	REP	G _{mb} Method t-statistics											
		SSD			CL			Dim.			AVG		
		T-M	B-M	T-B	T-M	B-M	T-B	T-M	B-M	T-B	T-M	B-M	T-B
AA937	1 (S1)	0.186	0.010	0.775	0.108	0.537	0.658	0.099	0.586	0.555	0.017	0.685	0.659
	2 (S3)												
	3 (S4)												
JAP909	1 (S2)	1.048	0.036	0.520	0.307	0.205	0.378	0.253	0.223	0.616	0.546	0.374	1.010
	2 (S3)												
	3 (S4)												
JFA060	1 (S2)	0.675	0.351	0.181	0.346	0.107	0.401	0.002	0.127	0.117	0.157	0.134	0.277
	2 (S3)												
	3 (S4)												
JFA115	1 (S3)	0.555	0.215	0.403	0.840	0.213	0.526	0.736	0.915	1.247	0.794	0.481	0.763
	2 (S4)												
	3 (S5)												
JFA429	1 (S3)	0.838	2.090	2.710	0.061	1.044	2.393	0.871	1.486	0.392	0.889	2.408	2.073
	2 (S4)												
	3 (S5)												
KP483	1 (S2)	0.501	0.724	1.295	0.584	0.910	1.044	0.322	0.741	0.853	0.475	0.787	1.064
	2 (S3)												
	3 (S4)												
WVP523	1 (S3)	3.335	0.634	1.194	7.691	2.048	1.699	1.680	1.249	0.156	4.191	1.281	1.009
	2 (S4)												
	3 (S5)												
WVP766	1 (S3)	1.896	0.384	1.405	1.948	0.647	0.659	0.094	0.370	0.570	1.113	0.158	0.857
	2 (S4)												
	3 (S5)												
WVP882	1 (S1)	0.713	3.023	0.633	0.614	1.568	0.148	1.309	1.949	0.190	0.851	2.135	0.288
	2 (S3)												
	3 (S4)												

Only one of the nine mixes was evaluated to have high variability when considering the CoreLok results, WVP523. For this sample the t-statistic was much higher than the t-statistics for the SSD and Dimensional methods. This suggests there was an issue with the CoreLok testing of this sample. The overall results in Table 17 demonstrate the air void variability within the samples is reasonable.

Comparing Sections and Intact Sample Air Voids

During the analysis of the sections, it was noticed that the air voids of the sections were higher than the air voids of the intact samples by 0.4 percent as compiled in Table 18. This issue is not addressed in AASHTO PP 60. The reason for the difference is not apparent and no further analysis was conducted.

Table 18: Comparison of Sample Third Air Void Averages to Entire Sample Air Void Average

Mix	REP	Ranking			AVG (%)			Thirds AVG	Intact Sample	Difference
		T	M	B	T	M	B			
AA937	1 (S1)	1	0	-1	8.2	7.9	7.0	7.7	7.3	0.4
	2 (S3)	0	1	-1	7.6	8.3	7.5	7.8	7.4	0.4
	3 (S4)	1	-1	0	8.0	7.7	8.0	7.9	7.5	0.4
JAP909	1 (S2)	1	0	-1	7.4	6.9	6.4	6.9	6.6	0.3
	2 (S3)	1	-1	0	7.5	7.0	7.5	7.3	6.9	0.4
	3 (S4)	-1	1	0	7.0	7.6	7.2	7.3	6.9	0.4
JFA060	1 (S2)	1	-1	0	8.1	7.6	7.9	7.9	7.5	0.4
	2 (S3)	0	1	-1	7.5	7.5	7.2	7.4	7.1	0.3
	3 (S4)	0	-1	1	7.3	7.3	7.3	7.3	7.0	0.3
JFA115	1 (S3)	1	0	-1	7.1	7.0	6.6	6.9	6.5	0.4
	2 (S4)	1	0	-1	7.5	7.1	6.6	7.1	6.6	0.5
	3 (S5)	-1	0	1	7.0	7.2	7.6	7.3	6.8	0.5
JFA429	1 (S3)	0	1	-1	7.1	7.7	6.7	7.2	6.9	0.3
	2 (S4)	0	1	-1	7.2	7.3	7.1	7.2	6.8	0.4
	3 (S5)	1	0	-1	7.1	6.9	6.8	6.9	6.5	0.4
KP483	1 (S2)	1	0	-1	8.2	7.6	7.1	7.6	7.2	0.4
	2 (S3)	1	-1	0	7.2	6.7	6.8	6.9	6.5	0.4
	3 (S4)	-1	1	0	6.8	7.0	6.9	6.9	6.6	0.3
WVP523	1 (S3)	1	-1	0	7.8	7.0	7.0	7.3	6.7	0.6
	2 (S4)	1	-1	0	7.7	7.3	7.4	7.5	6.8	0.7
	3 (S5)	1	-1	0	8.2	7.0	8.1	7.8	7.5	0.3
WVP766	1 (S3)	1	0	-1	7.5	6.9	6.7	7.0	6.6	0.4
	2 (S4)	0	-1	1	7.1	6.9	7.6	7.2	7.0	0.2
	3 (S5)	1	0	-1	7.7	7.6	7.2	7.5	7.2	0.3
WVP882	1 (S1)	1	-1	0	7.9	6.5	7.2	7.2	6.9	0.3
	2 (S3)	-1	0	1	6.7	7.2	7.3	7.1	6.7	0.4
	3 (S4)	0	-1	1	7.0	6.8	7.3	7.0	6.8	0.2
Total	1's	16	6	5						
	0's	7	10	10						
	-1's	4	11	12						

The middle section should have the lowest air void content because the most compactive effort occurs towards the center of a sample during compaction. However, this was not the case. The highest and lowest thirds varied among Top (T), Middle (M), and Bottom (B) thirds. For further review a 1, 0, or -1 was assigned to the highest, second highest, and lowest air void measurement for each sample third, Table 18. The hundredth decimal place was used when two air void measurements were equal. If the Top, Middle, and Bottom sections were always highest, second highest, and lowest the sum of the columns would be 27, 0, and negative 27. However, this was not the case. The Top section resulted in the highest summed value inferring the highest air void content occurred more frequently in the Top sample sections. The Middle and Bottom

sections ended with sums of negative five and negative seven. This infers the second highest or the lowest air void content occurred more frequently in the Middle and Bottom sections than in the Top.

An additional comparison of sections was completed using the 27 air void values for top, middle, and bottom in Table 28. An overall t-test comparing all top-middle, middle-bottom, and top-bottom air void measurements was completed. Respectively, a p-value of 0.06 to 0.6 was found when comparing the top-middle and bottom-middle and, therefore, fail to reject the null hypothesis of equal means for these two evaluations. The top-bottom comparison resulted in a p-value of 0.03 meaning there was sufficient evidence to reject the null hypothesis of equal means for this comparison.

Methods for Measuring G_{mb}

Next, line of equality graphs were made to compare the three G_{mb} methods. Both G_{mb} values from the gyratory specimen (Before) and the cored/sawed (After) are plotted in Figures 21-23.

Figure 21: Line of Equality Chart SSD Verses CoreLok Method

Figure 22: Line of Equality Chart Dimensional Verses SSD Method

Figure 23: Line of Equality Chart Dimensional Verses CoreLok Method

Each After comparison has an R^2 value higher than 0.99. This infers a good correlation between any two of the three bulk specific gravity methods reviewed. The G_{mb} values for compacted (Before) samples had lower R^2 values for each comparison. SSD compared with Dimensional resulted in the best After comparison, but the worst for Before. Griffith (2009) found that the difference between SSD and CoreLok method G_{mb} values diverged at high air voids (5 to 8 percent). The air void content in this study was 7.0 ± 0.5 percent so the correlation between CoreLok and SSD is consistent with Griffith's findings.

Effective Sample Trimming on Air Voids

Line of equality graphs using CoreLok VTM values were plotted for Before and After cored and sawed samples. Figure 24 displays all 9.5 mm NMA mixes and Figure 25 displays 19 mm NMA mixes. The 9.5 mm NMA show a good correlation between Before and After VTM measurements with an R^2 value of 0.96. The 19 mm NMA plot has a lower R^2 value of 0.80. The larger NMA could have more variability between the Before and After VTMs.

Figure 24: 9.5 mm NMA CoreLok VTM Before and After Trimming

Figure 25: 19 mm NMA CoreLok VTM Before and After Trimming

The equations in Figure 24 and 25 may be used to estimate if a compacted sample will have an acceptable VTM for AMPT testing after trimming. Thus, trimming samples can be avoided for samples that will not meet the AMPT requirements for VTM.

Air Voids of AMPT Samples

All dynamic modulus (DM) samples were made and tested before moving to fatigue (FT) testing. Next, the same was done with fatigue samples prior to flow number (FN) testing. To check the target of 7.0 ± 0.5 percent VTM range remained consistent between test apparatuses, all air voids were compared using a student t-test. For SSD, CoreLok, Dimensional, and Averaged air void values, the means of FN compared to DM test specimens were equal. FT compared with DM means were not equal for SSD, CoreLok, and Average, but were equal for the Dimensional measurements. FT compared with FN were not equal for all air void methods. Variability among mixes could influence the statistical comparison of the methods so each set of test replicates were compared within their mix sets (i.e. AA937 DM compared only to AA937 FN). Only the

average air voids were reviewed for DM-FT, FN-FT, and DM-FT and means were found to be equal within each mix design for each set of testing completed. All air void measurements are available in Appendix B.

Dynamic Modulus and Phase Angle

Phase angle (δ) and modulus (E^*) were obtained at the various testing temperatures for all nine mixes with three replicates per mix. Table 19 contains all phase angle averages and standard deviations from AMPT testing.

Table 19: Phase Angles Averages and Standard Deviations from DM Testing

Mix	STAT	Test Temperature									
		4°C			20°C			40°C			
		0.1 Hz	1.0 Hz	10 Hz	0.1 Hz	1.0 Hz	10 Hz	0.01 Hz	0.1 Hz	1.0 Hz	10 Hz
AA937	AVG	15.2	11.4	8.8	28.4	23.3	17.9	28.2	32.1	30.3	32.9
	SD	0.7	0.5	0.4	0.7	0.6	0.4	1.0	0.9	6.6	0.6
JAP909	AVG	21.7	16.1	11.7	33.5	29.7	23.6	22.5	28.2	32.5	38.4
	SD	1.0	0.9	0.7	0.1	0.1	0.0	0.5	0.4	2.4	0.9
JFA060	AVG	18.5	13.4	9.8	31.2	27.5	21.7	23.1	28.0	31.0	35.6
	SD	0.3	0.3	0.3	0.5	0.6	0.6	1.4	0.9	3.3	0.6
JFA115	AVG	17.5	12.9	9.8	29.8	25.8	20.7	24.2	28.7	30.0	33.7
	SD	0.2	0.3	0.3	0.3	0.3	0.3	0.6	0.5	3.3	0.6
JFA429	AVG	17.8	13.0	9.6	29.7	25.8	20.5	22.5	27.2	29.6	33.8
	SD	0.2	0.2	0.3	0.1	0.2	0.2	0.9	0.7	3.3	0.2
KP483	AVG	16.5	12.5	9.7	28.7	24.4	19.3	26.7	30.8	30.1	32.8
	SD	0.4	0.3	0.3	0.6	0.5	0.4	0.7	0.8	5.3	0.6
WVP523	AVG	16.4	12.3	9.5	30.3	25.4	19.7	27.1	32.1	31.7	34.6
	SD	0.3	0.1	0.1	0.5	0.4	0.3	0.3	0.5	5.9	0.9
WVP766	AVG	18.0	13.5	10.2	31.3	26.4	20.5	26.2	31.7	32.2	35.0
	SD	0.5	0.4	0.3	0.3	0.1	0.1	0.5	0.6	5.2	0.4
WVP882	AVG	18.5	13.7	10.4	31.8	27.6	21.9	26.1	31.6	32.8	36.2
	SD	0.7	0.5	0.4	0.6	0.6	0.4	1.0	0.6	4.1	0.4

Table 20 contains all the dynamic modulus values from testing and Table 21 displays the averages, standard deviation, and coefficient of variation for each mix set.

Table 20: Dynamic Modulus Values (MPa)

Mix	REP	Test Temperature									
		4°C			20°C			40°C			
		0.1 Hz	1.0 Hz	10 Hz	0.1 Hz	1.0 Hz	10 Hz	0.01 Hz	0.1 Hz	1.0 Hz	10 Hz
AA937	1 (S1)	8,684	11,791	15,000	2,713	4,853	7,754	180.4	407.3	977.8	2,195
	2 (S3)	8,275	11,448	14,768	2,669	4,849	7,878	186.6	388.6	909.5	2,107
	3 (S4)	8,677	11,675	14,701	2,536	4,669	7,540	154.9	341.4	845.2	2,022
JAP909	1 (S2)	7,483	11,782	16,800	1,904	4,181	7,815	127.1	233.7	567.6	1,493
	2 (S3)	8,396	12,821	17,817	2,001	4,282	7,859	110.8	220	574.5	1,610
	3 (S4)	9,283	14,390	19,908	2,106	4,569	8,475	117.3	228.5	595.3	1,644
JFA060	1 (S2)	8,277	11,857	15,491	2,100	4,184	7,262	147.7	272.4	639.9	1,667
	2 (S3)	7,363	10,711	14,139	1,761	3,590	6,399	125.4	239.9	570.3	1,408
	3 (S4)	8,961	13,041	17,248	2,249	4,503	7,921	184.3	338.2	788	1,902
JFA115	1 (S3)	7,800	11,188	14,756	2,012	3,843	6,628	164.9	318.8	735.7	1,709
	2 (S4)	8,133	11,947	15,802	2,172	4,153	7,137	149.6	295.1	704.5	1,705
	3 (S5)	7,127	10,213	13,555	2,002	3,749	6,330	166.1	303.8	661.3	1,557
JFA429	1 (S3)	8,492	12,165	15,932	2,396	4,577	7,786	197.3	349.6	783.3	1,938
	2 (S4)	7,730	10,971	14,290	2,245	4,277	7,224	165.5	299.3	681.5	1,697
	3 (S5)	8,245	11,679	15,073	2,213	42,10	7,176	204.5	349.9	753.3	1,764
KP483	1 (S2)	7,107	9,951	13,005	2,241	4,092	6,715	161.6	331.6	775.5	1,771
	2 (S3)	8,375	11,792	15,387	2,316	4,335	7,321	164.6	360.3	867.5	2,028
	3 (S4)	7,941	10,979	14,154	2,320	4,199	6,917	197.2	403.6	913.3	1,988
WVP523	1 (S3)	9,211	12,734	16,420	2,560	4,711	7,827	177.9	402.9	981.5	2,238
	2 (S4)	8,939	12,511	16,217	2,466	4,604	7,721	151.5	340.5	846.9	1,986
	3 (S5)	8,559	12,085	15,808	2,296	4,344	7,368	129.8	282.2	706.5	1,698
WVP766	1 (S3)	7,983	11,396	14,995	2,064	4,006	6,900	129.9	276.6	683.8	1,699
	2 (S4)	7,013	9,844	13,220	1,958	3,840	6,543	131.4	298.7	752	1,894
	3 (S5)	7,116	10,265	13,741	2,008	3,965	6,813	128.1	289.3	743.6	1,823
WVP882	1 (S1)	7,923	11,461	15,116	1,861	3,751	6,699	111.4	241.7	628.2	1,592
	2 (S3)	6,965	10,267	13,879	1,753	3,486	6,228	109.2	226	576.8	1,484
	3 (S4)	7,574	10,912	14,477	1,899	3,683	6,463	114	250.3	639.7	1,586

Table 21: Dynamic Modulus Averages, Standard Deviation, and Coefficient of Variation (MPa)

Mix	REP	Test Temperature									
		4°C			20°C			40°C			
		10 Hz	1.0 Hz	0.1 Hz	10 Hz	1.0 Hz	0.1 Hz	10 Hz	1.0 Hz	0.1 Hz	0.01 Hz
AA937	AVG	14,823	11,638	8,545	7,724	4,790	2,639	2,108	911	379	174
	SD	156.9	174.5	234.1	171.0	105.1	92.2	86.5	66.3	34.0	16.8
	CV (%)	1.1	1.5	2.7	2.2	2.2	3.5	4.1	7.3	9.0	9.7
JAP909	AVG	18,175	12,998	8,387	8,050	4,344	2,004	1,582	579	227	118
	SD	1,584.6	1,312.9	900.0	369.0	201.3	101.0	79.2	14.4	6.9	8.2
	CV (%)	8.7	10.1	10.7	4.6	4.6	5.0	5.0	2.5	3.0	6.9
JFA060	AVG	15,626	11,870	8,200	7,194	4,092	2,037	1,659	666	284	152
	SD	1,558.9	1,165.1	801.8	763.3	463.4	250.1	247.1	111.2	50.1	29.7
	CV (%)	10.0	9.8	9.8	10.6	11.3	12.3	14.9	16.7	17.7	19.5
JFA115	AVG	14,704	11,116	7,687	6,698	3,915	2,062	1,657	701	306	160
	SD	1,124.4	869.2	512.5	408.1	211.4	95.4	86.6	37.4	12.0	9.2
	CV (%)	7.6	7.8	6.7	6.1	5.4	4.6	5.2	5.3	3.9	5.7
JFA429	AVG	15,098	11,605	8,156	7,395	4,355	2,285	1,800	739	333	189
	SD	821.3	600.4	388.8	339.2	195.4	97.7	124.4	52.3	29.1	20.8
	CV (%)	5.4	5.2	4.8	4.6	4.5	4.3	6.9	7.1	8.7	11.0
KP483	AVG	14,182	10,907	7,808	6,984	4,209	2,292	1,929	852	365	174
	SD	1,191.2	922.6	644.4	308.6	121.8	44.5	138.3	70.2	36.2	19.7
	CV (%)	8.4	8.5	8.3	4.4	2.9	1.9	7.2	8.2	9.9	11.3
WVP523	AVG	16,148	12,443	8,903	7,639	4,553	2,441	1,974	845	342	153
	SD	311.7	329.7	327.5	240.3	188.7	133.8	270.2	137.5	60.4	24.1
	CV (%)	1.9	2.7	3.7	3.1	4.1	5.5	13.7	16.3	17.7	15.7
WVP766	AVG	13,985	10,502	7,371	6,752	3,937	2,010	1,805	726	288	130
	SD	912.4	802.6	532.8	186.2	86.5	53.0	98.7	37.2	11.1	1.7
	CV (%)	6.5	7.6	7.2	2.8	2.2	2.6	5.5	5.1	3.8	1.3
WVP882	AVG	14,491	10,880	7,487	6,463	3,640	1,838	1,554	615	239	112
	SD	618.6	597.6	484.8	235.5	137.6	75.7	60.7	33.5	12.3	2.4
	CV (%)	4.3	5.5	6.5	3.6	3.8	4.1	3.9	5.4	5.1	2.2

Each mix had coefficient of variation values below 15 percent for all dynamic modulus testing conducted at 4°C and 20°C. As the testing temperature increased, the coefficient of variation increased in some cases. However, all testing at 40°C coefficient of variation values remained below 20 percent.

To further compare the mixes, averages for the dynamic modulus values at each temperature and frequency were calculated and plotted by NMAAS. A comparison of all Wearing I mixes provided from four different companies are compared in Figures 26-28. The same was done for all Base II/19 mm mixes provided from three separate companies and are shown in Figures 29-31.

Figure 26: Wearing I Dynamic Modulus Averages at 4°C

Figure 27: Wearing I Dynamic Modulus Averages at 20°C

Figure 28: Wearing I Dynamic Modulus Averages at 40°C

The five Wearing I mixes performed within reasonable range of one another at 4°C testing. AA937 performed at the highest value while WVP766 had the lowest average dynamic modulus at each frequency tested. Similarly, the five Wearing I mixes performed within a reasonable range of one another with AA937 performing the highest at 20°C testing. However, WVP882 had the lowest average dynamic modulus values at this testing temperature. Moreover, at 40°C the five Wearing I dynamic modulus values varied. AA937 had the highest average values at each frequency, but performed approximately two and a half times higher than the lowest performing mix which was JFA115. WVP766, WVP882, and KP483 performed similarly.

Figure 29: Base II/19mm Dynamic Modulus Averages at 4°C

Figure 30: Base II/19mm Dynamic Modulus Averages at 20°C

Figure 31: Base II/19mm Dynamic Modulus Averages at 40°C

For the three Base II and one 19 mm mix, JAP909 had the highest average dynamic modulus values at 4°C while the other three mixes performed similarly. Moreover, at 20°C the four mixes performed similarly at each frequency with some overlapping at lower frequencies. At 40°C, JAP909 performed the lowest while WVP523 performed the highest.

Master Curve Comparison

Samples were analyzed using Mastersolver Version 2.2 for each individual mix. Using the Excel solver feature provided in the spreadsheet the master curves were generated. The shape of the master curve is characterized by five parameters: β , γ , $E_{\min}$, $E_{\max}$, and ΔEA . Table 22 shows the final parameters from each mix analyzed, the averages, and the goodness of fit. All goodness of fit ratings were excellent.

Witczak et al. (2013) found the β fitting parameter varied with VTM and with binder content. For PG 64-22 binder at 7.0 percent air voids, β values were 1.529, 1.120, and 1.036 for 4.0 percent, 4.5 percent, and 5.0 percent binder content. In this research, the binder content for the mixes varies between a range of 4.6 percent and 6.1 percent. The β values in this study all vary slightly. All mixes containing RAP had higher β values (AA937, KP483, WVP523, WVP766, and WVP882) than mixes not containing RAP. Smith (2015) found a difference in the β term between 0 percent RAP and 25 percent RAP with PG 70-22 was 0.47238. While this is a different binder grade, the inclusion of RAP appears to have a correlation to the β term.

Table 22: Master Curve Final Parameters

Mix	Binder Content (%)	Max E (ksi)	Min E (ksi)	β	γ	ΔEA	Goodness of Fit		
							R^2	S_e/S_y	Rating
AA937	5.6	3,186.6	2.2	-1.356	-0.471	205,255	0.999	0.02	Excellent
JAP909	4.6	3,239.9	5.3	-1.097	-0.616	196,033	0.998	0.02	Excellent
JFA060	4.9	3,214.1	5.8	-1.045	-0.553	201,283	0.998	0.03	Excellent
JFA115	5.8	3,212.7	4.5	-1.063	-0.503	204,246	0.998	0.03	Excellent
JFA429	4.9	3,246.9	6.4	-1.049	-0.522	205,637	0.999	0.03	Excellent
KP483	5.6	3,194.7	2.8	-1.214	-0.470	200,270	0.999	0.02	Excellent
WVP523	4.6	3,230.7	2.2	-1.311	-0.485	201,316	0.999	0.02	Excellent
WVP766	5.9	3,150.2	2.0	-1.228	-0.494	192,136	0.999	0.03	Excellent
WVP882	6.1	3,163.5	2.4	-1.156	-0.511	198,081	0.998	0.03	Excellent
Average		3,204.4	3.73	-1.17	-0.51	200,473			

The Master Curves are presented in Figure 32. All MEDPG output data are in Appendix C. The curves are consistent with no clear distinction between a 9.5 mm and a 19 mm NMAS. At lower frequencies there was more variation with the curves converging at a higher reduced frequency.

Figure 32: Dynamic Modulus Master Curves

Fatigue

A summary of fatigue testing was documented in Table 14 from Chapter 3. Three failure criterion were used to evaluate a completed test: 10 percent of the initial modulus reached, an increase in phase angle followed by an immediate drop, or the number of cycles exceeding 100,000. All the tests terminated before 100,000 cycles. There were issues with LVDT errors prior to test completion and a couple samples breaking prior to test completion. However, nearly all tested fatigue samples either a drop in phase angle or 10 percent of the modulus. All fatigue data is located in Appendix D.

Alpha Fatigue

The Alpha-FatigueTM software generates an output model from dynamic modulus and fatigue replicates. Each mix type was analyzed separately with two analyses performed: one allowing the software to select the failure point (Default) and a second choosing the peak point prior to the phase angle drop (Peak). Eight of twenty-seven tests did not display the sudden phase angle drop required in the “Identify Cycle at Failure” screen. In this case, the highest graph point was selected as the failure point. An example of a sample without a phase angle drop is shown in Figure 33.

Figure 33: Alpha-Fatigue Phase Angle Failure Cycle Identification Box without Drop

KP483 fatigue test samples had one erroneous sample (S6) which was excluded for the Default analysis. Alpha-Fatigue could not find an adequate model to fit the three samples so only two were analyzed. This could affect the accuracy of the fitted model and endurance limits for this replicate set.

The K-values for Equation 15 and the damage model coefficients for both failure criteria are summarized in Tables 23 and 24. K-values differ significantly between the two failure criteria. This was further investigated in graphical comparisons shown later. Moreover, from Table 24 the r parameter increased by one magnitude when picking the cycle corresponding to the phase angle drop. The s parameter increased by approximately 0.2 when the default was used and damage coefficients a and b had minor changes between the two failure criteria.

Table 23: K-Values (psi units) from Alpha-Fatigue

Mix	Peak K_1	Default K_1	Peak K_2	Default K_2	Peak K_3	Default K_3
AA937	9.16E+08	2.83E+02	7.188	4.237	-5.106	-2.361
JAP909	2.87E+11	1.03E+07	4.505	2.899	-3.812	-2.264
JFA060	3.59E+12	4.40E+07	5.191	4.077	-4.399	-3.078
JFA115	6.88E+12	3.07E+07	5.002	3.46	-4.286	-2.659
JFA429	3.84E+19	4.03E+06	7.851	3.542	-7.098	-2.621
*KP483	1.16E+16	4.20E+05	7.612	6.153	-6.45	-4.013
WVP523	1.40E+15	9.91E+03	8.161	4.62	-6.672	-2.851
WVP766	3.30E+13	2.07E+05	6.154	3.241	-5.129	-2.202
WVP882	1.40E+10	2.81E+06	4.178	3.069	-3.423	-2.296
Asphalt Institute	0.0796		3.291		-0.854	

Table 24: Damage Model Coefficients for Both Failure Criteria

Mix	Peak a	Default a	Peak b	Default b	Both a	Peak r	Default r	Peak s	Default s
AA937	-1.92E-05	-2.68E-05	0.932	0.900	3.711	3.83E+05	8.41E+04	-0.775	-0.594
JAP909	-4.80E-04	-7.48E-04	0.667	0.623	3.361	4.15E+05	9.14E+04	-0.674	-0.593
JFA060	-1.10E-04	-1.91E-04	0.789	0.737	3.657	4.79E+05	1.33E+05	-0.706	-0.623
JFA115	-2.97E-04	-3.27E-04	0.699	0.689	3.802	5.60E+05	1.22E+05	-0.696	-0.577
JFA429	-1.37E-04	-1.08E-04	0.773	0.796	3.850	7.89E+05	9.11E+04	-0.797	-0.577
KP483	-1.47E-05	-1.22E-05	0.957	0.977	3.811	6.01E+05	2.01E+05	-0.791	-0.725
WVP523	-3.54E-05	-3.57E-05	0.885	0.883	3.629	5.37E+05	5.08E+05	-0.807	-0.637
WVP766	-1.01E-04	-9.34E-04	0.792	0.799	3.580	5.33E+05	7.90E+04	-0.747	-0.540
WVP882	-2.74E-04	-3.85E-04	0.714	0.680	3.531	3.23E+05	7.48E+04	-0.647	-0.541

Table 25 contains the micro strain endurance limits for all Alpha-Fatigue analyses and Table 26 displays the rankings of each for the Peak failure criteria. The AMPT fatigue test was performed at 15°C. However, the Alpha-Fatigue software uses transfer functions to estimate endurance limits for other temperatures. The endurance limit approximately doubled at 5, 10, 15, and 20°C and nearly tripled at 25°C for the Peak failure as compared to the Default failure.

The rankings show that using the two different criteria resulted in mixes having different endurance limits. JFA429 had the highest endurance limit when the Peak failure was used, but had the sixth lowest endurance limit when the Default was used. WVP882 and JAP909 have the lowest endurance limit micro strains in all cases.

Underwood et al. (2012) reported endurance limit values in the range 100 to 150 for mixes with an unmodified asphalt content of 4.5 to 6.1 percent. Only the 25°C test results with the Peak failure criteria in Table 25 are similar to the results reported by Underwood et al. (2012). Based on this observation, only the peak failure criteria are considered in the following. The Superpave mix (JFA429) had the highest endurance limit threshold in all cases when using Peak K-values.

Table 25: Endurance Limits from Alpha-Fatigue Outputs

Endurance Limit (micro strain)										
	5°C		10°C		15°C		20°C		25°C	
Mix	Peak	Default	Peak	Default	Peak	Default	Peak	Default	Peak	Default
AA937	51	24	55	24	61	26	70	28	91	34
JAP909	33	9	36	10	42	11	50	13	69	17
JFA060	44	21	48	23	55	26	66	30	91	39
JFA115	48	17	54	19	63	21	76	25	104	33
JFA429	67	17	75	18	90	20	111	23	154	29
KP483	64	41	70	43	82	47	97	53	131	67
WVP523	58	25	63	26	73	28	86	30	117	38
WVP766	56	16	61	16	72	18	85	20	114	25
WVP882	33	11	36	12	41	14	49	16	66	21

Table 26: Endurance Limits Ranking for Peak and Default K-values

Mix	Peak Rank				
	5°C	10°C	15°C	20°C	25°C
AA937	5	5	6	6	6/7
JAP909	8/9	8/9	8	8	8
JFA060	7	6	7	7	6/7
JFA115	6	7	5	5	5
JFA429	1	1	1	1	1
KP483	2	2	2	2	2
WVP523	3	3	3	3	3
WVP766	4	4	4	4	4
WVP882	8/9	8/9	9	9	9

Fatigue K-values, Table 23, for each mix set vary from the Asphalt Institute constants. To compare laboratory values and the fatigue equation's behavior, a dynamic modulus value of 1,310,000 psi and several strain levels were plugged into Equation 15 for each Alpha-Fatigue K-values and are plotted in Figure 34 for the Peak failure criteria. The Asphalt Institute fatigue equation has a field calibration factor of 18.4 to adjust for laboratory to field differences (ARA, Inc., 2004). Field calibration factor was removed to adjust the Asphalt Institute equation to represent laboratory results. Both the adjusted Asphalt Institute and original equations are displayed in Figure 34 for comparison.

In Figure 34, both a representative full depth and conventional pavement strain found from the KENPAVE analysis was plotted. The KENPAVE analysis is explained in more detail in the Pavement Life Prediction section. As seen in Figure 34, JFA429, a 19 mm Superpave mix, showed the best performance. WVP882, a Wearing I Marshall mix, showed the worst performance. However, all mixes tested in this study show better fatigue properties than is predicted by the adjusted Asphalt Institute equation.

Underwood et al. (2012) says the limit of asphalt concrete mixtures is the strain level at which fatigue failure occurs at 50 million cycles. This limit is plotted in Figure 34, a vertical projection from this limit to the x-axis indicates the endurance limit for the mixes. JFA429 falls at approximately 100 micro strains at the endurance limit plotted in Figure 34. This micro strain value falls between the Alpha-Fatigue endurance limits, Table 26, for 15°C and 20°C. However, JFA115 meets the endurance limit at 60 micro strains which falls between Alpha-Fatigue endurance limits from for 10°C and 15°C. Similar discrepancies were found with the other mixes.

The reason for these discrepancies could not be determined from the Alpha-Fatigue documentation.

Figure 34: Visualization of Fatigue Equations Using Peak Analyzed K-Values

Figure 35 includes Hou (2009) and Witczak et al. (2013) models (Table 4) plotted with the highest and lowest performing fatigue coefficient results from this research, Table 23. The Hou models resulted in high number of cycles to failure; the only Hou model plotted is for the lowest fatigue performance (RI19B).

Figure 35: Visual Comparison of Fatigue Equations

Pavement Life Prediction

The dynamic modulus samples were analyzed using KENPAVE. Following Smith's (2015) KENPAVE analysis, modulus verses strain graphs were created for a range of moduli (200,000 to 1,000,000 psi) for both a full-depth pavement and conventional pavement. Images of both each pavement designs are displayed in Figure 36. The KENAPAVE analysis involved some assumptions. Subbase material moduli were chosen based on past knowledge, and the pavement was analyzed as linear as opposed to viscoelastic. Also, a traditional full-depth pavement is constructed with multiple lifts with the NMAAS increasing with the depth of the lift. For this analysis the asphalt lift consisted of a single layer of the material being analyzed.

For loading, a dual axle with a 4500 pound load per tire (18-kip ESAL) and 110 psi tire pressure with a contact radius of 3.61 inches, a travel speed of 55 mph was used to calculate a frequency of 1.866 Hz. The tensile strain at the bottom of the asphalt layer was computed for under one tire and between the tires; the maximum value was selected. The strain and dynamic modulus values were plotted, Figure 37.

Figure 36: KENPAVE Pavement Designs

Figure 37: Full Depth and Conventional Pavement Strain Based Fatigue

Using Figures 27 and 30, dynamic moduli corresponding to 1.866 Hz at 20°C were determined, as presented in Table 27. The Asphalt Institute fatigue coefficients were placed into Equation 15 to form Equation 22:

$$N_f = 0.0796 \left(\frac{1}{\epsilon_t} \right)^{3.291} \left(\frac{1}{E} \right)^{0.854} \quad (22)$$

Where:

N_f = number of passes to fatigue

ϵ = strain

E = dynamic modulus (psi)

Table 27: Dynamic Modulus Values for N_f Analysis

Mix	E (MPa)	E (psi)
AA937	5,071	735,000
JAP909	4,698	681,000
JFA060	4,389	637,000
JFA115	4,181	606,000
JFA429	4,645	674,000
KP483	4,474	649,000
WVP523	4,848	703,000
WVP766	4,206	610,000
WVP882	3,910	567,000

The dynamic moduli in Table 27 were used to find strain values from Figure 37. From there, the strain and modulus were used in Equation 22 to estimate fatigue life, Table 28.

Table 28: KENPAVE Full Depth and Conventional N_f Values

Mix	E (psi)	Full Depth		Conventional	
		ϵ (micro strain)	N_f	ϵ (micro strain)	N_f
AA937	735,000	52	9.77E+07	120	6.23E+06
JAP909	681,000	55	8.67E+07	123	6.13E+06
JFA060	637,000	58	7.70E+07	125	6.16E+06
JFA115	606,000	61	6.81E+07	127	6.10E+06
JFA429	674,000	56	8.24E+07	123	6.19E+06
KP483	649,000	57	8.03E+07	125	6.06E+06
WVP523	703,000	54	8.96E+07	121	6.30E+06
WVP766	610,000	60	7.15E+07	127	6.06E+06
WVP882	567,000	64	6.15E+07	130	5.98E+06

Strains for the full depth pavement are below recommended micro strain values for perpetual pavements of 70 micro strains (Lenz, 2011). The full depth analysis indicates this is a

perpetual pavement design. The minimum estimated fatigue life for the full depth pavement is 61.5×10^6 ESALs, which is much greater than the expected truck loads on West Virginia pavements. The conventional pavement fatigue lives were approximately six million ESALs regardless of the mix type, Table 28.

Alpha-Fatigue Pavement Life Prediction

The fatigue samples were analyzed using the KENPAVE strain values found previously and K-values produced from the Alpha-Fatigue analyses. As stated previously, strains for the full depth pavement are far below recommended micro strain values so the full depth pavement was not reviewed further. Alpha-Fatigue K-values and dynamic modulus averages were used in Equation 15 to produce the number of cycles to failure for conventional pavement design. The results are listed in Table 29. Choosing the Peak failure criteria resulted in higher N_f values in all cases compared to the Asphalt Institute. Even though the critical micro strains for the conventional pavement are well in excess of the criteria for a perpetual pavement, the estimates from the Alpha Fatigue equation show the expected fatigue life of the pavement is in excess of 50×10^6 applications, well in excess of the expected design traffic that would be used by the WVDOH when considering a conventional pavement. Furthermore the Alpha Fatigue results were not corrected with the field calibration factor which would increase the estimate of fatigue life by a factor of 18.4.

Table 29: Conventional Pavement KENPAVE Analysis Using Alpha-Fatigue K-Values

			Alpha-Fatigue	Asphalt Institute
Mix	E (psi)	ϵ (micro strain)	N_f	N_f
AA937	735,000	120	1.30E+07	6.29E+06
JAP909	681,000	123	6.15E+06	6.19E+06
JFA060	637,000	125	1.64E+07	6.11E+06
JFA115	606,000	127	2.98E+07	6.05E+06
JFA429	674,000	123	6.76E+08	6.18E+06
KP483	649,000	125	1.61E+08	6.13E+06
WVP523	703,000	121	9.72E+07	6.23E+06
WVP766	610,000	127	5.76E+07	6.06E+06
WVP882	567,000	130	4.29E+06	5.97E+06

Flow Number

AMPT Flow Number Results

All flow number data is summarized in Tables 30 and 31. Each Wearing I mix met AASHTO TP 79 specifications for acceptable range of replicates, but JFA115 coefficient of variation value was higher than the acceptable coefficient of variation value of 32.9 percent for 9.5 mm mixes. The acceptable coefficient of variance for 19 mm NMAS is 58.5 percent according to AASHTO TP 79. Each set of Base II/19 mm mix replicates met this requirement. The sample replicate range for all mixes are well within the acceptable range of the test method.

Tables 30 and 31 also present VTM, flow number, and permanent strain (micro strain at flow point) values per AASHTO TP 79 reporting requirements. AA937 resulted in the highest average flow number of the five Wearing I mixes with a value of 687. KP483 had the next highest flow number at a value of 567. JFA115 had a lower value of 321 with WVP766 and WVP882 performing comparably with values of 262 and 265.

Table 30: Data Smoothing Flow Number and Permanent Strain for Wearing I Mixes

Mix	REP	VTM	FN	AVG	SD	CV (%)	Microstrain at Flow Point	AVG	SD
AA937	1 (S8)	7.4	625	687	52	7.5	27,411	27,334	556
	2 (S9)	7.3	706				27,545		
	3 (S10)	7.3	671				26,543		
	4 (S11)	7.5	747				27,836		
JFA115	1 (S9)	7.1	232	321	111	34.6	20,219	21,766	1,540
	2 (S10)	6.9	285				23,298		
	3 (S11)	6.7	445				21,782		
	-	-	-				-		
KP483	1 (S5)	6.7	467	567	41	8.5	20,602	21,042	331
	2 (S9)	6.8	534				21,184		
	3 (S10)	6.8	437				21,002		
	4 (S11)	6.9	483				21,378		
WVP766	1 (S9)	6.6	201	262	55	21.1	20,173	20,913	984
	2 (S10)	6.9	238				22,277		
	3 (S11)	7.0	330				20,212		
	4 (S12)	6.8	279				20,988		
WVP882	1 (S5)	6.8	230	265	33	12.6	21,992	23,080	1,790
	2 (S6)	6.7	270				21,410		
	3 (S10)	6.7	250				23,502		
	4 (S11)	6.7	308				25,417		

Table 31: Data Smoothing Flow Number and Permanent Strain for Base II and 19 mm Mixes

Mix	REP	VTM	FN	AVG	SD	CV (%)	Microstrain at Flow Point	AVG	SD
JAP909	1 (S5)	7.0	260	266	13	5.0	20,986	22,591	1,074
	2 (S9)	6.6	255				23,075		
	3 (S10)	6.8	285				23,044		
	4 (S11)	6.5	264				23,260		
JFA060	1 (S8)	7.2	262	346	123	35.5	21,919	22,590	693
	2 (S9)	7.1	290				22,097		
	3 (S10)	7.0	303				23,360		
	4 (S11)	6.6	528				22,984		
JFA429	1 (S9)	6.6	370	459	126	27.4	18,792	19,311	734
	2 (S10)	7.0	548				19,830		
	3	-	-				-		
	4	-	-				-		
WVP523	1 (S9)	6.2	649	628	47	7.5	20,851	21,955	1,663
	2 (S10)	6.9	561				20,878		
	3 (S11)	6.6	632				21,715		
	4 (S12)	7.1	670				24,376		

The WVP523 S9 performed within the acceptable range for four replicates so an additional sample was not made. WVP523 resulted in the highest average flow number of the four Base II/19mm pavement designs with a value of 628. JFA429 had the next highest flow number at a value of 459 and JFA060 had the third with an average of 346. JAP909 resulted in the lowest average of 266.

Figure 38 displays one flow number test from this research. During this test tertiary flow appears to have been achieved. However, tertiary flow was barely reached during other flow number tests, Figure 39. This is an artifact of the definition of flow number used in the test method. Flow number occurs at either the minimum strain rate using the smoothing criteria or at the inflection point using the Francken model. Therefore, it is not necessary to extend the test into the tertiary stage.

Figure 38: WVP882 Flow Number Sample 5 Permanent Strain and Strain Rate

Figure 39: AA937 Flow Number Sample 8 Permanent Strain and Strain Rate

Francken Model Flow Number Results

For further review, the Francken model was pursued to see if there was any difference in the flow number values. The Francken model was fit to the data using nonlinear regression in MATLAB. All averages, standard deviations, and coefficient of variation values are reported in

Tables 32 and 33. The Francken model averages are moderately higher than the data smoothing averages for all mixes except WVP523.

Table 32: Francken Model Flow Number Summary of Wearing I Mixes

Mix	REP	VTM	FN	AVG	SD	CV (%)
AA937	1 (S8)	7.4	651	722	49	6.9
	2 (S9)	7.3	760			
	3 (S10)	7.3	725			
	4 (S11)	7.5	751			
JFA115	1 (S9)	7.1	263	338	119	35.2
	2 (S10)	6.9	276			
	3 (S11)	6.7	475			
KP483	1 (S5)	6.7	440	491	58	11.8
	2 (S9)	6.8	569			
	3 (S10)	6.8	454			
	4 (S11)	6.9	499			
WVP766	1 (S9)	6.6	218	274	54	19.6
	2 (S10)	6.9	246			
	3 (S11)	7.0	341			
	4 (S12)	6.8	290			
WVP882	1 (S5)	6.8	252	274	22	8.1
	2 (S6)	6.7	295			
	3 (S10)	6.7	257			
	4 (S11)	6.7	290			

Table 33: Francken Model Flow Number Summary of Base II and 19 mm Mixes

Mix	REP	VTM	FN	AVG	SD	CV (%)
JAP909	1 (S5)	7.0	276	284	20	6.9
	2 (S9)	6.6	267			
	3 (S10)	6.8	312			
	4 (S11)	6.5	282			
JFA060	1 (S8)	7.2	290	362	99	27.3
	2 (S9)	7.1	336			
	3 (S10)	7.0	314			
	4 (S11)	6.6	507			
JFA429	1 (S9)	6.6	423	517	133	25.7
	2 (S10)	7.0	611			
WVP523	1 (S9)	6.2	646	594	36	6.0
	2 (S10)	6.9	588			
	3 (S11)	6.6	577			
	4 (S12)	7.1	566			

Table 34 summarizes all flow number values and the difference between the two methods reviewed. In some cases, the Francken model value is higher while in other instances the data smoothing flow number is higher. However, for most mixes the Francken model resulted in a higher flow number.

Table 34: Flow Number Differences between Data Smoothing and Francken Model

Mix	REP	Data Smoothing	Francken Model	Difference
AA937	S8	625	651	26
	S9	706	760	54
	S10	671	725	54
	S11	747	751	4
JAP909	S5	260	276	16
	S9	255	267	12
	S10	285	312	27
	S11	264	282	18
JFA060	S8	262	290	28
	S9	290	336	46
	S10	303	314	11
	S11	528	507	-21
JFA115	S9	232	263	31
	S10	285	276	-9
	S11	445	475	30
JFA429	S9	370	423	53
	S10	548	611	63
KP483	S5	467	440	-27
	S9	534	569	35
	S10	437	454	17
	S11	483	499	16
WVP523	S9	649	646	-3
	S10	561	588	27
	S11	632	577	-55
	S12	670	566	-104
WVP766	S9	201	218	17
	S10	238	246	8
	S11	330	341	11
	S12	279	290	11
WVP882	S5	230	252	22
	S6	270	295	25
	S10	250	257	7
	S11	308	290	-18

Evaluation of Rutting Resistance

Two mixes do not have the four replicates required due to material shortage (JFA429 and JFA115), but all average flow number values were reviewed for rutting resistance. Table 6 from Chapter 2 shows the ESALs cutoff for HMA rutting from AASHTO TP 79. As shown in Tables 32 and 33, each mix analyzed had an average flow number greater than 190 and less than 740 which is the minimum average flow number limits for 10 to 30 million and greater than 30 million ESALs. This means each mix met rutting resistance criteria within this respect and could be expected to withstand 10 to 30 million ESALs without accumulating significant rutting.

AA937, KP483, WVP523, WVP766, and WVP882 all contained natural sands in their mix compositions. Excessive natural sand (30 percent) in a mix design has been found to be the most significant factor influencing permanent deformation (Rushing and Little, 2013). WVP766 and WVP882, both Wearing I mixes containing 25 percent natural sands, performed the worst for rutting. However, AA937, KP483, and WVP523 contained 30, 19, and 25 percent natural sands, but resulted as the three highest flow number averages of all mixes evaluated.

Significance of Work

The work completed herein was the first AMPT testing performed on West Virginia plant-produced mixes. All findings contribute insight into the mixes provided for this research. Additionally, expanding knowledge on the AMPT is beneficial for future work completed at the WVU Asphalt Technology laboratory. Gaining better understanding on all AMPT material property testing apparatuses ensures that the AMPT is functioning properly and producing acceptable data. This is integral to producing meaningful results and reaching conclusions from all AMPT research.

Chapter 5: Conclusions and Recommendations

Conclusions

Sample Uniformity

All sample sets met the AASHTO PP 60 uniformity requirements except WVP523 in the top-middle evaluation. The samples used for dynamic modulus testing were evaluated for uniformity on the assumption that the dynamic modulus test does not damage the samples since a low stress level is used for dynamic modulus testing. The target air void content of these samples was 7 percent whereas the recommended air voids for the uniformity test is 5.5 percent. There is a logical argument for evaluating the uniformity at the target air voids for the test being performed. The flow number and fatigue test samples were not tested for uniformity as these tests have a potential to alter the void structure of the sample. It was assumed the flow number and fatigue samples had acceptable uniformity based on the results of the tests on the dynamic modulus samples.

During the analysis of the sections, it was noticed that the air voids of the sections were higher than the air voids of the intact samples by 0.4 percent, Table 18. This issue is not addressed in AASHTO PP 60 and the reason for the difference is not apparent.

Strong correlations among all three G_{mb} methods (CoreLok, SSD, and Dimensional) were found when plotted on line of equality graphs. Moreover, the equations in Figure 22 and 23 may be used to estimate if a compacted sample will have an acceptable VTM for AMPT testing after trimming for 9.5 and 19 mm NMAS mixes. Trimming samples can be avoided for samples that will not meet the AMPT requirements for VTM.

When testing for uniformity all Dimensional G_{mb} comparisons for all mixes met the AASHTO PP 60 requirements. From these findings, Dimensional is arguably the most accurate method when calculating the G_{mb} value of a sample with cut faces. Moreover, all sample sets met the AASHTO PP 60 t-statistic limit for uniformity except WVP523 in the top-middle evaluation for SSD, CoreLok, and Average. While this set did not meet uniformity, all testing resulted in comparable dynamic modulus and flow number results to mixes with the same NMAS.

Dynamic Modulus

Dynamic modulus values fell within an acceptable coefficient of variation range at 4°C and 20°C. At 40°C the coefficient of variation increased above 15 percent for two mixes (JFA060 and WVP523), but still remained below 20 percent. These coefficient of variation and repeatability values for AMPT dynamic modulus testing were consistent with Robert et al. (2012) AMPT study. These findings show the AMPT produced reliable data for this research.

The β fitting parameter appears to have a correlation to the inclusion of RAP in a mix design consistent with Smith (2015) findings. However, at 20°C the average dynamic modulus of the RAP and virgin mixes was virtually identical. Lastly, the Master curves for all mix designs followed a similar fit. At lower reduced frequencies the values ranged slightly, but converged with increased reduced frequency. Two mix nominal maximum aggregate sizes were evaluated, but NMASS does not appear to have an impact on the curve fit.

Alpha-Fatigue

Two failure methods were analyzed using Alpha-Fatigue software: one using the phase angle drop failure criteria (Peak) and the second allowing the Alpha-Fatigue software to choose the failure point using built in functions (Default). The Peak criteria resulted in reasonable micro strain endurance limits while the Default did not. Therefore, only the Peak Alpha-Fatigue results were reviewed further. The one Superpave mix analyzed, JFA429, resulting in the highest endurance limit.

Results found in this research vary from the Asphalt Institute equation and the adjusted equation. Comparing the K-values found in this study to past results of Hou (2009) and Witczak et al. (2013), showed some discrepancies. No distinctions between mixes containing RAP or between different NMASS designs were apparent in this analysis.

KENPAVE

The full depth pavement evaluated indicated the pavement met the criteria for a perpetual pavement design with respect to fatigue life. For the conventional pavement design, the fatigue life estimate using the Alpha-Fatigue results and the Peak phase angle criteria were greater than the fatigue life estimated by the Asphalt Institute fatigue equation in all cases.

Flow Number

The flow number concept is often explained using conventional models of creep behavior that describes the creep rate in the secondary phase as linear behavior. The creep of asphalt concrete does not display linear behavior. Therefore, the flow number of asphalt concrete is defined as the point of minimum change in the rate of permanent strain accumulation. Due to minor fluctuations in the permanent strain data, the test method recommends a smoothing technique to determine the flow number with the Francken model being an alternative. Although the smoothing process is simple, it is sensitive to the sampling interval selected. The Francken model uses all the data from the flow number test and defines the flow number as the cycle where the second derivative changes from positive to negative. Although the analysis needed for the Francken model is somewhat complex, it can be readily handled with nonlinear regression using MATLAB or other statistical software packages.

Both the data smoothing and the Francken model are reasonable methods for determining flow number. All mix types met rutting resistance requirements for both methods evaluated. Each mix could be expected to withstand 10 to 30 million ESALs without accumulating significant permanent deformation. A Wearing I, RAP containing mix (AA937) performed the highest with an average flow number of 687. WVP523 which was a Base II mix had the second highest average flow number value of 625. This sample set also had a replicate fall below the air void range, but still performed well within the acceptable flow number range. All mix replicates met coefficient of variation requirements except JFA115. From this testing, the AMPT produced repeatable data.

Recommendations

Testing Protocol

The effect of air voids on fatigue performance should be evaluated with the intent of defining an air void level to use for fatigue testing.

Further investigation using the AMPT and Alpha-Fatigue software is needed. Values found with the WVU laboratory differ from that of the Asphalt Institute and other references.

Some fatigue samples did not break within the gauge points which infers the LVDT readings were not monitoring the strained area of the sample accurately. Looking into this in future AMPT fatigue testing can be done by breaking samples after each test to verify deformation is occurring within the LVDT gauge length.

In the AASHTO PP 60 assessing uniformity section, top-bottom bulk specific gravity comparison is not a requirement. Adding this comparison to the standard should be considered.

Material Evaluation

The Superpave 19 mm mix performed better than the other mixes with respect to fatigue. However, this observation is based on a single sample. A designed experiment should be performed with factors that include contractor, mix type, and aggregate type to develop a statistically significant data base. This would be a preliminary step into the use of a mechanistic pavement design method such as MEPDG. This investigation should include all the asphalt concrete materials used in the state.

The potential of evaluating mixes during the mix design should be evaluated to optimize material characteristics. For example surface mixes could be evaluated to minimized rutting potential while base mixes could be optimized to improve fatigue resistance.

A process should be implemented whereby different mix designs are evaluated with the AMPT and the performance of pavements constructed with these mixes is monitored over time.

A method to look at the variability among test replicates in Alpha-Fatigue would be ideal. How the program is currently designed, replicates are tested at different micro strain values and fatigue coefficients are produced from all three replicates. This does not allow a comparison to be completed.

Large quantities of one mix should be obtained to look at a range of air voids for fatigue testing. A large quantity of mix would also allow more than one set of fatigue replicates to be made and tested to review determine if there is any variability in the final Alpha-Fatigue coefficients.

For a more accurate KENPAVE analysis, WV-produced 37.5 mm mixes should be analyzed for more accurate strain values at the bottom of the asphalt layer.

To reduce segregation, mixes may need remixed immediately before being placed in the mold for compaction.

Lastly, in Table 25 the micro strain endurance limits increase at a linear rate until the last temperature shift between 20°C and 25°C where the micro strain endurance limit abruptly increases. The reason for this is unknown and should be investigated further.

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Appendix A: Mix Design

Job Mix Formulas

T400
04-10

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

Report Number: 1432937		Date Accepted: April 23, 2013	
HMA Type: Wearing-1 w/RAP		HMA Code: 13966	
Producer: American Asphalt of WV		Plant Location: St. Albans, WV	
Designed By: Bill Cottle		Design Lab: American Asphalt of WV, Kenova, WV	
Plant Type: Batch		Plant Make: Barber Greene	
Plant Code: A117C		Traffic Type: Heavy	

MIX COMPOSITION							
Coarse Aggregate Source				Fine Aggregate Source			
CA ₁	CA ₂	CA ₃	Code	FA ₁	FA ₂	FA ₃	Code
CA ₁	Mountain Materials, Olive Hill, KY		M378A	FA ₁	Mountain Materials, Olive Hill, KY		M378A
CA ₂				FA ₂	Lefart Sand & Gravel, Gallipolis Ferry, WV		E006A
CA ₃				FA ₃			
	CA ₁	CA ₂	CA ₃	FA ₁	FA ₂	FA ₃	
Agg. Type	#8 Limestone			Limestone	Natural		
Agg. Code	1135			1116	1115		
% Total Agg.	35			16	34		
% RAP Total Agg.: 15		Blended Binder G*/sin delta if > 25% RAP:					
% Binder In RAP Design: 4.8		Binder Type: PG 64-22		Binder Code: 1093			
Binder Source: Shelly Liquid Division, Kanauga, OH		Binder SourceCode: M001A					

Sieve Fraction								Voids filled with	Fines to
Sieve Size	Target	Allowable		Sieve Size	Target	Allowable		Asphalt (VFA) %	Asphalt Ratio
		Min.	Max.			Min.	Max.		
2" (50 mm)				#4 (4.75 mm)	66		80	74	0.9
1.5" (37.5 mm)				#8 (2.36 mm)	48	42	54	Temperature Range Completed Mixture (°F)	
1" (25 mm)				#16 (1.18 mm)	37			Desirable	Temp. Range
3/4" (19 mm)				#30 (600 µm)	28			Mean Temp.	Min. Max.
1/2" (12.5 mm)	100	100	100	#50 (300 µm)	11				
3/8" (9.5 mm)	96	85	100	#200 (75 µm)	5.3	2.0	9.0	300	275 325

JOB MIX FORMULA VALUES				
Specific gravity stone bulk (Gsb): 2.610	Design Property	Job Mix Formula Design Targets	Plant Mix Formula Tolerances	
	Asphalt (%)	5.6	Minimum	Maximum
Maximum Density (kg/m³)	Air Voids (%)	4.0	2.5	5.5
	VMA (%)	15.5	14.5	16.5
	Stability (N)	10737	8000	NA
2447	Flow (0.25mm)	11	8	14
Desirable Mean Temperature for Laboratory Specimens (°F):		Compaction Temperature:	288	Mixing Temperature:
Remarks:				

Figure 40: Job Mix Formula for AA937

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

Report Number:	1360465	Date Accepted:	March 9, 2004
HMA Type:	Wearing-1	HMA Code:	13966
Producer:	Greer Asphalt	Plant Location:	Greer, WV
Designed By:	Rich Nuzum	Design Lab:	Clarksburg Asphalt
Plant Type:	Batch	Plant Make:	McCarter
Plant Code:	G012A	Traffic Type:	Heavy

MIX COMPOSITION						
Coarse Aggregate Source		Code	Fine Agg. / Mineral Filler Source		Code	
CA ₁	Greer Industries, Greer, WV	G0120	FA ₁	Greer Industries, Greer, WV	G0120	
CA ₂			FA ₂	Greer Industries, Greer, WV	G0120	
CA ₃			FA ₃			
	CA ₁	CA ₂	CA ₃	FA ₁	FA ₂	FA ₃
Agg. Type	#8 Limestone			Limestone	Limestone	
Agg. Code	1135			1116	1116	
% Total Agg.	48			32	20	
% RAP Total Agg.:		Blended Binder G*/sin delta if > 25% RAP:				
% Binder In RAP Design:		Binder Type:		PG 64-22	Binder Code:	1093
Binder Source:		Marathon/Ashland Oil, Floreffe, Pa.			Binder SourceCode:	A022B

Sieve Fraction								Voids filled with Asphalt*VFA*(%)	Fines to Asphalt Ratio
Sieve Size	Target	Allowable Min.	Allowable Max.	Sieve Size	Target	Allowable Min.	Allowable Max.	75	0.8
2" (50 mm)				#4 (4.75 mm)	60		80	Temperature Range Completed Mixture (°F)	
1.5" (37.5mm)				#8 (2.36 mm)	39	33	45		
1" (25 mm)				#16 (1.18 mm)	23			Desirable Mean Temp.	Temp. Range Min. Max.
3/4" (19 mm)				#30 (600 µm)	12				
1/2" (12.5 mm)	100	100	100	#50 (300 µm)	7			295	270 320
3/8" (9.5 mm)	95	85	100	#200 (75 µm)	4.4	2.0	9.0		

JOB MIX FORMULA VALUES				
Job Mix Formula Targets			Job Mix Formula Tolerances	
Specific gravity stone bulk (G _{sb}):	Design Property	Accepted Target	Minimum	Maximum
2.662	Asphalt (%)	5.7	5.3	6.1
Maximum Density (kg/m ³)	Air Voids (%)	4.0	2.5	5.5
	VMA (%)	15.7	14.7	16.7
2476	Stability (N)	10400	8000	NA
	Flow (0.25mm)	11	8	14

Remarks: _____

Figure 41: Job Mix Formula for GR465

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WEST VIRGINIA DIVISION OF HIGHWAYS
PLANT MIX FORMULA FOR HOT-MIX ASPHALT

Report Number:	1314909	Date Accepted:	March 3, 1999
HMA Type:	Base 2	HMA Code:	13271
Producer:	Jefferson Asphalt	Plant Location:	Millville, WV
Designed By:	John Thomas	Design Lab:	Jefferson Asphalt
Plant Type:	Batch	Plant Make:	H & B
Plant Code:	J059B	Traffic Type:	Medium

MIX COMPOSITION							
Coarse Aggregate Source				Fine Agg. / Mineral Filler Source			
CA1	CA2	CA3	Code	FA1	FA2	FA3	Code
Millville Quarry, Millville, WV			M226A	Millville Quarry, Millville, WV			M226A
	CA1	CA2	CA3	FA1	FA2	FA3	MIN. FILL
Agg. Type	67Limestone			#10Limestone			
Agg. Code	1131			1138			
% Total Agg.	50			50			
% RAP Total Agg.:				Blended Binder G*/sin delta:			
% Virgin Binder In RAP Design:				Binder Type:	PG 64-22	Binder Code:	1093
Asphalt Source:				Chevron Asphalt, Baltimore, Md.		Asphalt Source Code: C172A	

Sieve Fraction								Optimum Asp.	Fines / Asp.
Sieve Size	Target	Allowable		Sieve Size	Target	Allowable		Content (%)	Ratio
		Min.	Max.			Min.	Max.		
50 mm				4.75 mm	52	45	59	4.6	1.1
37.5 mm				2.36 mm	35	29	41	Temperature Range Completed Mixture (°C)	
25 mm	100	100	100	1.18 mm					
19 mm	93	86	100	600 µm	14	9	19	Desirable Mean	Temp. Range
12.5 mm				300 µm	10	6	14	Temperature	Min.
9.5 mm	67	60	74	75 µm	5.0	2.0	8.0		Max.

PLANT MIX FORMULA VALUES				
Plant Mix Formula Targets			Plant Mix Formula Tolerances	
	Design Property	Accepted Target	Minimum	Maximum
Maximum	Stability (N)	7400	5900	8900
Density (KCM)	Flow (0.25mm)	9.3	6.8	11.8
2613	Air Voids (%)	4.0	2.5	5.5

Remarks:

Figure 42: Job Mix Formula for JAP909

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

Report Number:	1433060	Date Accepted:	March 20, 2014
HMA Type:	Base 2	HMA Code:	13965
Producer:	J. F. Allen Company	Plant Location:	Saltwell, WV
Designed By:	Chadley Miller	Design Lab:	J. F. Allen Company - Elkins, WV
Plant Type:	Drum	Plant Make:	Gencor
Plant Code:	A007D	Traffic Type:	Heavy

MIX COMPOSITION						
Coarse Aggregate Source			Code	Fine Aggregate Source		Code
CA₁	J.F. Allen Company - Mashey Gap	A007E	FA₁	J.F. Allen Company - Mashey Gap	A007E	
CA₂	J.F. Allen Company - Mashey Gap	A007E	FA₂	Bag House Fines (BHF)	I0000	
CA₃			FA₃			

	CA₁	CA₂	CA₃	FA₁	FA₂	FA₃
Agg. Type	# 67 Limestone	# 8 Limestone		Limestone Sand	BHF	
Agg. Code	1131	1135		1116	1116	
% Total Agg.	30	36		33	1	

% RAP Total Agg.:		Blended Binder G*/sin delta if > 25% RAP:	
% Binder In RAP Design:		Binder Type:	PG 64-22
Binder Source:	Marathon Petroleum - Catlettsburg, KY	Binder Code:	1093
		Binder SourceCode:	A022A

Sieve Fraction								Voids filled with Asphalt (VFA) %	Fines to Asphalt Ratio
Sieve Size	Target	Allowable		Sieve Size	Target	Allowable			
		Min.	Max.			Min.	Max.	72	1.0
2" (50 mm)				#4 (4.75 mm)	47			Temperature Range Completed Mixture (°F)	
1.5" (37.5mm)				#8 (2.36 mm)	30	24	36	Desirable Mean Temp.	
1" (25 mm)	100	100	100	#16 (1.18 mm)	18			Temp. Range Min. Max.	
3/4" (19 mm)	97	90	100	#30 (600 µm)	12			312	
1/2" (12.5 mm)	83		90	#50 (300 µm)	9			287	
3/8" (9.5 mm)	75			#200 (75 µm)	4.9	2.0	8.0	337	

JOB MIX FORMULA VALUES				
Design Property		Job Mix Formula Design Targets	Job Mix Formula Tolerances Minimum	Job Mix Formula Tolerances Maximum
Specific gravity stone bulk (Gsb):	2.658	Asphalt (%)	4.9	5.3
Maximum Density (kg/m³)		Air Voids (%)	4.0	5.5
		VMA (%)	14.1	15.1
		Stability (N)	12067	NA
2500		Flow (0.25mm)	11	14

Desirable Mean Temperature for Laboratory Specimens (°F):	Compaction Temperature:	287	Mixing Temperature:	312
Remarks:				

Figure 43: Job Mix Formula for JFA060

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

Report Number:	1361115	Date Accepted:	June 30, 2004
HMA Type:	Wearing - 1	HMA Code:	13273
Producer:	J. F. Allen Co.	Plant Location:	Saltwell, WV
Designed By:	Tarra Sponaugle	Design Lab:	J. F. Allen
Plant Type:	Drum	Plant Make:	Gencor
Plant Code:	A007D	Traffic Type:	Medium

MIX COMPOSITION							
Coarse Aggregate Source			Code	Fine Agg./ Mineral Filler Source			Code
CA1	J. F. Allen , Mashey Gap, WV		A007E	FA1	J. F. Allen, Mashey Gap, WV		A007E
CA2				FA2	J. F. Allen, Elkins, WV		A007A
CA3				FA3	Bag House Fines		I0000
Agg. Type		CA1 #8 Limestone	CA2	CA3	FA1 Limestone Sand	FA2 #9 Limestone	FA3 Bag House Fine
Agg. Code		1135			1116	1116	1116
%Total Agg.		40			50	9	1
% RAP Total Agg.:		Blended Binder G*/sin delta if > 25% RAP:					
% Binder In RAP Design:			Binder Type:	PG 64-22	Binder Code:	1093	
Binder Source:		Marathon/Ashland Oil, Catlettsburg, Ky.			Binder SourceCode:	A022A	

SIEVE FRACTION								Voids filled with Asphalt "VFA" (%)	Fines to Asphalt Ratio	
Sieve Size	Target	Allowable		Sieve Size	Target	Allowable				
		Min	Max			Min	Max	76	0.8	
2" (50mm)				#4 (4.75 mm)	66		80	Temperature Range Completed Mixture (°F)		
1.5" (37.5mm)				#8 (2.36 mm)	44	38	50			
1" (25mm)				#16 (1.18 mm)	28					
3/4" (19mm)				#30 (600 um)	19			Desirable Mean Temp.	Temp. Range	
									Min.	Max.
1/2" (12.5mm)	100	100	100	#50 (300 um)	13			310	285	335
3/8" (9.5mm)	98	85	100	#200 (75 um)	4.9	2.0	9.0			

JOB MIX FORMULA VALUES				
Job Mix Formula Targets			Job Mix Formula Tolerances	
Specific gravity bulk stone (Gsb): 2.629	Design Property	Accepted Target	Minimum	Maximum
Maximum Density (kg/m3)	Asphalt (%)	5.8	5.4	6.2
	Air Voids (%)	4.0	2.5	5.5
	VMA (%)	15.5	14.5	16.5
2459	Stability (N)	13,350	5,300	NA
	Flow (0.25mm)	10.0	8.0	14.0

Gsb : 2.639 / 2015

Max Density : 2470 / 2015

Oven Calibration : - 0.39 / 2009

Figure 44: Job Mix Formula for JFA115

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

Report Number: 1426429		Date Accepted: March 28, 2012	
HMA Type: 19 mm		HMA Code: 19242	
Producer: J. F. Allen Company		Plant Location: Saltwell, WV	
Designed By: Chadley Miller		Design Lab: J. F. Allen - Elkins, WV	
Plant Type: Drum		Plant Make: Gencor	
Plant Code: A007D		Design ESALs: 8 to < 30 Million (8)	

MIX COMPOSITION								
Coarse Aggregate Source			Code	Fine Aggregate Source		Code		
CA ₁	J. F. Allen Company, Mashey Gap, WV		A007E	FA ₁	J. F. Allen Company, Elkins, WV		A007A	
CA ₂	J. F. Allen Company, Mashey Gap, WV		A007E	FA ₂	J. F. Allen Company, Elkins, WV		A007A	
CA ₃				FA ₃	Bag House Fines (BHF)		10000	
	CA ₁	CA ₂	CA ₃	FA ₁	FA ₂	FA ₃		
Agg. Type	#67 Limestone	#8 Limestone		#8 Limestone	Limestone	BHF		
Agg. Code	1131	1135		1137	1116	1116		
% Total Agg.	33	20		14	32	1		
% RAP Total Agg.:			Blended Binder G ^o /aln delta If > 25% RAP:					
% Binder in RAP Design:			Binder Type:		PG 64 - 22	Binder Code:	1093	
Binder Source:			Marathon Petroleum - Catlettsburg, KY		Binder Source Code:			A022A

Sieve Fraction								Fines / Effective Asphalt Ratio	Tensile Strn. Ratio
Sieve Size	Target	Allowable		Sieve Size	Target	Allowable			
		Min.	Max.			Min.	Max.	1.0	98.2
2" (50 mm)				#4 (4.75 mm)	49			Temperature Range Completed Mixture (°F)	
1.5" (37.5 mm)				#8 (2.36 mm)	30	24	36		
1" (25 mm)	100	100	100	#16 (1.18 mm)	19			Desirable	Temp. Range
3/4" (19 mm)	100	90	100	#30 (600 µm)	13			Mean Temp.	Min. Max.
1/2" (12.5 mm)	81		90	#50 (300 µm)	8				
3/8" (9.5 mm)	70			#200 (75 µm)	4.3	2.0	8.0	308	264 334

JOB MIX FORMULA VALUES				
Specific gravity alone bulk (G _{sb}): 2.658	Design Property	Job Mix Formula	Job Mix Formula Tolerances	
		Design Targets	Minimum	Maximum
Maximum Density (lb/cu ft) 2500	Asphalt (%)	4.9	4.5	5.3
	Air Voids (%)	4.5	2.5	6.5
	VMA (%)	14.1	13.4	15.1
	VFA (%)	72	70	74
Systems @ N _{design} : 80	Desirable Mean Temp. for Lab. Specimens (°F): Comp. Temp.: 267 Mixing Temp.: 300			

Remarks:

Figure 45: Job Mix Formula for JFA429

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

Report Number: 1426483		Date Accepted: May 14, 2012	
HMA Type: Wearing - I Skid w/RAP		HMA Code: 13976	
Producer: Kelly Paving		Plant Location: Benwood WV	
Designed By: Tom Andreas		Design Lab: Mar-Zane Lab, Rayland, OH	
Plant Type: Drum		Plant Make: Dillion	
Plant Code: O070B		Traffic Type: Heavy	

MIX COMPOSITION										
Coarse Aggregate Source				Code		Fine Aggregate Source		Code		
CA ₁	Mulzer Stone, Charlestown, IN			M027E		FA ₁	Belpre Sand & Gravel, Belpre, OH			B010A
CA ₂						FA ₂	Mulzer Stone, Cape Sandy, IN			M289A
CA ₃						FA ₃				
	CA ₁	CA ₂	CA ₃	FA ₁	FA ₂	FA ₃				
Agg. Type	# 8 Limestone			Natural	Limestone					
Agg. Code	1135			1115	1116					
% Total Agg.	44			19	22					
% RAP Total Agg.:	15			Blended Binder G*/sin delta if > 25% RAP:						
% Binder In RAP Design:	4.8			Binder Type:	PG 64-22	Binder Code:	1093			
Binder Source:	S & S Terminal, Rayland, OH					Binder SourceCode:	T008A			

Sieve Fraction								Voids filled with	Fines to
Sieve Size	Target	Allowable		Sieve Size	Target	Allowable		Asphalt (VFA) %	Asphalt Ratio
		Min.	Max.			Min.	Max.	74	1.0
2" (50 mm)				#4 (4.75 mm)	58		80	Temperature Range Completed Mixture (°F)	
1.5" (37.5 mm)				#8 (2.36 mm)	38	32	44		
1" (25 mm)				#16 (1.18 mm)	23			Desirable Mean Temp.	Temp. Range Min. Max.
3/4" (19 mm)				#30 (600 µm)	13				
1/2" (12.5 mm)	100	100	100	#50 (300 µm)	9			300	275 325
3/8" (9.5 mm)	98	85	100	#200 (75 µm)	5.4	2.0	9.0		

PLANT MIX FORMULA VALUES					
		Job Mix Formula		Job Mix Formula Tolerances	
Specific gravity stone bulk (G _{sb}):	Design Property	Design Targets		Minimum	Maximum
2.619	Asphalt (%)	5.6		5.2	6.0
Maximum Density (kg/m³)	Air Voids (%)	4.0		2.5	5.5
	VMA (%)	15.8		14.8	16.8
2440	Stability (N)	14200		8000	NA
	Flow (0.25mm)	14		8	14

Desirable Mean Temperature for Laboratory Specimens (°F):	Compaction Temperature:	285	Mixing Temperature:	300
Remarks: Mix design data for this JMF can be found under T-400# 1390018.				

Figure 46: Job Mix Formula for KP483

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

Report Number: 1426523		Date Accepted: July 18, 2012	
HMA Type: Base-2 w/RAP		HMA Code: 13973	
Producer: West Virginia Paving, Inc		Plant Location: Dunbar, WV	
Designed By: John Boggess/Brad Saunders		Design Lab: WV Paving-Dunbar, WV	
Plant Type: Drum		Plant Make: Bituma Gencor	
Plant Code: W074C		Traffic Type: Heavy	

MIX COMPOSITION					
Coarse & Fine Aggregate Source		Code	Fine Aggregate Source		Code
CA₁	Mulzer Stone-New Amsterdam, IN	M289C	FA₂	Shelly Materials-Portland, OH	S301B
CA₂			FA₃	Mountain Slag-Greenup, KY	M365A
FA₁	Mulzer Stone-New Amsterdam, IN	M289C	FA₄	Bag House Fines (BHF)	10000
	CA₁	CA₂	FA₁	FA₂	FA₃
Agg. Type	#67 Limestone		Limestone	Natural	Slag
Agg. Code	1131		1116	1115	1114
% Total Agg.	40		9	25	10
% RAP Total Agg.:	15		Blended Binder G*/sin delta if > 25% RAP:		
% Binder In RAP Design:	3.8		Binder Type:	PG 64-22	Binder Code: 1093
Binder Source:	Shelly Liquid Division-Kanauga, OH			Binder SourceCode:	M001A

Sieve Fraction							Voids filled with Asphalt (VFA) %	Fines to Asphalt Ratio	
Sieve Size	Target	Allowable Min.	Allowable Max.	Sieve Size	Target	Allowable Min.	Allowable Max.	70	1.2
2" (50 mm)				#4 (4.75 mm)	57			Temperature Range	
1.5" (37.5mm)				#8 (2.36 mm)	43	37	49	Completed Mixture (°F)	
1" (25 mm)	100	100	100	#16 (1.18 mm)	33			Desirable	Temp. Range
3/4" (19 mm)	97	90	100	#30 (600 µm)	25			Mean Temp.	Min. Max.
1/2" (12.5 mm)	81		90	#50 (300 µm)	13				
3/8" (9.5 mm)	72			#200 (75 µm)	5.7	2.0	8.0	311	286 336

JOB MIX FORMULA VALUES				
Specific gravity stone bulk (Gsb): 2.626	Design Property	Job Mix Formula Design Targets	Job Mix Formula Tolerances Minimum	Job Mix Formula Tolerances Maximum
	Asphalt (%)	4.6	4.2	5.0
Maximum	Air Voids (%)	4.0	2.5	5.5
Density (kg/m³)	VMA (%)	14.0	13.0	15.0
	Stability (N)	15333	8000	NA
2473	Flow (0.25mm)	10	8	14
Desirable Mean Temperature for Laboratory Specimens (°F):		Compaction Temperature:	288	Mixing Temperature: 330

Remarks: Additional data for this JMF can be found under T-400# 1426521.

Figure 47: Job Mix Formula for WVP523

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04-10

Approved 3/9/2015

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

Report Number:		1436766		Date Accepted:		March 9, 2015			
HMA Type:		Wearing 1-RAP		HMA Code:		13974			
Producer:		Camden Materials		Plant Location:		Parkersburg, WV			
Designed By:		Brad Saunders/ Jason Frame		Design Lab:		WV Paving-Dunbar, WV			
Plant Type:		Drum		Plant Make:		ASTEC			
Plant Code:		B104H		Traffic Type:		Heavy			
MIX COMPOSITION									
Coarse Aggregate Source			Code		Fine Aggregate Source			Code	
CA ₁	Carneuse Lime-Maysville, KY		D113A		FA ₂	Belpre S & G-Little Hocking, OH		B010A	
CA ₂					FA ₃	Mountain Slag-Greenup, KY		M365A	
FA ₁	Carneuse Lime-Maysville, KY		D113A		FA ₄	Bag House Fines		10000	
	CA ₁		CA ₂		FA ₁		FA ₂		FA ₃
Agg. Type	#8 Limestone				Limestone		Natural		Slag
Agg. Code	1135				1116		1115		1114
% Total Agg.	40				9		25		10
% RAP Total Agg.:		15		Blended Binder G*/sin delta if > 25% RAP:					
% Binder In RAP Design:		5.2		Binder Type:		PG 64-22		Binder Code:	
Binder Source:		Shelly Liquid Division-Kanauga, OH				Binder SourceCode:		M001A	
Sieve Fraction									
Sieve Size	Target	Allowable		Sieve Size	Target	Allowable		Voids filled with Asphalt (VFA) %	Fines to Asphalt Ratio
		Min.	Max.			Min.	Max.		
2" (50 mm)				#4 (4.75 mm)	62		80	Temperature Range Completed Mixture (°F)	Desirable Mean Temp.
1.5" (37.5mm)				#8 (2.36 mm)	41	35	47		
1" (25 mm)				#16 (1.18 mm)	30				
3/4" (19 mm)				#30 (600 µm)	22				
1/2" (12.5 mm)	100	100	100	#50 (300 µm)	11			311	Temp. Range Min. Max.
3/8" (9.5 mm)	95	85	100	#200 (75 µm)	4.8	2.0	9.0		
JOB MIX FORMULA VALUES									
		Job Mix Formula				Job Mix Formula Tolerances			
Specific gravity stone bulk (Gsb): 2.643		Design Property		Design Targets		Minimum		Maximum	
		Asphalt (%)		5.9		5.5		6.3	
Maximum Density (kg/m ³)		Air Voids (%)		4.0		2.5		5.5	
		VMA (%)		15.5		14.5		16.5	
		Stability (N)		12199		8000		NA	
2476		Flow (0.25mm)		10.0		8		14	
Desirable Mean Temperature for Laboratory Specimens (°F):				Compaction Temperature:		288		Mixing Temperature:	
								312	
Remarks:									

Figure 48: Job Mix Formula for WVP766

T400
04-10

WV DOH MCS&T Approval
Reviewed by: D. Phipps / T. Walbeck
Approved by:
Date: Aug 21, 2015

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

Report Number: 1436882				Date Accepted: August 18, 2015			
HMA Type: Wearing 1 Skid-RAP				HMA Code: 13976			
Producer: West Virginia Paving, Inc				Plant Location: Dunbar, WV			
Designed By: Mark Isaacs				Design Lab: Southern WV Asphalt-Alta, WV			
Plant Type: Drum				Plant Make: ASTEC			
Plant Code: W074C				Traffic Type: Heavy			

MIX COMPOSITION							
Coarse Aggregate Source			Code	Fine Aggregate Source			Code
CA ₁	Mountain Slag-Greenup, KY		M365A	FA ₂	Shelly Materials-Portland, OH		S301B
CA ₂				FA ₃			
FA ₁	Mulzer Stone-New Amsterdam, IN		M289C	FA ₄	Bag House Fines		10000
	CA ₁	CA ₂	FA ₁	FA ₂	FA ₃	FA ₄	
Agg. Type	#8 Slag		Limestone	Natural			BHF
Agg. Code	1192		1116	1115			1116
% Total Agg.	30		29	25			1
% RAP Total Agg.:		15		Blended Binder G*/sin delta if > 25% RAP:			
% Binder In RAP Design:		5.3		Binder Type:	PG 64-22	Binder Code:	1093
Binder Source:		Shelly Liquid Division-Kanauga, OH				Binder SourceCode:	M001A

Sieve Fraction								Voids filled with Asphalt (VFA) %	Fines to Asphalt Ratio
Sieve Size	Target	Allowable		Sieve Size	Target	Allowable		76	1.0
		Min.	Max.			Min.	Max.		
2" (50 mm)				#4 (4.75 mm)	66		80	Temperature Range Completed Mixture (°F)	
1.5" (37.5 mm)				#8 (2.36 mm)	43	37	49		
1" (25 mm)				#16 (1.18 mm)	30			Desirable Mean Temp.	Temp. Range Min. Max.
3/4" (19 mm)				#30 (600 µm)	23				
1/2" (12.5 mm)	100	100	100	#50 (300 µm)	13			311	286 336
3/8" (9.5 mm)	94	85	100	#200 (75 µm)	6.2	2.0	9.0		

JOB MIX FORMULA VALUES				
Specific gravity stone bulk (Gsb): 2.605	Design Property	Job Mix Formula Design Targets	Job Mix Formula Tolerances	
			Minimum	Maximum
Maximum Density (kg/m³) 2408	Asphalt (%)	6.1	5.7	6.5
	Air Voids (%)	4.0	2.5	5.5
	VMA (%)	16.8	15.8	17.8
	Stability (N)	14877	8000	NA
	Flow (0.25mm)	10.0	8	14

Desirable Mean Temperature for Laboratory Specimens (°F):		Compaction Temperature:	288	Mixing Temperature:	312
Remarks:					

Figure 49: Job Mix Formula for WVP882

Figure 50: AA937 Gradation Chart

Figure 51: GR465 Gradation Chart

Jefferson Asphalt Paving 909 - 0.45 Power Gradation Chart

Figure 52: JAP909 Gradation Chart

Figure 53: JFA060 Gradation Chart

Figure 54: JFA115 Gradation Chart

J. F. Allen 429 - 0.45 Power Gradation Chart

Figure 55: JFA429 Gradation Chart

Figure 56: KP483 Gradation Chart

West Virginia Paving 523 - 0.45 Power Gradation Chart

Figure 57: WVP523 Gradation Chart

West Virginia Paving 766 - 0.45 Power Gradation Chart

Figure 58: WVP766 Gradation Chart

West Virginia Paving 882 - 0.45 Power Gradation Chart

Figure 59: WVP882 Gradation Chart

Appendix B: Volumetric Properties and SGC Data

Complete G_{mm} Calculations

Table 35: Lab G_{mm} Calculations

Mix ID	Trial 1	Trial 2	Average	Range	SD
GR456	2.475	2.479	2.477	0.0040	0.0029
AA937	2.488	2.490	2.489	0.0017	0.0012
JAP909	2.644	2.643	2.644	0.0011	0.0008
JFA060	2.527	2.530	2.528	0.0028	0.0020
JFA115	2.496	2.492	2.494	0.0033	0.0023
JFA429	2.532	2.526	2.529	0.0056	0.0040
KP483	2.474	2.468	2.471	0.0059	0.0042
WVP523	2.495	2.491	2.493	0.0048	0.0034
WVP766	2.474	2.473	2.474	0.0010	0.0007
WVP882	2.450	2.443	2.447	0.0078	0.0049

*Single operator precision: standard deviation = 0.0051 and range of two results = 0.014

SGC Data

Table 36: AA937 SGC Data

	Height Increments (mm)										
GYR	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
0	202.7	210.3	204.7	202.7	206.1	203.8	204.4	203.2	202.6	202.9	204.1
1	195.2	203.0	197.4	195.4	198.8	196.5	197.1	195.8	195.2	195.4	196.7
2	190.9	198.6	192.9	191.0	194.5	192.3	192.7	191.4	190.9	191.2	192.3
3	187.8	195.3	189.7	187.8	191.3	189.0	189.5	188.2	187.7	188.0	189.2
4	185.3	192.7	187.1	185.3	188.7	186.5	187.0	185.6	185.1	185.5	186.6
5	183.2	190.7	185.0	183.3	186.6	184.4	185.0	183.5	183.1	183.4	184.6
6	181.4	188.9	183.2	181.5	184.9	182.7	183.3	181.7	181.3	181.7	182.8
7	179.9	187.4	181.7	180.0	183.4	181.2	181.8	180.2	179.8	180.2	181.3
8	178.6	186.0	180.3	178.7	182.0	179.9	180.5	178.9	178.5	178.9	180.0
9	177.5	184.8	179.2	177.5	180.9	178.7	179.3	177.7	177.4	177.8	178.8
10	176.4	183.8	178.1	176.5	179.8	177.7	178.2	176.6	176.3	176.7	177.7
11	175.5	182.8	177.1	175.6	178.8	176.7	177.3	175.7	175.4	175.7	176.8
12	174.6	181.9	176.3	174.8	178.0	175.9	176.4	174.8	174.5	174.9	175.9
13	173.9	181.2	175.5	174.0	177.2	175.1	175.6	174.0	173.7	174.1	175.1
14	173.1	180.4	174.8	173.3	176.4	174.4	174.9	173.3	173.0	173.4	174.4
15	172.5	179.7	174.1	172.6	175.7	173.7	174.2	172.6	172.3	172.7	173.7
16	171.9	179.1	173.4	172.0	175.1	173.1	173.5	172.0	171.7	172.1	173.0
17	171.3	178.5	172.9	171.4	174.5	172.5	172.9	171.4	171.1	171.5	172.5
18	170.7	178.0	172.3	170.9	174.0	171.9	172.4	170.8	170.6	170.9	171.9
19	170.2	177.4	171.8	170.4	173.4	171.4	171.9	170.3	170.0	170.4	171.4
20	169.7	176.9	171.3	169.9	172.9	170.9	171.4	169.8	169.6	169.9	170.9
21	169.3	176.5	170.8	169.4	172.5	170.4	170.9	169.3	169.1	169.4	170.4
22		176.0	170.4		172.0	170.0	170.5				170.0
23		175.6	169.9		171.6	169.6	170.0				169.5
24		175.2	169.5		171.2	169.2	169.6				
25		174.8			170.8		169.2				
26		174.4			170.5						
27		174.1			170.1						
28		173.7			169.8						
29		173.4			169.4						
Break		...									
40		170.4									
41		170.2									
42		170.0									
43		169.8									
44		169.6									

Table 37: GR465 SGC Data

	Height Increments (mm)				
GYR	S0	S1	S2	S3	Bulk Sample
0	0.0	227.6	226.8	226.5	157.8
1	0.0	219.2	218.5	218.1	150.7
2	227.5	214.2	213.5	213.2	146.8
3	224.8	210.2	209.8	209.4	144.1
4	222.0	207.2	206.8	206.4	141.9
5	219.6	204.7	204.2	203.8	140.1
6	217.5	202.5	202.0	201.7	138.7
7	215.8	200.7	200.2	199.9	137.4
8	214.2	199.1	198.6	198.3	136.4
9	212.8	197.7	197.2	196.9	135.4
10	211.6	196.4	195.9	195.7	134.5
11	210.5	195.3	194.7	194.5	133.8
12	209.4	194.2	193.7	193.5	133.1
13	208.5	193.3	192.7	192.6	132.5
14	207.6	192.4	191.9	191.7	131.9
15	206.8	191.6	191.0	190.9	131.3
16	206.1	190.9	190.3	190.2	130.8
17	205.3	190.2	189.6	189.5	130.4
18	204.7	189.5	189.0	188.8	129.9
19	204.1	188.9	188.4	188.2	129.5
20	203.5	188.4	187.8	187.6	129.2
21	202.9	187.8	187.2	187.1	128.8
22	202.4	187.3	186.7	186.6	128.5
23	201.9	186.9	186.3	186.1	128.1
24	201.4	186.4	185.8	185.6	127.8
25	201.0	186.0	185.4	185.2	127.5
26	200.5	185.6	184.9	184.8	127.3
27	200.1	185.2	184.6	184.4	127.0
28	199.7	184.8	184.2	184.0	126.7
29	199.3	184.4	183.8	183.7	126.5
30	199.0	184.1	183.5	183.3	126.3
31	198.6	183.8	183.1	183.0	126.0
32	198.3	183.5	182.8	182.7	125.8
33	198.0	183.2	182.5	182.3	125.6
34	197.6	182.9	182.2	182.0	125.4
35	197.3	182.6	181.9	181.8	125.2
36	197.1	182.3	181.7	181.5	125.1
37	196.8	182.1	181.4	181.2	124.9
38	196.5	181.8	181.2	181.0	124.7
39	196.2	181.6	180.9	180.7	124.5
40	196.0	181.3	180.7	180.5	124.4
41	195.7	181.1	180.4	180.2	124.2
Break					

42	195.5	180.9	180.2	180.0	124.1
43	195.3	180.7	180.0	179.8	123.9
44	195.0	180.4	179.8	179.6	123.8
45	194.8	180.2	179.6		123.7
46	194.6	180.0			123.5
47	194.4	179.9			123.4
48	194.2	179.7			123.3
49	194.0				123.1
50	193.8				123.0
51	193.6				122.9
52	193.4				122.8
53	193.2				122.7
54	193.1				122.6
55	192.9				122.5
56	192.7				122.4
57	192.6				122.3
58	192.4				122.2
59	192.3				122.1
60	192.1				122.0
61	192.0				121.9
62	191.8				121.8
63	191.7				121.7
64	191.5				121.6
65	191.4				121.5
66	191.3				121.4
67	191.1				121.4
68	191.0				121.3
69	190.9				121.2
70	190.7				121.1
71	190.6				121.1
72	190.5				121.0
73	190.4				120.9
74	190.3				120.8
75	190.2				120.8
76	190.1				120.7
77	189.9				120.6
78	189.8				120.6
79	189.7				120.5
80	189.6				120.5
81	189.5				
82	189.4				
83	189.3				
84	189.2				

Table 38: JAP909 SGC Data

	Height Increments (mm)										
GYR	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
0	200.1	204.2	203.1	203.1	203.3	203.0	202.8	201.9	201.5	202.6	201.6
1	192.6	196.9	195.4	195.6	195.8	195.6	195.5	194.5	194.2	195.2	194.3
2	188.5	192.7	191.2	191.5	191.7	191.6	191.2	190.4	190.1	190.9	190.0
3	185.5	189.7	188.2	188.5	188.6	188.5	188.2	187.4	187.1	188.0	187.0
4	183.2	187.3	185.8	186.2	186.2	186.3	185.8	185.1	184.7	185.6	184.7
5	181.3	185.4	183.9	184.3	184.3	184.3	183.9	183.2	182.9	183.7	182.8
6	179.7	183.8	182.3	182.7	182.7	182.8	182.2	181.6	181.3	182.1	181.3
7	178.4	182.4	181.0	181.3	181.4	181.4	180.9	180.2	179.9	180.7	179.9
8	177.2	181.2	179.8	180.1	180.2	180.2	179.7	179.0	178.8	179.5	178.7
9	176.1	180.2	178.7	179.1	179.1	179.2	178.6	178.0	177.7	178.5	177.7
10	175.2	179.2	177.8	178.1	178.2	178.3	177.7	177.1	176.8	177.5	176.8
11	174.4	178.3	177.0	177.3	177.4	177.5	176.8	176.3	176.0	176.7	176.0
12	173.6	177.6	176.2	176.6	176.6	176.7	176.0	175.5	175.2	175.9	175.3
13	172.9	176.9	175.5	175.9	175.9	176.0	175.3	174.8	174.6	175.3	174.6
14	172.3	176.2	174.9	175.2	175.3	175.4	174.7	174.2	173.9	174.6	174.0
15	171.7	175.6	174.3	174.7	174.7	174.8	174.1	173.6	173.3	174.0	173.4
16	171.2	175.1	173.7	174.1	174.1	174.3	173.5	173.1	172.8	173.5	172.9
17	170.7	174.6	173.2	173.6	173.6	173.8	173.0	172.6	172.3	173.0	172.4
18	170.2	174.1	172.8	173.1	173.1	173.3	172.5	172.1	171.8	172.5	171.9
19	169.8	173.6	172.3	172.7	172.6	172.8	172.1	171.7	171.4	172.1	171.5
20	169.3	173.2	171.9	172.3	172.2	172.4	171.6	171.2	171.0	171.6	171.1
21		172.8	171.5	171.9	171.8	172.0	171.2	170.8	170.6	171.3	170.7
22		172.4	171.1	171.5	171.4	171.6	170.8	170.5	170.2	170.9	170.3
23		172.0	170.7	171.1	171.1	171.3	170.5	170.1	169.9	170.5	170.0
24		171.7	170.4	170.8	170.7	170.9	170.1	169.7	169.5	170.2	169.6
25		171.3	170.0	170.5	170.4	170.6	169.8	169.4		169.9	
26		171.0	169.7	170.1	170.0	170.3	169.5			169.5	
27		170.7	169.4	169.9	169.7	170.0					
28		170.4		169.6	169.4	169.7					
29		170.1				169.5					
30		169.9									
31		169.6									

Table 39: JFA060 SGC Data

	Height Increments (mm)										
GYR	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
0	221.4	204.4	206.4	206.5	206.5	207.0	205.7	206.0	205.4	205.9	207.2
1	213.6	196.7	198.7	198.8	198.7	199.4	198.2	198.4	197.7	198.4	199.8
2	209.0	192.5	194.4	194.6	194.4	195.2	193.9	194.1	193.5	194.3	195.5
3	205.6	189.4	191.2	191.4	191.3	192.1	190.7	190.9	190.4	191.2	192.3
4	203.0	186.8	188.7	189.0	188.8	189.6	188.2	188.5	187.9	188.8	189.9
5	200.8	184.9	186.7	187.0	186.7	187.5	186.2	186.5	185.9	186.8	187.9
6	199.0	183.2	185.0	185.3	185.1	185.8	184.5	184.8	184.3	185.1	186.2
7	197.4	181.8	183.5	183.9	183.6	184.4	183.0	183.3	182.8	183.7	184.8
8	196.1	180.5	182.3	182.6	182.3	183.1	181.8	182.1	181.6	182.4	183.5
9	194.9	179.5	181.1	181.5	181.2	182.0	180.7	181.0	180.5	181.3	182.4
10	193.8	178.5	180.2	180.5	180.2	181.0	179.6	180.0	179.5	180.3	181.4
11	192.8	177.6	179.2	179.6	179.3	180.1	178.8	179.1	178.6	179.4	180.4
12	192.0	176.8	178.4	178.8	178.5	179.3	178.0	178.3	177.8	178.6	179.6
13	191.2	176.1	177.7	178.1	177.8	178.5	177.2	177.5	177.1	177.9	178.9
14	190.4	175.4	177.0	177.4	177.1	177.8	176.5	176.8	176.4	177.2	178.2
15	189.7	174.8	176.3	176.8	176.5	177.2	175.9	176.2	175.8	176.5	177.5
16	189.1	174.2	175.7	176.2	175.9	176.6	175.3	175.6	175.2	175.9	176.9
17	188.5	173.7	175.1	175.6	175.3	176.0	174.8	175.1	174.6	175.4	176.4
18	187.9	173.2	174.6	175.1	174.8	175.5	174.3	174.6	174.1	174.9	175.8
19	187.4	172.7	174.1	174.6	174.3	175.0	173.8	174.1	173.6	174.4	175.4
20	186.9	172.2	173.7	174.2	173.9	174.5	173.3	173.6	173.2	173.9	174.9
21	186.4	171.8	173.2	173.7	173.4	174.1	172.9	173.2	172.7	173.5	174.5
22	186.0	171.4	172.8	173.3	173.0	173.7	172.5	172.8	172.3	173.1	174.0
23	185.6	171.0	172.4	172.9	172.6	173.3	172.1	172.4	171.9	172.7	173.6
24	185.2	170.7	172.1	172.5	172.3	172.9	171.7	172.0	171.6	172.3	173.3
25	184.8	170.3	171.7	172.2	171.9	172.5	171.3	171.7	171.2	172.0	172.9
26	184.4	170.0	171.4	171.9	171.6	172.2	171.0	171.3	170.9	171.6	172.6
27	184.1	169.7	171.0	171.5	171.2	171.9	170.6	171.0	170.5	171.3	172.2
28	183.7		170.7	171.2	170.9	171.5	170.3	170.7	170.2	171.0	171.9
29	183.4		170.4	170.9	170.6	171.2	170.0	170.4	169.9	170.7	171.6
30	183.1		170.1	170.6	170.3	170.9	169.7	170.1	169.6	170.4	171.3
31	182.8		169.9	170.4	170.1	170.6	169.5	169.8		170.1	171.1
32	182.5		169.6	170.1	169.8	170.4		169.6		169.9	170.8
33	182.2			169.8	169.6	170.1				169.6	170.5
34	182.0			169.6		169.9					170.3
35	181.7					169.6					170.0
36	181.5										169.8
37	181.2										169.6
Break	...										
159	170.1										
160	170.0										
161	170.0										
162	170.0										
163	170.0										

Table 40: JFA429 SGC Data

	Height Increments (mm)											
GYR	SS1	SS2	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0	138.4	140.8	208.7	215.2	213.9	213.9	213.4	212.3	211.5	210.9	211.7	212.1
1	132.6	134.7	201.1	207.4	206.1	206.1	205.6	204.4	203.6	203.1	203.8	204.4
2	129.5	131.7	196.7	202.9	201.6	201.6	201.2	200.0	199.2	198.7	199.4	200.0
3	127.3	129.5	193.5	199.6	198.3	198.3	197.9	196.7	195.9	195.5	196.2	196.7
4	125.6	127.8	191.1	197.0	195.7	195.7	195.4	194.2	193.4	193.0	193.7	194.1
5	124.3	126.5	189.1	194.9	193.5	193.6	193.4	192.2	191.4	190.9	191.6	192.0
6	123.2	125.4	187.4	193.1	191.7	191.8	191.6	190.5	189.7	189.1	189.8	190.3
7	122.2	124.4	186.0	191.6	190.1	190.3	190.1	189.1	188.2	187.7	188.4	188.7
8	121.4	123.6	184.7	190.2	188.8	189.0	188.8	187.8	187.0	186.4	187.0	187.4
9	120.7	122.8	183.6	189.0	187.6	187.8	187.7	186.7	185.8	185.2	185.9	186.2
10	120.1	122.1	182.6	187.9	186.6	186.8	186.6	185.6	184.8	184.2	184.8	185.1
11	119.5	121.5	181.7	187.0	185.6	185.8	185.7	184.7	183.9	183.3	183.9	184.2
12	118.9	121.0	180.9	186.1	184.8	185.0	184.9	183.9	183.1	182.4	183.1	183.3
13	118.5	120.5	180.2	185.3	184.0	184.2	184.1	183.2	182.3	181.7	182.3	182.5
14	118.0	120.0	179.5	184.6	183.2	183.5	183.4	182.5	181.6	181.0	181.6	181.8
15	117.6	119.6	178.8	183.9	182.6	182.8	182.8	181.8	181.0	180.3	180.9	181.1
16	117.2	119.2	178.2	183.3	181.9	182.2	182.2	181.2	180.3	179.7	180.3	180.4
17	116.8	118.8	177.7	182.7	181.4	181.6	181.6	180.7	179.8	179.1	179.8	179.8
18	116.5	118.5	177.1	182.1	180.8	181.1	181.0	180.1	179.2	178.6	179.2	179.3
19	116.2	118.1	176.6	181.6	180.3	180.6	180.5	179.6	178.7	178.1	178.7	178.8
20	115.9	117.8	176.2	181.1	179.8	180.1	180.1	179.2	178.3	177.6	178.2	178.3
21	115.6	117.5	175.7	180.6	179.4	179.6	179.6	178.7	177.8	177.2	177.8	177.9
22	115.3	117.3	175.3	180.2	178.9	179.2	179.2	178.3	177.4	176.8	177.3	177.4
23	115.1	117.0	174.9	179.8	178.5	178.8	178.8	177.9	177.0	176.3	177.0	177.0
24	114.8	116.8	174.5	179.4	178.1	178.4	178.4	177.5	176.6	176.0	176.6	176.6
25	114.6	116.5	174.1	179.0	177.7	178.1	178.0	177.2	176.2	175.6	176.2	176.3
26	114.4	116.3	173.8	178.6	177.4	177.7	177.7	176.8	175.9	175.2	175.8	175.9
27	114.1	116.1	173.4	178.3	177.0	177.4	177.3	176.5	175.6	174.9	175.5	175.6
28	113.9	115.9	173.1	177.9	176.7	177.1	177.0	176.2	175.2	174.6	175.2	175.3
29	113.7	115.7	172.8	177.6	176.4	176.8	176.7	175.9	174.9	174.3	174.9	174.9
30	113.5	115.5	172.5	177.3	176.1	176.5	176.4	175.6	174.6	174.0	174.6	174.7
31	113.4	115.3	172.2	177.0	175.8	176.2	176.1	175.3	174.3	173.7	174.3	174.4
32	113.2	115.1	171.9	176.7	175.5	175.9	175.8	175.0	174.0	173.4	174.0	174.1
33	113.0	114.9	171.7	176.4	175.2	175.6	175.6	174.8	173.8	173.2	173.8	173.8
34	112.9	114.8	171.4	176.2	175.0	175.4	175.3	174.5	173.5	172.9	173.5	173.6
35	112.7	114.6	171.2	175.9	174.7	175.1	175.1	174.3	173.3	172.7	173.3	173.3
36	112.5	114.5	170.9	175.7	174.5	174.9	174.8	174.0	173.0	172.4	173.0	173.1
37	112.4	114.3	170.7	175.4	174.2	174.6	174.6	173.8	172.8	172.2	172.8	172.8

38	112.3	114.2	170.5	175.2	174.0	174.4	174.4	173.6	172.6	171.9	172.6	172.6
39	112.1	114.0	170.3	175.0	173.8	174.2	174.2	173.4	172.3	171.7	172.3	172.4
40	112.0	113.9	170.1	174.7	173.6	174.0	174.0	173.2	172.1	171.5	172.1	172.2
41	111.9	113.8	169.9	174.5	173.4	173.8	173.8	173.0	171.9	171.3	171.9	172.0
42	111.7	113.6	169.7	174.3	173.1	173.6	173.6	172.8	171.7	171.1	171.7	171.8
43	111.6	113.5		174.1	173.0	173.4	173.4	172.6	171.5	170.9	171.5	171.6
44	111.5	113.4		173.9	172.8	173.2	173.2	172.4	171.3	170.8	171.3	171.4
45	111.4	113.3		173.7	172.6	173.0	173.0	172.2	171.1	170.6	171.1	171.2
46	111.3	113.2		173.6	172.4	172.8	172.8	172.0	171.0	170.4	171.0	171.0
47	111.1	113.1		173.4	172.2	172.6	172.6	171.8	170.8	170.3	170.8	170.8
48	111.0	113.0		173.2	172.0	172.5	172.5	171.7	170.6	170.1	170.6	170.7
49	110.9	112.8		173.0	171.9	172.3	172.3	171.5	170.5	169.9	170.4	170.5
50	110.8	112.7		172.9	171.7	172.1	172.1	171.3	170.3	169.8	170.3	170.3
51	110.7	112.6		172.7	171.5	172.0	172.0	171.2	170.1		170.1	170.2
52	110.6	112.5		172.6	171.4	171.8	171.8	171.0	170.0		169.9	170.0
53	110.5	112.4		172.4	171.2	171.6	171.7	170.9	169.8		169.8	169.9
54	110.5	112.3		172.2	171.0	171.5	171.5	170.7				169.7
55	110.4	112.3		172.1	170.9	171.3	171.4	170.6				
56	110.3	112.2		172.0	170.7	171.2	171.3	170.5				
57	110.2	112.1		171.8	170.6	171.0	171.1	170.3				
58	110.1	112.0		171.7	170.5	170.9	171.0	170.2				
59	110.0	111.9		171.5	170.3	170.7	170.9	170.0				
60	109.9	111.8		171.4	170.2	170.6	170.7	169.9				
61	109.9	111.7		171.3	170.1	170.5	170.6	169.8				
62	109.8	111.7		171.1	169.9	170.4	170.5					
63	109.7	111.6		171.0	169.8	170.2	170.4					
64	109.6	111.5		170.9		170.1	170.2					
65	109.6	111.4		170.8		170.0	170.1					
66	109.5	111.3		170.7		169.9	170.0					
67	109.4	111.3		170.5			169.9					
68	109.3	111.2		170.4			169.8					
69	109.3	111.1		170.3								
70	109.2	111.1		170.2								
71	109.1	111.0		170.1								
72	109.1	110.9		170.0								
73	109.0	110.9		169.9								
74	108.9	110.8		169.8								
75	108.9	110.7										
76	108.8	110.7										
77	108.8	110.6										
78	108.7	110.5										
79	108.6	110.5										
80	108.6	110.4										

Table 41: JFA115 SGC Data

	Height Increments (mm)										
GYR	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
0	215.1	186.3	210.1	208.2	209.8	208.4	208.8	208.1	208.5	208.5	209.5
1	207.5	179.2	202.4	200.8	202.1	200.8	201.4	200.5	200.8	201.0	201.8
2	203.0	175.1	198.0	196.4	197.7	196.5	197.1	196.1	196.5	196.6	197.4
3	199.6	172.3	194.7	193.3	194.5	193.3	193.9	193.0	193.2	193.4	194.2
4	197.1	170.0	192.1	190.8	191.9	190.8	191.3	190.4	190.7	190.9	191.7
5	194.9	168.2	190.0	188.7	189.8	188.8	189.3	188.4	188.6	188.8	189.6
6	193.1	166.6	188.2	187.0	188.1	187.0	187.5	186.6	186.9	187.0	187.8
7	191.6		186.7	185.5	186.6	185.6	186.0	185.2	185.4	185.5	186.4
8	190.2		185.4	184.2	185.2	184.2	184.7	183.9	184.1	184.2	185.0
9	189.0		184.2	183.1	184.1	183.1	183.6	182.7	182.9	183.0	183.9
10	187.9		183.2	182.0	183.0	182.0	182.5	181.7	181.9	182.0	182.8
11	187.0		182.2	181.1	182.1	181.1	181.6	180.8	181.0	181.0	181.9
12	186.1		181.3	180.3	181.2	180.2	180.7	179.9	180.1	180.1	181.0
13	185.3		180.5	179.5	180.4	179.5	180.0	179.1	179.3	179.4	180.3
14	184.5		179.8	178.8	179.7	178.7	179.2	178.4	178.6	178.6	179.5
15	183.8		179.2	178.1	179.0	178.1	178.6	177.7	177.9	178.0	178.9
16	183.2		178.5	177.5	178.4	177.4	178.0	177.1	177.3	177.4	178.2
17	182.6		177.9	176.9	177.8	176.9	177.4	176.5	176.7	176.8	177.7
18	182.1		177.4	176.4	177.2	176.3	176.8	176.0	176.2	176.2	177.1
19	181.5		176.9	175.9	176.7	175.8	176.3	175.5	175.7	175.7	176.6
20	181.0		176.4	175.4	176.2	175.3	175.8	175.0	175.2	175.2	176.1
21	180.6		175.9	175.0	175.8	174.9	175.3	174.6	174.7	174.8	175.6
22	180.1		175.5	174.5	175.3	174.4	174.9	174.1	174.3	174.3	175.2
23	179.7		175.1	174.1	174.9	174.0	174.5	173.7	173.9	173.9	174.8
24	179.3		174.7	173.7	174.5	173.6	174.1	173.3	173.5	173.5	174.4
25	178.9		174.3	173.4	174.1	173.3	173.7	172.9	173.1	173.1	174.0
26	178.5		173.9	173.0	173.8	172.9	173.4	172.6	172.8	172.8	173.6
27	178.2		173.6	172.7	173.4	172.6	173.0	172.2	172.4	172.4	173.3
28	177.8		173.3	172.4	173.1	172.2	172.7	171.9	172.1	172.1	173.0
29	177.5		172.9	172.0	172.8	171.9	172.4	171.6	171.8	171.8	172.7
30	177.2		172.6	171.7	172.5	171.6	172.1	171.3	171.5	171.5	172.4
31	176.9		172.3	171.5	172.2	171.3	171.8	171.0	171.2	171.2	172.1
32	176.6		172.1	171.2	171.9	171.0	171.5	170.7	170.9	170.9	171.8
33	176.3		171.8	170.9	171.6	170.8	171.2	170.4	170.6	170.6	171.5
34	176.0		171.5	170.6	171.4	170.5	171.0	170.2	170.4	170.4	171.2
35	175.8		171.3	170.4	171.1	170.2	170.7	169.9	170.1	170.1	171.0
36	175.5		171.0	170.1	170.9	170.0	170.5	169.7	169.9	169.9	170.7
37	175.3		170.8	169.9	170.6	169.8	170.2		169.7	169.6	170.5

38	175.0		170.5	169.7	170.4		170.0				170.3
39	174.8		170.3		170.2		169.8				170.1
40	174.6		170.1		170.0						169.8
41	174.4		169.9		169.8						169.7
42	174.2		169.7								
Break	...										
67	170.3										
68	170.2										
69	170.1										
70	170.0										
71	169.9										

Table 42: KP483 SGC Data

	Height Increments (mm)										
GYR	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
0	210.6	201.5	203.5	204.7	202.7	202.4	201.8	202.3	203.3	202.9	203.2
1	203.2	194.1	196.1	197.6	195.4	195.2	194.7	195.0	196.1	195.6	196.0
2	198.9	190.1	192.1	193.4	191.4	191.2	190.6	190.9	191.9	191.5	191.9
3	195.8	187.1	189.2	190.4	188.3	188.2	187.6	187.9	188.9	188.5	188.8
4	193.4	184.8	186.9	188.1	185.9	185.9	185.3	185.6	186.6	186.2	186.5
5	191.3	182.9	185.0	186.1	184.0	184.0	183.4	183.7	184.7	184.3	184.6
6	189.6	181.4	183.4	184.5	182.5	182.4	181.8	182.1	183.1	182.8	183.0
7	188.2	180.0	182.1	183.2	181.1	181.1	180.5	180.8	181.7	181.4	181.7
8	187.0	178.8	180.9	182.0	179.9	179.9	179.3	179.6	180.6	180.2	180.5
9	185.9	177.8	179.9	180.9	178.9	178.9	178.3	178.6	179.6	179.2	179.5
10	185.0	176.9	179.0	180.0	178.0	177.9	177.4	177.7	178.6	178.3	178.5
11	184.1	176.1	178.2	179.2	177.2	177.1	176.5	176.8	177.8	177.4	177.7
12	183.3	175.3	177.4	178.4	176.4	176.4	175.8	176.1	177.1	176.7	176.9
13	182.6	174.6	176.7	177.7	175.8	175.7	175.1	175.4	176.4	176.0	176.3
14	181.9	174.0	176.1	177.1	175.1	175.1	174.5	174.8	175.8	175.4	175.6
15	181.3	173.4	175.5	176.5	174.6	174.5	173.9	174.2	175.2	174.8	175.0
16	180.8	172.9	175.0	175.9	174.0	174.0	173.3	173.7	174.7	174.2	174.5
17	180.3	172.4	174.5	175.4	173.5	173.4	172.8	173.1	174.2	173.7	174.0
18	179.8	171.9	174.0	174.9	173.0	173.0	172.4	172.7	173.7	173.2	173.5
19	179.3	171.5	173.6	174.5	172.6	172.5	171.9	172.2	173.3	172.8	173.1
20	178.9	171.1	173.2	174.1	172.2	172.1	171.5	171.8	172.9	172.4	172.6
21	178.5	170.7	172.8	173.7	171.8	171.7	171.1	171.4	172.5	172.0	172.3
22	178.1	170.3	172.4	173.3	171.4	171.4	170.8	171.1	172.1	171.6	171.9
23	177.7	170.0	172.0	172.9	171.1	171.0	170.4	170.7	171.7	171.3	171.5
24	177.4	169.7	171.7	172.6	170.7	170.7	170.1	170.4	171.4	170.9	171.2
25	177.0		171.4	172.3	170.4	170.4	169.7	170.1	171.1	170.6	170.9
26	176.7		171.1	171.9	170.1	170.1	169.4	169.8	170.8	170.3	170.6
27	176.4		170.8	171.6	169.8	169.8		169.5	170.5	170.0	170.3
28	176.1		170.5	171.4	169.6	169.5			170.2	169.7	170.0
29	175.8		170.2	171.1					170.0		169.7
30	175.6		170.0	170.8					169.7		
31	175.3		169.7	170.6							
32	175.1			170.3							
33	174.8			170.1							
34	174.6			169.9							
35	174.3			169.7							
Break	...										
63	170.0										
64	169.9										
65	169.8										

Table 43: WVP523 SGC Data

	Height Increments (mm)											
GYR	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
0	197.0	203.5	193.1	191.5	190.8	191.5	191.4	192.5	193.2	192.7	192.7	191.9
1	190.3	196.7	186.5	185.0	184.5	185.0	184.7	185.9	186.5	186.0	186.1	185.4
2	186.6	193.0	182.9	181.6	181.1	181.5	181.4	182.4	182.9	182.4	182.6	181.9
3	184.1	190.5	180.4	179.2	178.7	179.1	179.0	179.9	180.4	179.9	180.2	179.5
4	182.2	188.5	178.5	177.3	176.9	177.2	177.1	178.1	178.5	178.1	178.3	177.7
5	180.6	186.9	177.0	175.9	175.5	175.7	175.7	176.6	176.9	176.6	176.8	176.2
6	179.3	185.6	175.7	174.7	174.2	174.5	174.4	175.3	175.7	175.3	175.5	175.0
7	178.3	184.5	174.7	173.6	173.2	173.5	173.4	174.3	174.6	174.3	174.5	174.0
8	177.3	183.5	173.7	172.7	172.4	172.6	172.5	173.4	173.7	173.4	173.6	173.1
9	176.5	182.7	173.0	172.0	171.6	171.8	171.8	172.6	172.9	172.6	172.8	172.3
10	175.8	182.0	172.2	171.3	170.9	171.1	171.1	171.9	172.2	171.9	172.1	171.6
11	175.2	181.3	171.6	170.7	170.4	170.5	170.5	171.2	171.6	171.2	171.4	171.0
12	174.6	180.7	171.0	170.1	169.8	169.9	169.9	170.7	171.0	170.7	170.9	170.4
13	174.0	180.2	170.5	169.6	169.3	169.4	169.4	170.2	170.5	170.2	170.3	169.9
14	173.6	179.7	170.0	169.1				169.7	170.0	169.7	169.9	169.4
15	173.1	179.2	169.6					169.2	169.6	169.2	169.4	
16	172.7	178.8	169.2						169.1			
17	172.3	178.4										
18	171.9	178.0										
19	171.6	177.7										
20	171.3	177.3										
21	171.0	177.0										
22	170.7	176.7										
23	170.4	176.4										
24	170.2	176.2										
25	169.9	175.9										
26	169.7	175.7										
Break		...										
71		170.2										
72		170.1										
73		170.0										
74		170.0										
75		169.9										

Table 44: WVP766 SGC Data

	Height Increments (mm)											
GYR	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
0	196.4	211.8	200.9	201.1	201.2	201.3	200.0	199.5	200.1	200.8	201.0	201.0
1	189.4	204.6	193.9	193.9	194.1	194.2	193.1	192.6	193.0	193.7	193.9	194.1
2	185.4	200.5	189.9	190.0	190.1	190.3	189.2	188.6	189.1	189.7	190.0	190.1
3	182.6	197.4	187.0	187.1	187.2	187.4	186.3	185.8	186.1	186.8	187.1	187.2
4	180.4	195.1	184.8	184.9	185.0	185.2	184.1	183.6	183.9	184.6	184.9	185.0
5	178.6	193.2	183.0	183.1	183.1	183.4	182.3	181.8	182.2	182.8	183.1	183.1
6	177.1	191.6	181.5	181.6	181.6	181.9	180.8	180.3	180.6	181.2	181.6	181.7
7	175.9	190.2	180.2	180.3	180.3	180.6	179.5	179.0	179.4	180.0	180.3	180.4
8	174.8	189.0	179.1	179.2	179.2	179.4	178.4	177.9	178.3	178.8	179.2	179.3
9	173.8	188.0	178.1	178.2	178.2	178.4	177.4	177.0	177.3	177.9	178.2	178.3
10	172.9	187.1	177.3	177.4	177.3	177.6	176.5	176.1	176.4	177.0	177.3	177.4
11	172.2	186.2	176.5	176.6	176.5	176.8	175.7	175.4	175.6	176.2	176.5	176.6
12	171.4	185.5	175.8	175.9	175.8	176.1	175.0	174.6	174.9	175.5	175.8	175.9
13	170.8	184.8	175.1	175.2	175.1	175.4	174.4	174.0	174.3	174.8	175.1	175.3
14	170.2	184.2	174.5	174.6	174.5	174.8	173.8	173.4	173.7	174.2	174.5	174.7
15	169.7	183.6	173.9	174.1	173.9	174.2	173.2	172.9	173.1	173.6	174.0	174.1
16	169.1	183.0	173.4	173.5	173.4	173.7	172.7	172.4	172.6	173.1	173.5	173.6
17		182.5	172.9	173.1	172.9	173.2	172.2	171.9	172.1	172.6	173.0	173.1
18		182.0	172.5	172.6	172.5	172.8	171.8	171.4	171.6	172.2	172.5	172.7
19		181.6	172.1	172.2	172.1	172.4	171.3	171.0	171.2	171.8	172.1	172.3
20		181.2	171.7	171.8	171.6	172.0	170.9	170.6	170.8	171.4	171.7	171.9
21		180.8	171.3	171.4	171.3	171.6	170.5	170.2	170.4	171.0	171.3	171.5
22		180.4	170.9	171.1	170.9	171.2	170.2	169.9	170.1	170.6	170.9	171.1
23		180.0	170.6	170.7	170.6	170.9	169.8	169.5	169.7	170.3	170.6	170.8
24		179.7	170.3	170.4	170.2	170.6	169.5		169.4	169.9	170.3	170.5
25		179.4	170.0	170.1	169.9	170.3				169.6	170.0	170.2
26		179.1	169.7	169.8	169.6	170.0					169.7	169.9
27		178.8		169.5		169.7						169.6
Break		...										
98		170.1										
99		170.1										
100		170.0										
101		170.0										
102		169.9										

Table 45: WVP882 SGC Data

	Height Increments (mm)										
GYR	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
0	191.4	201.3	191.9	191.6	192.1	191.9	192.9	191.4	190.7	192.4	192.7
1	184.6	194.4	185.2	184.8	185.4	185.3	186.1	184.8	183.9	185.7	186.0
2	181.0	190.6	181.5	181.3	181.8	181.6	182.5	181.1	180.3	182.1	182.3
3	178.3	187.8	178.9	178.8	179.2	178.9	179.9	178.5	177.7	179.4	179.6
4	176.3	185.7	176.9	176.7	177.1	177.0	177.8	176.4	175.7	177.3	177.6
5	174.7	184.0	175.2	175.1	175.4	175.3	176.2	174.8	174.1	175.7	175.9
6	173.3	182.6	173.9	173.8	174.1	174.0	174.8	173.4	172.8	174.3	174.5
7	172.2	181.4	172.7	172.6	172.9	172.8	173.6	172.2	171.6	173.1	173.3
8	171.2	180.3	171.7	171.6	171.9	171.8	172.6	171.2	170.6	172.1	172.3
9	170.3	179.4	170.8	170.7	171.0	170.9	171.6	170.3	169.8	171.2	171.5
10	169.5	178.5	170.0	170.0	170.2	170.1	170.8	169.5	168.9	170.4	170.6
11	168.8	177.8	169.2	169.2	169.5	169.4	170.1	168.7		169.7	169.9
12		177.1			168.8	168.81	169.5			169.0	169.2
13		176.5					168.8				
14		175.9									
15		175.4									
16		174.9									
17		174.4									
18		174.0									
19		173.5									
20		173.2									
21		172.8									
22		172.5									
23		172.1									
24		171.8									
25		171.5									
26		171.3									
27		171.0									
28		170.7									
29		170.5									
30		170.3									
31		170.1									
32		169.8									
33		169.7									

Verification Data

Table 46: Marshall Verification Data

Sample #	Diameter (mm)		Height (mm)		SSD		CL		Dim.	
	AVG	SD	AVG	SD	G _{mb}	VTM	G _{mb}	VTM	G _{mb}	VTM
AA937_10	101.60	0.00	62.19	0.05	2.424	2.6	2.394	3.8	2.380	4.4
AA937_11	101.60	0.00	62.46	0.06	2.422	2.7	2.386	4.2	2.366	5.0
AA937_12	101.60	0.00	62.23	0.05	2.423	2.7	2.389	4.0	2.373	4.7
JAP909_22	101.50	0.00	61.19	0.15	2.539	4.1	2.503	5.5	2.472	6.7
JAP909_23	101.60	0.00	61.10	0.02	2.543	4.0	2.505	5.4	2.470	6.7
JAP909_24	101.60	0.00	61.22	0.15	2.534	4.3	2.499	5.6	2.464	6.9
JFA060_1	101.70	0.00	63.00	0.04	2.436	3.6	2.395	5.2	2.349	7.1
JFA060_2	101.70	0.00	62.68	0.12	2.446	3.2	2.412	4.6	2.364	6.5
JFA060_3	101.60	0.00	61.85	0.15	2.447	3.2	2.414	4.5	2.395	5.3
JFA115_7	101.70	0.00	62.89	0.02	2.387	4.1	2.360	5.2	2.378	4.5
JFA115_8	101.70	0.00	64.56	0.08	2.380	4.4	2.347	5.7	2.324	6.6
JFA115_9	101.70	0.00	64.64	0.07	2.386	4.1	2.346	5.7	2.322	6.7
KP483_16	101.60	0.00	63.75	0.09	2.362	4.4	2.333	5.6	2.313	6.4
KP483_17	101.60	0.00	63.59	0.03	2.365	4.3	2.341	5.3	2.323	6.0
KP483_18	101.70	0.00	63.15	0.04	2.367	4.2	2.339	5.3	2.321	6.1
WVP523_13	101.60	0.00	63.04	0.08	2.404	3.6	2.386	4.3	2.374	4.8
WVP523_14	101.70	0.00	63.32	0.05	2.400	3.7	2.384	4.4	2.368	5.0
WVP523_15	101.65	0.00	63.66	0.07	2.401	3.7	2.384	4.4	2.363	5.2
WVP766_19	101.60	0.00	63.80	0.22	2.384	3.6	2.361	4.6	2.334	5.7
WVP766_20	101.60	0.00	63.70	0.17	2.383	3.7	2.362	4.5	2.335	5.6
WVP766_21	101.65	0.00	63.60	0.20	2.384	3.6	2.362	4.5	2.336	5.6
WVP882_4	101.60	0.00	63.33	0.07	2.386	2.5	2.369	3.2	2.354	3.8
WVP882_5	101.60	0.00	62.89	0.02	2.400	1.9	2.374	3.0	2.368	3.2
WVP882_6	101.60	0.00	63.42	0.03	2.394	2.2	2.377	2.8	2.364	3.4

Table 47: Superpave Verification Data

Sample #	Diameter (mm)		Height (mm)		SSD		CoreLok		Dimensional	
	AVG	SD	AVG	SD	G _{mb}	VTM	G _{mb}	VTM	G _{mb}	VTM
JFA429_SS1	149.97	0.07	108.54	0.08	2.378	6.1	2.349	7.1	2.301	9.0
JFA429_SS2	149.83	0.07	110.36	0.07	2.378	6.1	2.351	7.1	2.307	8.8

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

Table 48: Bulk Mix Specific Gravities (G_{mb}) for Thirds

Mix	Section	G_{mb}		
		SSD	CoreLok	Dimensional
937	TOP	2.298	2.286	2.275
	TOP	2.317	2.370	2.349
	TOP	2.296	2.304	2.275
	MIDDLE	2.304	2.303	2.272
	MIDDLE	2.296	2.377	2.358
	MIDDLE	2.308	2.292	2.257
	BOTTOM	2.322	2.326	2.299
	BOTTOM	2.309	2.397	2.378
	BOTTOM	2.301	2.310	2.286
909	TOP	2.460	2.457	2.389
	TOP	2.450	2.454	2.431
	TOP	2.470	2.476	2.430
	MIDDLE	2.470	2.469	2.382
	MIDDLE	2.470	2.469	2.445
	MIDDLE	2.460	2.456	2.441
	BOTTOM	2.480	2.488	2.404
	BOTTOM	2.450	2.451	2.448
	BOTTOM	2.460	2.462	2.434
060	TOP	2.337	2.325	2.465
	TOP	2.347	2.349	2.314
	TOP	2.349	2.350	2.324
	MIDDLE	2.340	2.335	2.450
	MIDDLE	2.348	2.343	2.329
	MIDDLE	2.357	2.357	2.324
	BOTTOM	2.334	2.330	2.475
	BOTTOM	2.356	2.356	2.322
	BOTTOM	2.348	2.353	2.330
115	TOP	2.324	2.318	2.307
	TOP	2.315	2.313	2.297
	TOP	2.326	2.325	2.306
	MIDDLE	2.324	2.321	2.311
	MIDDLE	2.324	2.322	2.306
	MIDDLE	2.322	2.322	2.302
	BOTTOM	2.339	2.326	2.321
	BOTTOM	2.326	2.337	2.322
	BOTTOM	2.311	2.308	2.298

429	TOP	2.359	2.350	2.359
	TOP	2.358	2.348	2.339
	TOP	2.364	2.346	2.332
	MIDDLE	2.346	2.335	2.343
	MIDDLE	2.353	2.344	2.328
	MIDDLE	2.366	2.364	2.334
	BOTTOM	2.371	2.357	2.357
	BOTTOM	2.363	2.350	2.351
	BOTTOM	2.371	2.363	2.334
483	TOP	2.282	2.270	2.256
	TOP	2.301	2.296	2.281
	TOP	2.313	2.308	2.290
	MIDDLE	2.290	2.290	2.267
	MIDDLE	2.317	2.307	2.289
	MIDDLE	2.308	2.300	2.283
	BOTTOM	2.306	2.303	2.281
	BOTTOM	2.314	2.306	2.286
	BOTTOM	2.312	2.301	2.287
523	TOP	2.312	2.294	2.295
	TOP	2.312	2.302	2.288
	TOP	2.293	2.294	2.279
	MIDDLE	2.331	2.317	2.309
	MIDDLE	2.326	2.320	2.287
	MIDDLE	2.325	2.321	2.310
	BOTTOM	2.339	2.317	2.300
	BOTTOM	2.321	2.309	2.293
	BOTTOM	2.301	2.297	2.274
766	TOP	2.297	2.291	2.277
	TOP	2.303	2.302	2.288
	TOP	2.286	2.290	2.269
	MIDDLE	2.310	2.310	2.289
	MIDDLE	2.309	2.313	2.287
	MIDDLE	2.300	2.296	2.261
	BOTTOM	2.312	2.311	2.298
	BOTTOM	2.297	2.284	2.272
	BOTTOM	2.304	2.305	2.279
882	TOP	2.267	2.246	2.251
	TOP	2.290	2.287	2.272
	TOP	2.283	2.284	2.264
	MIDDLE	2.289	2.290	2.284
	MIDDLE	2.279	2.268	2.264
	MIDDLE	2.288	2.288	2.271
	BOTTOM	2.276	2.271	2.265
	BOTTOM	2.275	2.268	2.260
	BOTTOM	2.277	2.273	2.258

Sample Thirds Geometry and VTM

Table 49: AA937 Sample Thirds Geometry and VTM

	Diameter		Height		VTM			
S#	AVG	SD	AVG	SD	SSD	CL	Dim.	AVG
S1_T	100.49	0.04	47.48	0.05	7.7	8.2	8.6	8.2
S1_M	100.46	0.01	47.07	0.25	7.5	7.5	8.7	7.9
S1_B	100.46	0.00	48.67	0.29	6.7	6.6	7.6	7.0
S2_T	100.45	0.05	49.28	0.29	4.6	4.8	5.6	5.0
S2_M	100.45	0.06	49.66	0.12	4.6	4.5	5.3	4.8
S2_B	100.41	0.03	46.21	0.08	4.0	3.7	4.5	4.1
S3_T	100.46	0.01	49.34	0.36	6.9	7.4	8.6	7.6
S3_M	100.47	0.01	48.15	0.48	7.8	7.9	9.3	8.3
S3_B	100.48	0.01	46.34	0.25	7.2	7.2	8.2	7.5
S4_T	100.46	0.01	48.44	0.25	7.8	7.9	8.4	8.0
S4_M	100.45	0.02	47.42	0.31	7.3	7.6	8.3	7.7
S4_B	100.48	0.02	47.75	0.13	7.6	7.9	8.5	8.0

Table 50: JAP909 Sample Thirds Geometry and VTM

	Diameter		Height		VTM			
S#	AVG	SD	AVG	SD	SSD	CL	Dim.	AVG
S1_T	100.45	0.10	43.81	0.25	8.1	8.1	9.6	8.6
S1_M	100.51	0.01	49.19	0.31	8.9	8.8	9.9	9.2
S1_B	100.33	0.04	49.99	0.49	7.9	8	9.1	8.3
S2_T	100.60	0.05	49.66	0.33	7.1	7.1	8.1	7.4
S2_M	100.56	0.06	47.58	0.10	6.6	6.6	7.5	6.9
S2_B	100.59	0.02	45.86	0.40	6	5.9	7.4	6.4
S3_T	100.63	0.06	47.31	0.05	7.3	7.2	8.1	7.5
S3_M	100.59	0.06	46.31	0.06	6.7	6.6	7.7	7.0
S3_B	100.57	0.01	47.34	0.12	7.2	7.3	7.9	7.5
S4_T	100.76	0.18	46.96	0.33	6.7	6.3	7.9	7.0
S4_M	100.66	0.11	48.57	0.77	7.1	7.1	8.7	7.6
S4_B	100.51	0.04	46.20	0.17	7.1	6.9	7.6	7.2

Table 51: JFA060 Sample Thirds Geometry and VTM

S#	Diameter		Height		VTM			
	AVG	SD	AVG	SD	SSD	CL	Dim.	AVG
S1_T	100.33	0.07	47.4	0.46	1.8	1.9	2.5	2.1
S1_M	100.38	0	48.5	0.29	2.4	2.5	3.1	2.7
S1_B	100.37	0.04	46.76	0.11	1.6	2.0	2.1	1.9
S2_T	100.43	0.01	46.07	0.2	7.6	8.1	8.5	8.1
S2_M	100.45	0.01	46.8	0.1	7.4	7.6	7.9	7.6
S2_B	100.36	0.04	47.87	0.15	7.7	7.8	8.2	7.9
S3_T	100.5	0.13	46.54	0.12	7.2	7.1	8.1	7.5
S3_M	100.6	0.08	47.45	0.09	7.1	7.3	8.1	7.5
S3_B	100.44	0.01	48.62	0.22	6.8	6.8	7.9	7.2
S4_T	100.5	0.04	47.66	0.07	7.1	7.0	7.7	7.3
S4_M	100.5	0.04	47.38	0.34	6.8	6.8	8.2	7.3
S4_B	100.41	0.03	48.11	0.2	7.1	6.9	8	7.3

Table 53: JFA115 Sample Thirds Geometry and VTM

S#	Diameter		Height		VTM			
	AVG	SD	AVG	SD	SSD	CL	Dim.	AVG
S1_T	100.36	0	47.5	0.16	4.7	4.7	5.2	4.9
S1_M	100.35	0.02	48.28	0.08	4.9	5.1	5.4	5.1
S1_B	100.35	0.01	48.19	0.11	4.5	4.6	4.9	4.7
S2_T	100.17	0.07	45.99	0.25	14.6	14.9	16.2	15.2
S2_M	100.29	0.01	48.19	0.09	14.2	14.6	13.9	14.2
S2_B	100.23	0.01	49	0.1	15.2	16	17.6	16.3
S3_T	100.49	0.01	47.98	0.12	6.8	7.1	7.5	7.1
S3_M	100.39	0.01	49.36	0.19	6.8	6.9	7.3	7.0
S3_B	100.41	0.02	45.93	0.17	6.2	6.7	6.9	6.6
S4_T	100.46	0.02	46.18	0.2	7.2	7.3	7.9	7.5
S4_M	100.44	0.01	48.38	0.32	6.8	6.9	7.6	7.1
S4_B	100.46	0.04	47.58	0.16	6.7	6.3	6.9	6.6
S5_T	100.43	0.02	47.33	0.25	6.7	6.8	7.5	7.0
S5_M	100.48	0.01	48.15	0.22	6.9	6.9	7.7	7.2
S5_B	100.42	0.01	46.37	0.07	7.4	7.5	7.9	7.6

Table 52: JFA429 Sample Thirds Geometry and VTM

S#	Diameter		Height		VTM			
	AVG	SD	AVG	SD	SSD	CL	Dim.	AVG
S1_T	100.35	0.02	47.25	0.34	7.2	7.2	8.3	7.6
S1_M	100.33	0.00	48.62	0.24	8.4	9.3	9.2	9.0
S1_B	100.34	0.02	37.94	19.70	7.7	8.0	9.0	8.2
S2_T	100.41	0.00	47.55	0.26	5.7	5.9	6.7	6.1
S2_M	100.39	0.00	46.84	0.20	6.4	6.2	7.3	6.6
S2_B	100.39	0.03	49.30	0.58	5.4	5.7	6.8	6.0
S3_T	100.46	0.03	49.79	0.13	6.7	7.1	7.5	7.1
S3_M	100.48	0.01	49.07	0.16	7.3	7.7	8.0	7.7
S3_B	100.42	0.03	43.78	0.15	6.2	6.8	7.0	6.7
S4_T	100.44	0.04	47.44	0.25	6.8	7.1	7.8	7.2
S4_M	100.46	0.01	47.59	0.07	7.0	7.3	7.7	7.3
S4_B	100.49	0.01	48.28	0.28	6.5	7.1	7.7	7.1
S5_T	100.43	0.01	48.07	0.26	6.5	7.2	7.7	7.1
S5_M	100.44	0.02	47.97	0.42	6.4	6.5	7.7	6.9
S5_B	100.47	0.01	47.80	0.21	6.2	6.6	7.5	6.8

Table 54: KP483 Sample Thirds Geometry and VTM

S#	Diameter		Height		VTM			
	AVG	SD	AVG	SD	SSD	CL	Dim.	AVG
S1_T	100.41	0.02	47.61	0.45	4.4	4.5	5.3	4.7
S1_M	100.40	0.03	48.05	0.14	4.4	4.5	5.1	4.7
S1_B	100.45	0.05	46.97	0.07	3.8	4.2	4.2	4.1
S2_T	100.55	0.04	47.87	0.36	7.6	8.2	8.7	8.2
S2_M	100.49	0.05	47.97	0.17	7.3	7.3	8.2	7.6
S2_B	100.42	0.04	47.71	0.32	6.7	6.8	7.7	7.1
S3_T	100.45	0.01	47.13	0.27	6.9	7.1	7.7	7.2
S3_M	100.48	0.00	48.84	0.16	6.2	6.6	7.4	6.7
S3_B	100.44	0.04	46.54	0.32	6.3	6.7	7.5	6.8
S4_T	100.45	0.01	46.60	0.25	6.4	6.6	7.3	6.8
S4_M	100.44	0.00	49.12	0.25	6.6	6.9	7.6	7.0
S4_B	100.47	0.02	47.71	0.11	6.4	6.9	7.5	6.9

Table 55: WVP523 Sample Thirds Geometry and VTM

S#	Diameter		Height		VTM			
	AVG	SD	AVG	SD	SSD	CL	Dim.	AVG
S1_T	100.41	0.01	46.89	0.31	5.2	5.4	6.0	5.5
S1_M	100.43	0.01	48.49	0.33	4.9	4.8	6.0	5.2
S1_B	100.45	0.03	47.22	0.07	5.4	5.4	6.0	5.6
S2_T	100.46	0.04	47.56	0.13	2.6	2.6	4.6	3.3
S2_M	100.43	0.01	49.56	0.29	2.3	2.5	3.5	2.8
S2_B	100.46	0.02	47.26	0.31	2.4	2.5	2.6	2.5
S3_T	100.44	0.01	48.35	0.05	7.3	8.0	8.0	7.8
S3_M	100.48	0.01	47.5	0.26	6.5	7.1	7.4	7.0
S3_B	100.47	0.04	48.53	0.12	6.2	7.1	7.8	7.0
S4_T	100.47	0.01	45.54	0.18	7.3	7.7	8.2	7.7
S4_M	100.48	0.01	50.96	0.61	6.7	6.9	8.3	7.3
S4_B	100.50	0.05	47.02	0.28	6.9	7.4	8.0	7.4
S5_T	100.43	0.01	47.28	0.09	8.0	8.0	8.6	8.2
S5_M	100.43	0.02	48.58	0.31	6.7	6.9	7.3	7.0
S5_B	100.46	0.01	47.21	0.38	7.7	7.9	8.8	8.1

Table 56: WVP766 Sample Thirds Geometry and VTM

S#	Diameter		Height		VTM			
	AVG	SD	AVG	SD	SSD	CL	Dim.	AVG
S1_T	100.58	0.09	48.41	0.27	8.7	8.9	9.7	9.1
S1_M	100.52	0.01	46.70	0.35	9.0	9.1	10.1	9.4
S1_B	100.50	0.09	47.83	0.06	8.9	9.2	9.8	9.3
S2_T	100.50	0.14	45.73	0.07	2.6	2.7	3.3	2.9
S2_M	100.51	0.03	48.52	0.41	2.4	2.2	3.2	2.6
S2_B	100.47	0.01	48.02	0.28	2.5	2.5	3.0	2.7
S3_T	100.59	0.03	49.81	0.08	7.2	7.4	7.8	7.5
S3_M	100.67	0.06	45.46	0.19	6.6	6.6	7.4	6.9
S3_B	100.56	0.06	47.38	0.07	6.5	6.6	7.0	6.7
S4_T	100.54	0.01	48.25	0.07	6.9	7.0	7.4	7.1
S4_M	100.53	0.03	47.64	0.46	6.7	6.5	7.5	6.9
S4_B	100.52	0.05	46.02	0.15	7.1	7.7	8.0	7.6
S5_T	100.54	0.05	47.41	0.13	7.6	7.4	8.2	7.7
S5_M	100.53	0.06	47.89	0.37	7.0	7.2	8.5	7.6
S5_B	100.50	0.08	47.79	0.46	6.9	6.8	7.8	7.2

Table 57: WVP882 Sample Thirds Geometry and VTM

S#	Diameter		Height		VTM			
	AVG	SD	AVG	SD	SSD	CL	Dim.	AVG
S1_T	100.50	0.00	48.00	0.28	7.4	8.2	8.0	7.9
S1_M	100.49	0.06	45.89	0.05	6.5	6.4	6.6	6.5
S1_B	100.49	0.01	49.75	0.14	7.1	7.2	7.4	7.2
S2_T	100.50	0.01	49.65	0.08	3.3	3.2	3.9	3.5
S2_M	100.49	0.01	47.34	0.26	2.8	2.9	3.8	3.2
S2_B	100.39	0.01	46.84	0.30	2.8	3.0	3.9	3.2
S3_T	100.46	0.01	48.68	0.08	6.5	6.5	7.2	6.7
S3_M	100.47	0.03	46.97	0.19	6.9	7.3	7.5	7.2
S3_B	100.42	0.03	47.89	0.20	7.1	7.3	7.6	7.3
S4_T	100.46	0.01	47.58	0.22	6.8	6.6	7.5	7.0
S4_M	100.44	0.05	46.25	0.16	6.6	6.5	7.2	6.8
S4_B	100.44	0.04	47.70	0.15	7.0	7.1	7.7	7.3

Full Sample Volumetrics - Bulk Mix Specific Gravities (G_{mb}) Before and After Coring and Sawing

Table 58: AA937 G_{mb} Before and After Trimming

Test	S#	Before			After		
		Dim.	CoreLok	SSD	Dim.	CoreLok	SSD
DM	1	2.230	2.267	2.293	2.302	2.309	2.315
L	2	2.310	2.345	2.362	2.378	2.382	2.387
DM	3	2.230	2.264	2.303	2.297	2.305	2.312
DM	4	2.231	2.267	2.294	2.295	2.303	2.308
FT	5	2.236	2.273	2.298	2.313	2.301	2.328
FT	6	2.239	2.276	2.305	2.324	2.335	2.331
FT	7	2.239	2.275	2.300	2.325	2.336	2.334
FN	8	2.229	2.264	2.293	2.294	2.31	2.311
FN	9	2.231	2.266	2.293	2.298	2.312	2.311
FN	10	2.227	2.263	2.291	2.299	2.311	2.313
FN	11	2.226	2.259	2.290	2.293	2.306	2.308

Table 59: JAP909 G_{mb} Before and After Trimming

Test	S #	Before			After		
		Dim.	CoreLok	SSD	Dim.	CoreLok	SSD
H	1	2.344	2.398	2.403	2.411	2.422	2.427
DM	2	2.392	2.445	2.472	2.463	2.471	2.475
DM	3	2.386	2.436	2.464	2.459	2.459	2.465
DM	4	2.382	2.431	2.457	2.458	2.452	2.470
FN	5	2.385	2.430	2.455	2.452	2.459	2.464
FT	6	2.380	2.431	2.452	2.467	2.474	2.479
FT	7	2.373	2.422	2.447	2.458	2.474	2.471
FT	8	2.371	2.422	2.453	2.456	2.474	2.470
FN	9	2.383	2.427	2.457	2.457	2.477	2.472
FN	10	2.383	2.428	2.455	2.453	2.472	2.468
FN	11	2.381	2.426	2.451	2.462	2.48	2.474

Table 60: JFA060 G_{mb} Before and After Trimming

Test	S #	Before			After		
		Dim.	CoreLok	SSD	Dim.	CoreLok	SSD
L	1	2.412	2.452	2.465	2.481	2.474	2.485
DM	2	2.242	2.292	2.326	2.333	2.345	2.341
DM	3	2.260	2.311	2.34	2.343	2.351	2.354
DM	4	2.259	2.302	2.341	2.345	2.351	2.356
FT	5	2.260	2.310	2.339	2.339	2.361	2.360
FT	6	2.256	2.301	2.331	2.362	2.375	2.371
FT	7	2.252	2.297	2.328	2.342	2.358	2.356
FN	8	2.258	2.305	2.334	2.341	2.348	2.353
FN	9	2.257	2.300	2.33	2.340	2.353	2.354
FN	10	2.257	2.300	2.33	2.342	2.356	2.354
FN	11	2.257	2.294	2.336	2.354	2.367	2.365

Table 61: JFA115 G_{mb} Before and After Trimming

Test	S #	Before			After		
		Dim.	CoreLok	SSD	Dim.	CoreLok	SSD
L	1	2.311	2.343	2.357	2.375	2.383	2.381
H	2	2.048	2.077	2.156	2.109	2.124	2.133
DM	3	2.257	2.290	2.306	2.327	2.337	2.331
DM	4	2.259	2.292	2.309	2.324	2.334	2.333
DM	5	2.256	2.287	2.304	2.316	2.331	2.323
FT	6	2.247	2.279	2.297	2.314	2.32	2.323
FT	7	2.247	2.280	2.300	2.326	2.335	2.335
FT	8	2.247	2.277	2.294	2.317	2.325	2.326
FN	9	2.253	2.282	2.300	2.310	2.321	2.320
FN	10	2.254	2.284	2.302	2.314	2.325	2.325
FN	11	2.253	2.282	2.301	2.320	2.334	2.329

Table 62: JFA429 G_{mb} Before and After Trimming

Test	S #	Before			After		
		Dim.	CoreLok	SSD	Dim.	CoreLok	SSD
H	1	2.239	2.291	2.329	2.318	2.328	2.335
L	2	2.299	2.347	2.372	2.373	2.389	2.385
DM	3	2.275	2.325	2.350	2.349	2.356	2.361
DM	4	2.272	2.320	2.350	2.348	2.357	2.364
DM	5	2.274	2.321	2.351	2.358	2.366	2.370
FT	6	2.269	2.315	2.347	2.364	2.371	2.373
FT	7	2.262	2.313	2.346	2.355	2.37	2.366
FT	8	2.255	2.296	2.332	2.347	2.362	2.359
FN	9	2.271	2.316	2.348	2.354	2.368	2.365
FN	10	2.272	2.314	2.346	2.345	2.359	2.358

Table 63: KP483 G_{mb} Before and After Trimming

Test	S #	Before			After		
		Dim.	CoreLok	SSD	Dim.	CoreLok	SSD
L	1	2.305	2.335	2.349	2.362	2.368	2.370
DM	2	2.224	2.257	2.278	2.288	2.292	2.296
DM	3	2.239	2.270	2.288	2.303	2.315	2.313
DM	4	2.241	2.273	2.290	2.303	2.309	2.314
FN	5	2.228	2.260	2.281	2.295	2.306	2.306
FT	6	2.229	2.260	2.281	2.303	2.315	2.313
FT	7	2.228	2.258	2.281	2.299	2.306	2.308
FT	8	2.226	2.257	2.279	2.298	2.311	2.308
FN	9	2.232	2.262	2.285	2.295	2.307	2.307
FN	10	2.233	2.257	2.283	2.297	2.308	2.306
FN	11	2.232	2.260	2.279	2.292	2.306	2.304

Table 64: WVP523 G_{mb} Before and After Trimming

Test	S #	Before			After		
		Dim.	CoreLok	SSD	Dim.	CoreLok	SSD
H	1	2.304	2.336	2.350	2.363	2.364	2.367
L	2	2.372	2.392	2.410	2.428	2.431	2.434
DM	3	2.257	2.282	2.303	2.321	2.331	2.327
DM	4	2.259	2.286	2.306	2.319	2.325	2.324
DM	5	2.257	2.292	2.296	2.302	2.307	2.310
FT	6	2.252	2.279	2.292	2.315	2.321	2.304
FT	7	2.252	2.284	2.301	2.315	2.333	2.326
FT	8	2.254	2.285	2.293	2.317	2.334	2.330
FN	9	2.261	2.293	2.316	2.333	2.343	2.341
FN	10	2.259	2.288	2.307	2.314	2.327	2.324
FN	11	2.257	2.289	2.305	2.321	2.332	2.330
FN	12	2.257	2.277	2.297	2.307	2.322	2.317

Table 65: WVP766 G_{mb} Before and After Trimming

Test	S #	Before			After		
		Dim.	CoreLok	SSD	Dim.	CoreLok	SSD
H	1	2.194	2.220	2.236	2.244	2.249	2.255
L	2	2.361	2.387	2.392	2.412	2.414	2.416
DM	3	2.245	2.273	2.287	2.315	2.308	2.310
DM	4	2.244	2.265	2.289	2.293	2.302	2.307
DM	5	2.242	2.268	2.285	2.289	2.298	2.301
FT	6	2.239	2.253	2.280	2.304	2.308	2.312
FT	7	2.237	2.262	2.281	2.300	2.312	2.310
FT	8	2.234	2.261	2.277	2.292	2.305	2.305
FN	9	2.246	2.271	2.287	2.301	2.315	2.312
FN	10	2.243	2.267	2.283	2.295	2.307	2.305
FN	11	2.241	2.265	2.282	2.291	2.306	2.303
FN	12	2.243	2.266	2.283	2.297	2.308	2.309

Table 66: WVP882 G_{mb} Before and After Trimming

Test	S #	Before			After		
		Dim.	CoreLok	SSD	Dim.	CoreLok	SSD
DM	1	2.214	2.248	2.265	2.276	2.276	2.283
L	2	2.305	2.339	2.351	2.373	2.377	2.379
DM	3	2.212	2.243	2.261	2.278	2.284	2.285
DM	4	2.212	2.244	2.264	2.279	2.281	2.286
FN	5	2.210	2.243	2.260	2.277	2.286	2.283
FN	6	2.210	2.242	2.260	2.277	2.285	2.288
FT	7	2.214	2.245	2.266	2.291	2.289	2.301
FT	8	2.209	2.241	2.262	2.276	2.288	2.286
FT	9	2.204	2.238	2.253	2.275	2.288	2.286
FN	10	2.211	2.242	2.263	2.276	2.287	2.289
FN	11	2.209	2.233	2.257	2.274	2.287	2.285

Geometry and VTM, VMA, and VFA for Full Samples

Table 67: AA937 Sample Geometry

		Diameter		Height	
Test	S#	AVG	SD	AVG	SD
DM	1	100.40	0.03	150.11	0.11
L	2	100.38	0.03	152.22	0.10
DM	3	100.43	0.02	150.32	0.12
DM	4	100.40	0.03	150.84	0.11
FT	5	100.43	0.02	131.86	0.18
FT	6	100.39	0.02	130.44	0.05
FT	7	100.41	0.04	130.82	0.04
FN	8	100.45	0.02	149.85	0.30
FN	9	100.45	0.01	150.73	0.16
FN	10	100.44	0.02	150.65	0.15
FN	11	100.44	0.01	150.57	0.10

Table 68: AA937 VTM Before and After Trimming

VTM (%)															
Test	S#	Before					After					Difference			
		Abs.	SSD	CL	Dim.	AVG	Abs.	SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
DM	1	2.0	7.9	8.9	10.4	9.1	0.6	7.0	7.2	7.5	7.3	0.9	1.7	2.9	1.8
L	2	0.5	5.1	5.8	7.2	6.0	0.2	4.1	4.3	4.5	4.3	1.0	1.5	2.7	1.7
DM	3	1.2	7.5	9.0	10.4	9.0	0.9	7.1	7.4	7.7	7.4	0.4	1.6	2.7	1.6
DM	4	1.8	7.8	8.9	10.4	9.0	1.0	7.3	7.5	7.8	7.5	0.5	1.4	2.6	1.5
FT	5	2.1	7.7	8.7	10.2	8.9	0.8	6.5	7.5	7.1	7.0	1.2	1.2	3.1	1.9
FT	6	1.6	7.4	8.6	10.1	8.7	0.4	6.3	6.2	6.6	6.4	1.1	2.4	3.5	2.3
FT	7	2.0	7.6	8.6	10.1	8.8	0.5	6.2	6.1	6.6	6.3	1.4	2.5	3.5	2.5
FN	8	1.9	7.9	9.1	10.5	9.2	0.9	7.2	7.2	7.9	7.4	0.7	1.9	2.6	1.8
FN	9	1.8	7.9	9.0	10.4	9.1	0.6	7.2	7.1	7.7	7.3	0.7	1.9	2.7	1.8
FN	10	2.0	8.0	9.1	10.5	9.2	0.7	7.1	7.2	7.7	7.3	0.9	1.9	2.8	1.9
FN	11	2.2	8.0	9.2	10.6	9.3	1.2	7.3	7.3	7.9	7.5	0.7	1.9	2.7	1.8

Table 69: AA937 VMA Before and After Trimming

VMA (%)									
Test	S#	Before				After			
		SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
DM	1	17.1	18.0	19.4	18.2	16.3	16.5	16.7	16.5
L	2	14.6	15.2	16.4	15.4	13.7	13.8	14.0	13.8
DM	3	16.7	18.1	19.4	18.1	16.4	16.6	16.9	16.6
DM	4	17.0	18.0	19.3	18.1	16.5	16.7	17.0	16.7
FT	5	16.9	17.8	19.1	17.9	15.8	16.8	16.4	16.3
FT	6	16.6	17.7	19.0	17.8	15.7	15.6	16.0	15.7
FT	7	16.8	17.7	19.0	17.8	15.6	15.5	15.9	15.7
FN	8	17.1	18.1	19.4	18.2	16.4	16.4	17.0	16.6
FN	9	17.1	18.0	19.3	18.1	16.4	16.4	16.9	16.6
FN	10	17.1	18.2	19.5	18.3	16.3	16.4	16.9	16.5
FN	11	17.2	18.3	19.5	18.3	16.5	16.6	17.1	16.7

Table 70: AA937 VFA Before and After Trimming

VFA (%)									
Test	S#	Before				After			
		SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
DM	1	53.8	50.4	46.1	50.1	56.9	56.1	55.1	56.0
L	2	64.9	61.9	56.3	61.0	69.9	69.0	68.1	69.0
DM	3	55.2	50.1	46.1	50.5	56.6	55.5	54.4	55.5
DM	4	53.9	50.5	46.2	50.2	55.9	55.2	54.1	55.1
FT	5	54.4	51.1	46.8	50.8	59.0	55.0	56.6	56.9
FT	6	55.5	51.6	47.2	51.4	59.6	60.1	58.3	59.3
FT	7	54.9	51.4	47.1	51.1	60.0	60.4	58.5	59.6
FN	8	53.8	50.0	46.0	49.9	56.4	56.3	53.9	55.5
FN	9	53.8	50.3	46.3	50.1	56.4	56.5	54.5	55.8
FN	10	53.5	49.9	45.8	49.7	56.7	56.4	54.6	55.9
FN	11	53.4	49.5	45.7	49.5	55.9	55.7	53.9	55.2

Table 71: JAP909 Sample Geometry

		Diameter		Height	
Test	S#	AVG	SD	AVG	SD
H	1	100.43	0.10	149.99	0.50
DM	2	100.45	0.02	150.22	0.09
DM	3	100.43	0.03	148.39	0.07
DM	4	100.42	0.05	148.76	0.02
FN	5	100.41	0.03	150.35	0.10
FT	6	100.42	0.04	130.04	0.13
FT	7	100.42	0.03	131.62	0.12
FT	8	100.44	0.02	130.42	0.09
FN	9	100.48	0.02	151.35	0.08
FN	10	100.45	0.04	149.96	0.08
FN	11	100.45	0.03	149.58	0.08

Table 72: JAP909 VTM Before and After Trimming

VTM (%)															
Test	S#	Before					After					Difference			
		Abs.	SSD	CL	Dim.	AVG	Abs.	SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
H	1	1.9	9.1	9.3	11.4	9.9	0.5	8.2	8.4	8.8	8.5	0.9	0.9	2.6	1.4
DM	2	1.2	6.5	7.5	9.5	7.8	0.3	6.4	6.5	6.8	6.6	0.1	1.0	2.7	1.2
DM	3	1.2	6.8	7.9	9.8	8.2	0.4	6.8	7.0	7.0	6.9	0.0	0.9	2.8	1.3
DM	4	1.0	7.1	8.0	9.9	8.3	0.3	6.6	7.2	7.0	6.9	0.5	0.8	2.9	1.4
FN	5	1.2	7.1	8.1	9.8	8.3	0.4	6.8	7.0	7.3	7.0	0.3	1.1	2.5	1.3
FT	6	1.2	7.2	8.1	10.0	8.4	0.2	6.2	6.4	6.7	6.4	1.0	1.7	3.3	2.0
FT	7	1.1	7.4	8.4	10.2	8.7	0.2	6.5	6.4	7.0	6.7	0.9	2.0	3.2	2.0
FT	8	1.2	7.2	8.4	10.3	8.6	0.2	6.6	6.4	7.1	6.7	0.6	2.0	3.2	1.9
FN	9	1.2	7.1	8.2	9.9	8.4	0.4	6.5	6.3	7.0	6.6	0.6	1.9	2.9	1.8
FN	10	1.1	7.1	8.2	9.9	8.4	0.3	6.6	6.5	7.2	6.8	0.5	1.7	2.7	1.6
FN	11	1.3	7.3	8.3	9.9	8.5	0.3	6.4	6.2	6.9	6.5	0.9	2.1	3.0	2.0

Table 73: JAP909 VMA Before and After Trimming

VMA (%)									
Test	S#	Before				After			
		SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
H	1	17.8	17.9	19.8	18.5	16.9	17.1	17.5	17.2
DM	2	15.4	16.3	18.1	16.6	15.3	15.5	15.7	15.5
DM	3	15.7	16.7	18.4	16.9	15.7	15.9	15.9	15.8
DM	4	15.9	16.8	18.5	17.1	15.5	16.1	15.9	15.8
FN	5	16.0	16.8	18.4	17.1	15.7	15.9	16.1	15.9
FT	6	16.1	16.8	18.6	17.2	15.2	15.3	15.6	15.4
FT	7	16.3	17.1	18.8	17.4	15.5	15.3	15.9	15.6
FT	8	16.1	17.1	18.9	17.4	15.5	15.3	16.0	15.6
FN	9	15.9	17.0	18.5	17.1	15.4	15.3	15.9	15.5
FN	10	16.0	16.9	18.4	17.1	15.5	15.4	16.0	15.7
FN	11	16.1	17.0	18.5	17.2	15.4	15.2	15.8	15.4

Table 74: JAP909 VFA Before and After Trimming

VFA (%)									
Test	S#	Before				After			
		SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
H	1	48.8	48.2	42.7	46.6	51.7	51.0	49.7	50.8
DM	2	57.9	53.9	47.6	53.1	58.3	57.7	56.5	57.5
DM	3	56.6	52.7	46.8	52.0	56.7	55.9	55.9	56.2
DM	4	55.7	52.2	46.4	51.4	57.6	55.0	55.7	56.1
FN	5	55.4	52.1	46.7	51.4	56.6	55.9	54.9	55.8
FT	6	55.0	52.1	46.3	51.1	59.0	58.2	57.1	58.1
FT	7	54.2	51.0	45.5	50.2	57.7	58.2	55.7	57.2
FT	8	55.0	51.0	45.3	50.4	57.5	58.1	55.4	57.0
FN	9	55.6	51.6	46.5	51.2	57.8	58.6	55.7	57.3
FN	10	55.3	51.8	46.6	51.2	57.3	57.9	55.1	56.8
FN	11	54.8	51.5	46.4	50.9	58.1	59.0	56.3	57.8

Table 75: JFA060 Sample Geometry

		Diameter		Height	
Test	S#	AVG	SD	AVG	SD
L	1	100.33	0.03	149.55	0.14
DM	2	100.33	0.04	148.51	0.06
DM	3	100.38	0.04	150.21	0.06
DM	4	100.36	0.02	150.55	0.04
FT	5	100.39	0.02	129.43	0.25
FT	6	100.41	0.02	130.83	0.12
FT	7	100.45	0.01	131.52	0.10
FN	8	100.44	0.02	150.44	0.11
FN	9	100.43	0.03	150.48	0.08
FN	10	100.45	0.01	152.18	0.11
FN	11	100.44	0.02	150.57	0.07

Table 76: JFA060 VTM Before and After Trimming

VTM (%)															
Test	S#	Before					After					Difference			
		Abs.	SSD	CL	Dim.	AVG	Abs.	SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
L	1	0.2	2.5	3.0	4.6	3.4	0.1	1.7	2.2	1.9	1.9	0.8	0.8	2.7	1.5
DM	2	1.7	8.0	9.3	11.3	9.5	0.4	7.4	7.2	7.7	7.5	0.6	2.1	3.6	2.0
DM	3	1.3	7.5	8.6	10.6	8.9	0.3	6.9	7.0	7.3	7.1	0.6	1.6	3.3	1.8
DM	4	1.4	7.4	8.9	10.6	9.0	0.3	6.8	7.0	7.2	7.0	0.6	1.9	3.4	2.0
FT	5	1.3	7.5	8.7	10.6	8.9	0.4	6.7	6.6	7.5	6.9	0.8	2.1	3.1	2.0
FT	6	1.4	7.8	9.0	10.8	9.2	0.2	6.2	6.1	6.6	6.3	1.6	2.9	4.2	2.9
FT	7	1.3	7.9	9.1	10.9	9.3	0.2	6.8	6.7	7.4	7.0	1.1	2.4	3.5	2.3
FN	8	1.2	7.7	8.8	10.7	9.1	0.3	6.9	7.1	7.4	7.2	0.8	1.7	3.3	1.9
FN	9	1.4	7.8	9.0	10.7	9.2	0.3	6.9	6.9	7.4	7.1	0.9	2.1	3.3	2.1
FN	10	1.4	7.8	9.0	10.7	9.2	0.4	6.9	6.8	7.4	7.0	0.9	2.2	3.3	2.2
FN	11	1.5	7.6	9.3	10.7	9.2	0.5	6.4	6.4	6.9	6.6	1.2	2.9	3.8	2.6

Table 77: JFA060 VMA Before and After Trimming

VMA (%)									
Test	S#	Before				After			
		SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
L	1	11.8	12.3	13.7	12.6	11.1	11.5	11.2	11.3
DM	2	16.8	18.0	19.8	18.2	16.2	16.1	16.5	16.3
DM	3	16.3	17.3	19.2	17.6	15.8	15.9	16.2	15.9
DM	4	16.2	17.6	19.2	17.7	15.7	15.9	16.1	15.9
FT	5	16.3	17.4	19.1	17.6	15.6	15.5	16.3	15.8
FT	6	16.6	17.7	19.3	17.9	15.2	15.0	15.5	15.2
FT	7	16.7	17.8	19.4	18.0	15.7	15.6	16.2	15.8
FN	8	16.5	17.5	19.2	17.7	15.8	16.0	16.2	16.0
FN	9	16.6	17.7	19.3	17.9	15.8	15.8	16.3	16.0
FN	10	16.6	17.7	19.2	17.8	15.8	15.7	16.2	15.9
FN	11	16.4	17.9	19.2	17.8	15.4	15.3	15.8	15.5

Table 78: JFA060 VFA Before and After Trimming

VFA (%)									
Test	S#	Before				After			
		SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
L	1	78.9	75.5	66.5	73.6	84.5	81.2	83.4	83.0
DM	2	52.3	48.1	42.8	47.7	54.4	55.0	53.3	54.2
DM	3	54.2	50.3	44.5	49.7	56.4	55.9	54.6	55.6
DM	4	54.5	49.3	44.5	49.4	56.6	55.8	55.0	55.8
FT	5	54	50.2	44.5	49.6	57.2	57.4	54.1	56.2
FT	6	53	49.1	44.2	48.8	59.0	59.6	57.5	58.7
FT	7	52.5	48.7	43.8	48.3	56.6	57.0	54.5	56.0
FN	8	53.4	49.6	44.3	49.1	56.1	55.5	54.4	55.3
FN	9	52.9	49.0	44.2	48.7	56.3	56.2	54.3	55.6
FN	10	52.9	49.1	44.3	48.8	56.2	56.5	54.5	55.8
FN	11	53.7	48.3	44.2	48.7	58.1	58.3	56.3	57.6

Table 79: JFA115 Sample Geometry

		Diameter		Height	
Test	S#	AVG	SD	AVG	SD
L	1	100.34	0.03	151.35	0.08
H	2	100.26	0.08	150.08	0.06
DM	3	100.35	0.02	150.89	0.05
DM	4	100.38	0.06	149.47	0.03
DM	5	100.36	0.02	149.36	0.15
FT	6	100.39	0.03	131.20	0.12
FT	7	100.43	0.02	131.52	0.06
FT	8	100.44	0.03	131.27	0.01
FN	9	100.43	0.02	150.43	0.07
FN	10	100.45	0.02	149.85	0.10
FN	11	100.46	0.02	151.18	0.04

Table 80: JFA115 VTM Before and After Trimming

VTM (%)															
Test	S#	Before					After					Difference			
		Abs.	SSD	CL	Dim.	AVG	Abs.	SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
L	1	0.3	5.5	6.1	7.4	6.3	0.1	4.5	4.5	4.8	4.6	1.0	1.6	2.6	1.7
H	2	7.6	13.6	16.7	17.9	16.1	6.5	14.5	14.9	15.4	14.9	-0.9	1.8	2.5	1.2
DM	3	0.7	7.5	8.2	9.5	8.4	0.2	6.5	6.3	6.7	6.5	1.0	1.9	2.8	1.9
DM	4	0.8	7.4	8.1	9.4	8.3	0.2	6.5	6.4	6.8	6.6	0.9	1.7	2.6	1.7
DM	5	0.7	7.6	8.3	9.5	8.5	0.2	6.8	6.6	7.1	6.8	0.8	1.7	2.4	1.7
FT	6	0.8	7.9	8.6	9.9	8.8	0.3	6.9	7.0	7.2	7.0	1.0	1.6	2.7	1.8
FT	7	0.9	7.8	8.6	9.9	8.8	0.2	6.4	6.4	6.7	6.5	1.4	2.2	3.2	2.3
FT	8	0.7	8.0	8.7	9.9	8.9	0.2	6.7	6.8	7.1	6.9	1.3	1.9	2.8	2.0
FN	9	0.6	7.8	8.5	9.7	8.7	0.2	7.0	6.9	7.4	7.1	0.8	1.6	2.3	1.6
FN	10	0.7	7.7	8.4	9.6	8.6	0.2	6.8	6.8	7.2	6.9	0.9	1.6	2.4	1.7
FN	11	0.9	7.7	8.5	9.7	8.6	0.3	6.6	6.4	7.0	6.7	1.1	2.1	2.7	1.9

Table 81: JFA115 VMA Before and After Trimming

VMA (%)									
Test	S#	Before				After			
		SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
L	1	15.5	16.1	17.2	16.3	14.7	14.6	14.9	14.7
H	2	22.8	25.6	26.6	25.0	23.6	23.9	24.4	24.0
DM	3	17.4	18.0	19.1	18.2	16.5	16.3	16.6	16.5
DM	4	17.3	17.9	19.1	18.1	16.4	16.4	16.7	16.5
DM	5	17.4	18.1	19.1	18.2	16.8	16.5	17.0	16.8
FT	6	17.7	18.4	19.5	18.5	16.8	16.9	17.1	16.9
FT	7	17.6	18.3	19.5	18.5	16.3	16.3	16.7	16.4
FT	8	17.8	18.4	19.5	18.6	16.7	16.7	17.0	16.8
FN	9	17.6	18.2	19.3	18.4	16.9	16.8	17.2	17.0
FN	10	17.5	18.1	19.2	18.3	16.7	16.7	17.1	16.8
FN	11	17.6	18.2	19.3	18.4	16.5	16.4	16.9	16.6

Table 82: JFA115 VFA Before and After Trimming

VFA (%)									
Test	S#	Before				After			
		SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
L	1	64.7	62.2	57.3	61.4	69.1	69.5	68.0	68.9
H	2	40.4	34.6	32.8	35.9	38.6	37.9	36.8	37.7
DM	3	56.6	54.4	50.3	53.8	60.4	61.3	59.7	60.5
DM	4	57.1	54.7	50.5	54.1	60.7	60.8	59.3	60.3
DM	5	56.3	54.0	50.3	53.5	59.2	60.3	58.1	59.2
FT	6	55.3	52.9	49.1	52.4	59.0	58.6	57.8	58.5
FT	7	55.8	53.1	49.2	52.7	61.0	60.9	59.6	60.5
FT	8	55.0	52.7	49.2	52.3	59.5	59.4	58.2	59.0
FN	9	55.8	53.4	49.8	53.0	58.7	58.8	57.1	58.2
FN	10	56.1	53.7	49.9	53.2	59.5	59.3	57.7	58.8
FN	11	55.9	53.4	49.9	53.1	60.1	60.8	58.7	59.8

Table 83: JFA429 Sample Geometry

		Diameter		Height	
Test	S#	AVG	SD	AVG	SD
H	1	100.39	0.04	150.87	0.07
L	2	100.38	0.03	150.49	0.04
DM	3	100.41	0.04	149.97	0.13
DM	4	100.42	0.03	150.53	0.06
DM	5	100.36	0.03	150.72	0.07
FT	6	100.43	0.05	131.27	0.07
FT	7	100.41	0.03	131.51	0.36
FT	8	100.42	0.03	131.66	0.17
FN	9	100.44	0.04	150.64	0.07
FN	10	100.45	0.02	151.61	0.07

Table 84: JFA429 VTM Before and After Trimming

VTM (%)															
Test	S#	Before					After					Difference			
		Abs.	SSD	CL	Dim.	AVG	Abs.	SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
H	1	1.6	7.9	9.4	11.5	9.6	0.5	7.7	8.0	8.4	8.0	0.2	1.4	3.1	1.6
L	2	0.6	6.2	7.2	9.1	7.5	0.2	5.7	5.6	6.2	5.8	0.5	1.6	2.9	1.7
DM	3	0.9	7.1	8.1	10.1	8.4	0.4	6.7	6.8	7.1	6.9	0.4	1.3	3.0	1.5
DM	4	0.9	7.1	8.3	10.1	8.5	0.4	6.5	6.8	7.2	6.8	0.6	1.5	2.9	1.7
DM	5	1.1	7.0	8.2	10.1	8.4	0.3	6.3	6.5	6.8	6.5	0.7	1.7	3.3	1.9
FT	6	1.3	7.2	8.5	10.3	8.7	0.3	6.2	6.3	6.6	6.3	1.0	2.2	3.7	2.4
FT	7	1.0	7.2	8.5	10.5	8.7	0.2	6.4	6.3	6.9	6.5	0.8	2.2	3.6	2.2
FT	8	1.3	7.8	9.2	10.9	9.3	0.2	6.7	6.7	7.2	6.9	1.1	2.5	3.7	2.4
FN	9	1.0	7.1	8.5	10.2	8.6	0.3	6.5	6.4	6.9	6.6	0.6	2.1	3.3	2.0
FN	10	1.0	7.2	8.5	10.2	8.6	0.3	6.8	6.8	7.3	7.0	0.4	1.7	2.9	1.6

Table 85: JFA429 VMA Before and After Trimming

VMA (%)									
Test	S#	Before				After			
		SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
H	1	16.7	18.0	19.9	18.2	16.5	16.7	17.1	16.7
L	2	15.1	16.0	17.7	16.3	14.7	14.5	15.1	14.8
DM	3	15.9	16.8	18.6	17.1	15.5	15.7	16.0	15.7
DM	4	15.9	17.0	18.7	17.2	15.4	15.7	16.0	15.7
DM	5	15.9	17.0	18.6	17.2	15.2	15.4	15.6	15.4
FT	6	16.0	17.2	18.8	17.3	15.1	15.2	15.4	15.2
FT	7	16.1	17.2	19.1	17.5	15.3	15.2	15.7	15.4
FT	8	16.6	17.9	19.3	17.9	15.6	15.5	16.0	15.7
FN	9	16.0	17.2	18.8	17.3	15.4	15.3	15.8	15.5
FN	10	16.1	17.2	18.7	17.3	15.7	15.6	16.1	15.8

Table 86: JFA429 VFA Before and After Trimming

VFA (%)									
Test	S#	Before				After			
		SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
H	1	52.6	47.9	42.3	47.6	53.3	52.4	51.0	52.2
L	2	59.0	55.1	48.8	54.3	61.0	61.7	59.1	60.6
DM	3	55.5	52.0	46.0	51.2	57.1	56.4	55.3	56.2
DM	4	55.6	51.3	45.7	50.9	57.6	56.5	55.2	56.4
DM	5	55.8	51.5	45.9	51.1	58.5	57.7	56.6	57.6
FT	6	55.2	50.7	45.4	50.4	59.1	58.4	57.5	58.3
FT	7	55.0	50.5	44.7	50.1	58.0	58.5	56.2	57.6
FT	8	53.0	48.4	43.9	48.4	56.8	56.8	54.9	56.2
FN	9	55.3	50.4	45.6	50.4	57.7	58.1	56.1	57.3
FN	10	54.9	50.6	45.7	50.4	56.6	56.4	54.8	55.9

Table 87: KP483 Sample Geometry

		Diameter		Height	
Test	S#	AVG	SD	AVG	SD
L	1	100.43	0.03	149.87	0.18
DM	2	100.38	0.02	150.59	0.07
DM	3	100.40	0.03	149.67	0.08
DM	4	100.40	0.04	150.51	0.11
FN	5	100.45	0.02	150.62	0.09
FT	6	100.41	0.03	131.40	0.15
FT	7	100.41	0.04	131.53	0.17
FT	8	100.44	0.02	130.85	0.15
FN	9	100.44	0.02	150.00	0.04
FN	10	100.45	0.03	151.34	0.10
FN	11	100.43	0.02	150.63	0.09

Table 88: KP483 VTM Before and After Trimming

		VTM (%)													
Test	S #	Before					After					Difference			
		Abs.	SSD	CL	Dim.	AVG	Abs.	SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
L	1	0.4	4.9	5.5	6.7	5.7	0.3	4.1	4.2	4.4	4.2	0.8	1.3	2.3	1.5
DM	2	1.5	7.8	8.7	10.0	8.8	0.5	7.1	7.3	7.4	7.2	0.7	1.4	2.6	1.6
DM	3	1.3	7.4	8.2	9.4	8.3	0.4	6.4	6.3	6.8	6.5	1.0	1.9	2.6	1.8
DM	4	1.2	7.3	8.0	9.3	8.2	0.4	6.4	6.5	6.8	6.6	0.9	1.5	2.5	1.6
FN	5	1.4	7.7	8.5	9.8	8.7	1.1	6.7	6.7	7.1	6.8	1.0	1.8	2.7	1.9
FT	6	1.7	7.7	8.6	9.8	8.7	0.4	6.4	6.3	6.8	6.5	1.3	2.3	3.0	2.2
FT	7	1.6	7.7	8.6	9.8	8.7	0.4	6.6	6.7	7.0	6.8	1.1	1.9	2.8	1.9
FT	8	1.5	7.8	8.6	9.9	8.8	0.3	6.6	6.5	7.0	6.7	1.2	2.1	2.9	2.1
FN	9	1.4	7.5	8.5	9.7	8.6	0.5	6.6	6.6	7.1	6.8	0.9	1.9	2.6	1.8
FN	10	1.4	7.6	8.7	9.6	8.6	0.5	6.7	6.6	7.1	6.8	0.9	2.1	2.5	1.8
FN	11	1.6	7.8	8.5	9.7	8.7	0.6	6.8	6.7	7.2	6.9	1.0	1.8	2.5	1.8

Table 89: KP483 VMA Before and After Trimming

VMA (%)									
Test	S#	Before				After			
		SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
L	1	15.3	15.8	16.9	16.0	14.7	14.9	14.7	14.7
DM	2	17.9	18.7	19.8	18.8	17.4	17.5	17.4	17.4
DM	3	17.5	18.2	19.3	18.3	16.6	17.0	16.7	16.6
DM	4	17.4	18.1	19.2	18.2	16.8	17.0	16.8	16.8
FN	5	17.8	18.5	19.7	18.7	16.9	17.3	17.0	16.9
FT	6	17.8	18.6	19.7	18.7	16.6	17.0	16.7	16.6
FT	7	17.8	18.6	19.7	18.7	16.9	17.1	17.0	16.9
FT	8	17.9	18.6	19.8	18.8	16.7	17.2	16.9	16.7
FN	9	17.6	18.5	19.5	18.5	16.8	17.3	17.0	16.8
FN	10	17.7	18.7	19.5	18.6	16.8	17.2	17.0	16.8
FN	11	17.9	18.5	19.6	18.7	17.0	16.9	17.4	17.1

Table 90: KP483 VFA Before and After Trimming

VFA (%)									
Test	S#	Before				After			
		SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
L	1	67.9	65.2	60.4	64.5	71.9	71.5	70.2	71.2
DM	2	56.4	53.5	49.6	53.2	59	58.3	57.8	58.4
DM	3	57.8	55.2	51.4	54.8	61.5	61.9	59.9	61.1
DM	4	58.1	55.6	51.6	55.1	61.7	60.9	60	60.9
FN	5	56.8	54.0	50.1	53.6	60.4	60.4	58.7	59.9
FT	6	56.7	53.9	50.2	53.6	61.6	61.8	60	61.2
FT	7	56.7	53.8	50.0	53.5	60.7	60.4	59.4	60.2
FT	8	56.5	53.6	49.9	53.3	60.8	61.2	59.2	60.4
FN	9	57.3	54.2	50.6	54.0	60.6	60.7	58.7	60
FN	10	57.1	53.6	50.6	53.8	60.4	60.8	59	60.1
FN	11	56.4	53.9	50.5	53.6	60.1	60.4	58.4	59.6

Table 91: WVP523 Sample Geometry

		Diameter		Height	
Test	S#	AVG	SD	AVG	SD
H	1	100.43	0.02	149.40	0.03
L	2	100.45	0.03	150.86	0.07
DM	3	100.37	0.02	151.49	0.06
DM	4	100.35	0.13	150.11	0.04
DM	5	100.40	0.04	150.58	0.07
FT	6	100.41	0.02	130.71	0.16
FT	7	100.43	0.02	132.09	0.04
FT	8	100.46	0.04	131.33	0.12
FN	9	100.44	0.02	148.56	0.05
FN	10	100.46	0.03	150.74	0.04
FN	11	100.45	0.03	150.61	0.03
FN	12	100.43	0.03	149.22	0.10

Table 92: WVP523 VTM Before and After Trimming

VTM (%)															
Test	S#	Before					After					Difference			
		Abs.	SSD	CL	Dim.	AVG	Abs.	SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
H	1	0.6	5.7	6.3	7.6	6.5	0.2	5.1	5.2	5.2	5.2	0.6	1.1	2.4	1.3
L	2	0.3	3.3	4.1	4.9	4.1	0.2	2.4	2.5	2.6	2.5	0.9	1.6	2.3	1.6
DM	3	1.5	7.6	8.5	9.5	8.5	0.4	6.7	6.5	6.9	6.7	0.9	2.0	2.6	1.8
DM	4	1.5	7.5	8.3	9.4	8.4	0.4	6.8	6.7	7.0	6.8	0.7	1.6	2.4	1.6
DM	5	1.2	7.9	8.1	9.5	8.5	0.3	7.3	7.5	7.7	7.5	0.6	0.6	1.8	1.0
FT	6	1.6	8.1	8.6	9.7	8.8	0.4	7.6	6.9	7.1	7.2	0.5	1.7	2.6	1.6
FT	7	1.6	7.7	8.4	9.7	8.6	0.3	6.7	6.4	7.2	6.8	1.0	2.0	2.5	1.8
FT	8	1.8	8.0	8.4	9.6	8.7	0.3	6.6	6.4	7.0	6.7	1.4	2.0	2.6	2.0
FN	9	1.7	7.1	8.0	9.3	8.1	0.4	6.1	6.0	6.4	6.2	1.0	2.0	2.9	1.9
FN	10	1.6	7.5	8.2	9.4	8.4	0.5	6.8	6.7	7.2	6.9	0.7	1.5	2.2	1.5
FN	11	1.5	7.5	8.2	9.5	8.4	0.3	6.6	6.5	6.9	6.6	0.9	1.7	2.6	1.8
FN	12	1.5	7.9	8.7	9.5	8.7	0.4	7.1	6.9	7.5	7.1	0.8	1.8	2.0	1.6

Table 93: WVP523 VMA Before and After Trimming

VMA (%)									
Test	S#	Before				After			
		SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
H	1	14.6	15.1	16.3	15.3	14.0	14.1	14.2	14.1
L	2	12.4	13.1	13.8	13.1	11.6	11.7	11.8	11.7
DM	3	16.4	17.1	18.0	17.2	15.5	15.3	15.7	15.5
DM	4	16.2	16.9	17.9	17.0	15.6	15.5	15.7	15.6
DM	5	16.6	16.8	18.0	17.1	16.1	16.2	16.4	16.2
FT	6	16.7	17.2	18.2	17.4	16.3	15.7	15.9	16.0
FT	7	16.4	17.0	18.2	17.2	15.5	15.2	15.9	15.5
FT	8	16.7	17.0	18.1	17.3	15.4	15.2	15.8	15.5
FN	9	15.9	16.7	17.9	16.8	15.0	14.9	15.3	15.0
FN	10	16.2	16.9	17.9	17.0	15.6	15.5	15.9	15.7
FN	11	16.2	16.8	18.0	17.0	15.4	15.3	15.7	15.4
FN	12	16.5	17.3	18.0	17.3	15.8	15.7	16.2	15.9

Table 94: WVP523 VFA Before and After Trimming

VFA (%)									
Test	S#	Before				After			
		SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
H	1	60.7	58.4	53.5	57.5	63.8	63.4	63.1	63.4
L	2	73.3	69.0	64.8	69.0	79.6	78.7	77.8	78.7
DM	3	53.3	50.5	47.4	50.4	56.9	57.5	56.0	56.8
DM	4	53.8	51.1	47.7	50.9	56.5	56.6	55.8	56.3
DM	5	52.3	51.7	47.4	50.5	54.3	53.9	53.1	53.8
FT	6	51.8	50.1	46.8	49.6	53.5	56.0	55.1	54.9
FT	7	53	50.7	46.8	50.2	56.8	57.9	55.0	56.6
FT	8	51.9	50.8	47.0	49.9	57.3	58.0	55.4	56.9
FN	9	55.2	51.9	47.9	51.7	59.2	59.6	57.8	58.9
FN	10	53.9	51.3	47.7	51.0	56.4	56.9	54.9	56.1
FN	11	53.7	51.4	47.5	50.9	57.3	57.7	56.0	57.0
FN	12	52.5	49.8	47.5	49.9	55.3	56.1	53.9	55.1

Table 95: WVP766 Sample Geometry

		Diameter		Height	
Test	S#	AVG	SD	AVG	SD
H	1	100.53	0.07	149.94	0.16
L	2	100.49	0.07	149.27	0.45
DM	3	100.45	0.04	150.34	0.06
DM	4	100.47	0.04	149.41	0.14
DM	5	100.43	0.06	150.00	0.02
FT	6	100.39	0.02	131.62	0.19
FT	7	100.42	0.02	131.71	0.16
FT	8	100.42	0.03	131.52	0.11
FN	9	100.41	0.01	150.53	0.15
FN	10	100.47	0.01	150.71	0.05
FN	11	100.43	0.03	149.83	0.12
FN	12	100.42	0.04	150.66	0.17

Table 96: WVP766 VTM Before and After Trimming

VTM (%)															
Test	S#	Before					After					Difference			
		Abs.	SSD	CL	Dim.	AVG	Abs.	SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
H	1	2.7	9.6	10.3	11.2	10.4	1.1	8.8	9.1	9.2	9.0	0.8	1.2	2.0	1.4
L	2	0.2	3.3	3.5	4.5	3.8	0.1	2.3	2.4	2.4	2.4	1.0	1.1	2.1	1.4
DM	3	1.1	7.6	8.1	9.1	8.3	0.4	6.6	6.7	6.3	6.6	1.0	1.4	2.8	1.7
DM	4	1.1	7.5	8.5	9.2	8.4	0.4	6.7	6.9	7.2	7.0	0.8	1.6	2.0	1.4
DM	5	1.1	7.7	8.3	9.3	8.4	0.4	7.0	7.1	7.4	7.2	0.7	1.2	1.9	1.2
FT	6	1.6	7.8	8.9	9.4	8.7	0.4	6.5	6.7	6.8	6.7	1.3	2.2	2.6	2.0
FT	7	1.2	7.8	8.6	9.5	8.6	0.3	6.6	6.5	6.9	6.7	1.2	2.1	2.6	1.9
FT	8	1.3	7.9	8.6	9.6	8.7	0.3	6.8	6.8	7.2	7.0	1.1	1.8	2.4	1.7
FN	9	1	7.5	8.2	9.1	8.3	0.3	6.5	6.4	6.9	6.6	1.0	1.8	2.2	1.7
FN	10	1.1	7.7	8.4	9.2	8.4	0.4	6.8	6.7	7.1	6.9	0.9	1.7	2.1	1.5
FN	11	1.2	7.7	8.5	9.3	8.5	0.5	6.9	6.8	7.3	7.0	0.8	1.7	2.0	1.5
FN	12	1.3	7.7	8.4	9.2	8.4	0.4	6.7	6.7	7.1	6.8	1.0	1.7	2.1	1.6

Table 97: WVP766 VMA Before and After Trimming

VMA (%)									
Test	S#	Before				After			
		SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
H	1	20.4	21.0	21.9	21.1	19.7	19.9	20.1	19.9
L	2	14.8	15.0	15.9	15.2	14.0	14.0	14.1	14.0
DM	3	18.6	19.1	20.1	19.3	17.8	17.8	17.6	17.7
DM	4	18.5	19.4	20.1	19.3	17.8	18.0	18.4	18.1
DM	5	18.7	19.2	20.2	19.4	18.1	18.2	18.5	18.3
FT	6	18.8	19.8	20.3	19.6	17.7	17.8	18.0	17.8
FT	7	18.8	19.5	20.4	19.6	17.8	17.7	18.1	17.9
FT	8	18.9	19.5	20.5	19.6	17.9	17.9	18.4	18.1
FN	9	18.6	19.1	20.0	19.2	17.7	17.6	18.1	17.8
FN	10	18.7	19.3	20.1	19.4	18.0	17.9	18.3	18.0
FN	11	18.7	19.4	20.2	19.4	18.0	17.9	18.4	18.1
FN	12	18.7	19.3	20.1	19.4	17.8	17.8	18.2	18.0

Table 98: WVP766 VFA Before and After Trimming

VFA (%)									
Test	S#	Before				After			
		SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
H	1	52.9	51.0	48.8	50.9	55.1	54.4	54.3	54.6
L	2	77.7	76.7	72.1	75.5	83.3	82.8	83.1	83.1
DM	3	59.3	57.5	54.5	57.1	62.6	62.4	64.1	63.0
DM	4	59.6	56.3	54.3	56.7	62.3	61.5	60.8	61.5
DM	5	59.0	56.8	54.1	56.6	61.4	60.8	60.2	60.8
FT	6	58.4	54.9	53.7	55.7	63.1	62.3	62.4	62.6
FT	7	58.5	56.0	53.5	56.0	62.6	63.0	61.8	62.5
FT	8	58.0	55.9	53.2	55.7	62.0	61.9	60.7	61.5
FN	9	59.4	57.2	54.5	57.0	63.0	63.4	61.9	62.8
FN	10	58.7	56.6	54.2	56.5	61.9	62.3	61.0	61.7
FN	11	58.7	56.3	54.0	56.3	61.7	62.0	60.5	61.4
FN	12	58.8	56.5	54.2	56.5	62.5	62.3	61.3	62.0

Table 99: WVP882 Sample Geometry

		Diameter		Height	
Test	S#	AVG	SD	AVG	SD
DM	1	100.37	0.01	151.26	0.07
L	2	100.42	0.06	150.63	0.07
DM	3	100.37	0.02	150.93	0.08
DM	4	100.37	0.02	148.88	0.05
FN	5	100.32	0.16	151.83	0.03
FN	6	100.39	0.05	150.16	0.04
FT	7	100.43	0.02	131.93	0.11
FT	8	100.42	0.02	132.20	0.07
FT	9	100.45	0.02	130.68	0.11
FN	10	100.44	0.02	150.01	0.07
FN	11	100.44	0.02	149.45	0.14

Table 100: WVP882 VTM Before and After Trimming

VTM (%)															
Test	S#	Before					After					Difference			
		Abs.	SSD	CL	Dim.	AVG	Abs.	SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
DM	1	0.9	7.5	8.1	9.5	8.4	0.4	6.8	7.0	7.0	6.9	0.7	1.1	2.5	1.5
L	2	0.2	4.0	4.4	5.8	4.7	0.2	2.9	2.8	3.0	2.9	1.1	1.6	2.8	1.8
DM	3	0.9	7.7	8.3	9.6	8.5	0.5	6.7	6.6	6.9	6.7	1.0	1.7	2.7	1.8
DM	4	1.0	7.6	8.3	9.6	8.5	0.3	6.7	6.8	6.8	6.8	0.9	1.5	2.8	1.7
FN	5	1.2	7.7	8.3	9.7	8.6	0.4	6.8	6.6	6.9	6.8	0.9	1.7	2.8	1.8
FN	6	1.2	7.7	8.3	9.7	8.6	0.3	6.6	6.6	6.9	6.7	1.1	1.7	2.8	1.9
FT	7	1.2	7.5	8.3	9.5	8.4	0.3	6.0	6.5	6.3	6.3	1.5	1.8	3.2	2.1
FT	8	1.0	7.7	8.4	9.7	8.6	0.4	6.7	6.5	7.0	6.7	1.0	1.9	2.7	1.9
FT	9	1.3	8.0	8.5	9.9	8.8	0.3	6.7	6.5	7.0	6.7	1.3	2.0	2.9	2.1
FN	10	1.1	7.6	8.4	9.6	8.5	0.4	6.6	6.5	7.0	6.7	1.0	1.9	2.6	1.8
FN	11	1.3	7.8	8.7	9.7	8.7	0.4	6.7	6.5	7.0	6.7	1.1	2.2	2.7	2.0

Table 101: WVP882 VMA Before and After Trimming

VMA (%)									
Test	S#	Before				After			
		SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
DM	1	18.4	19.0	20.2	19.2	17.7	17.9	18.0	17.9
L	2	15.3	15.7	16.9	16.0	14.3	14.3	14.5	14.3
DM	3	18.5	19.1	20.3	19.3	17.6	17.7	17.9	17.7
DM	4	18.4	19.1	20.3	19.3	17.6	17.8	17.8	17.7
FN	5	18.6	19.1	20.3	19.3	17.7	17.6	17.9	17.7
FN	6	18.5	19.2	20.3	19.3	17.5	17.6	17.9	17.7
FT	7	18.3	19.1	20.2	19.2	17.0	17.5	17.4	17.3
FT	8	18.5	19.2	20.4	19.4	17.6	17.5	18.0	17.7
FT	9	18.8	19.3	20.6	19.6	17.6	17.5	18.0	17.7
FN	10	18.4	19.2	20.3	19.3	17.5	17.6	18.0	17.7
FN	11	18.6	19.5	20.4	19.5	17.6	17.6	18.0	17.7

Table 102: WVP882 VFA Before and After Trimming

VFA (%)									
Test	S#	Before				After			
		SSD	CL	Dim.	AVG	SSD	CL	Dim.	AVG
DM	1	59.0	57.1	52.9	56.3	61.7	61.3	61.2	61.4
L	2	73.7	71.9	65.9	70.5	79.8	80.2	79.1	79.7
DM	3	58.5	56.6	52.7	55.9	62.0	62.4	61.5	62.0
DM	4	58.9	56.7	52.6	56.1	62.1	61.9	61.7	61.9
FN	5	58.3	56.6	52.5	55.8	61.7	62.7	61.3	61.9
FN	6	58.3	56.5	52.5	55.8	62.4	62.6	61.3	62.1
FT	7	59.1	56.8	52.9	56.3	64.6	62.9	63.5	63.7
FT	8	58.6	56.3	52.3	55.7	62.1	62.9	61.1	62.0
FT	9	57.4	55.9	51.7	55.0	62.1	62.9	61.0	62.0
FN	10	58.8	56.4	52.6	55.9	62.5	63.0	61.2	62.2
FN	11	57.9	55.3	52.3	55.2	62.1	63.0	60.9	62.0

Appendix C: Dynamic Modulus

Dynamic Modulus MEPDG Outputs

Table 103: AA937 MEPDG Outputs

Temp (°C)	Temp (°F)	Frequency (Hz)	Shift Factor	Reduced Frequency	E* (ksi)	E* (MPa)
-10.0	14	25	4.167357	367533.5	2786.5	19218.3
-10.0	14	10	4.167357	147013.4	2712.1	18705.5
-10.0	14	5	4.167357	73506.7	2648.0	18263.1
-10.0	14	1	4.167357	14701.34	2469.8	17034.2
-10.0	14	0.5	4.167357	7350.67	2379.5	16411.2
-10.0	14	0.1	4.167357	1470.134	2136.7	14736.7
4.4	40	25	2.048433	2794.947	2239.1	15443.4
4.4	40	10	2.048433	1117.979	2090.8	14420.5
4.4	40	5	2.048433	558.9893	1969.2	13581.4
4.4	40	1	2.048433	111.7979	1659.9	11448.3
4.4	40	0.5	2.048433	55.89893	1518.2	10471.0
4.4	40	0.1	2.048433	11.17979	1182.7	8156.9
21.1	70	25	-0.13803	18.1932	1284.1	8856.1
21.1	70	10	-0.13803	7.277281	1094.3	7547.5
21.1	70	5	-0.13803	3.638641	955.3	6588.5
21.1	70	1	-0.13803	0.727728	660.9	4558.5
21.1	70	0.5	-0.13803	0.363864	551.0	3800.3
21.1	70	0.1	-0.13803	0.072773	342.7	2363.5
37.8	100	25	-2.09013	0.203146	467.8	3226.3
37.8	100	10	-2.09013	0.081259	354.8	2447.1
37.8	100	5	-2.09013	0.040629	283.8	1957.1
37.8	100	1	-2.09013	0.008126	162.4	1120.2
37.8	100	0.5	-2.09013	0.004063	126.2	870.1
37.8	100	0.1	-2.09013	0.000813	69.4	478.4
54.4	130	25	-3.84363	0.003584	120.5	830.8
54.4	130	10	-3.84363	0.001433	85.7	591.1
54.4	130	5	-3.84363	0.000717	66.2	456.6
54.4	130	1	-3.84363	0.000143	36.8	254.0
54.4	130	0.5	-3.84363	7.17E-05	28.9	199.6
54.4	130	0.1	-3.84363	1.43E-05	17.2	118.6

Table 104: JAP909 MEPDG Outputs

Temp (°C)	Temp (°F)	Frequency (Hz)	Shift Factor	Reduced Frequency	E* (ksi)	E* (MPa)
-10.0	14	25	3.980122	238815.5	3000.0	20691.0
-10.0	14	10	3.980122	95526.18	2937.5	20259.9
-10.0	14	5	3.980122	47763.09	2880.4	19866.4
-10.0	14	1	3.980122	9552.618	2708.5	18680.2
-10.0	14	0.5	3.980122	4776.309	2614.5	18032.2
-10.0	14	0.1	3.980122	955.2618	2342.9	16159.2
4.4	40	25	1.9564	2261.204	2497.9	17228.3
4.4	40	10	1.9564	904.4816	2332.3	16086.2
4.4	40	5	1.9564	452.2408	2190.1	15105.2
4.4	40	1	1.9564	90.44816	1808.0	12469.8
4.4	40	0.5	1.9564	45.22408	1625.9	11213.9
4.4	40	0.1	1.9564	9.044816	1188.6	8197.7
21.1	70	25	-0.13183	18.45486	1382.5	9535.3
21.1	70	10	-0.13183	7.381943	1134.2	7822.3
21.1	70	5	-0.13183	3.690972	953.8	6578.2
21.1	70	1	-0.13183	0.738194	588.1	4056.4
21.1	70	0.5	-0.13183	0.369097	461.6	3183.7
21.1	70	0.1	-0.13183	0.073819	246.3	1699.0
37.8	100	25	-1.99622	0.252183	400.9	2764.9
37.8	100	10	-1.99622	0.100873	279.9	1930.5
37.8	100	5	-1.99622	0.050437	210.2	1449.7
37.8	100	1	-1.99622	0.010087	105.7	729.1
37.8	100	0.5	-1.99622	0.005044	78.8	543.6
37.8	100	0.1	-1.99622	0.001009	41.5	286.1
54.4	130	25	-3.67094	0.005333	80.7	556.5
54.4	130	10	-3.67094	0.002133	55.4	382.2
54.4	130	5	-3.67094	0.001067	42.4	292.1
54.4	130	1	-3.67094	0.000213	24.3	167.7
54.4	130	0.5	-3.67094	0.000107	19.8	136.6
54.4	130	0.1	-3.67094	2.13E-05	13.3	92.0

Table 105: JFA060 MEPDG Outputs

Temp (°C)	Temp (°F)	Frequency (Hz)	Shift Factor	Reduced Frequency	E* (ksi)	E* (MPa)
-10.0	14	25	4.086707	305243.7	2892.6	19950.6
-10.0	14	10	4.086707	122097.5	2820.1	19450.4
-10.0	14	5	4.086707	61048.74	2755.7	19006.3
-10.0	14	1	4.086707	12209.75	2569.4	17721.5
-10.0	14	0.5	4.086707	6104.874	2471.6	17046.3
-10.0	14	0.1	4.086707	1220.975	2199.8	15172.3
4.4	40	25	2.00879	2551.118	2332.0	16084.0
4.4	40	10	2.00879	1020.447	2165.7	14936.7
4.4	40	5	2.00879	510.2235	2026.8	13979.0
4.4	40	1	2.00879	102.0447	1667.9	11503.7
4.4	40	0.5	2.00879	51.02235	1502.5	10362.5
4.4	40	0.1	2.00879	10.20447	1114.6	7687.7
21.1	70	25	-0.13536	18.30545	1254.2	8650.4
21.1	70	10	-0.13536	7.322181	1037.1	7152.8
21.1	70	5	-0.13536	3.66109	881.2	6077.8
21.1	70	1	-0.13536	0.732218	566.1	3904.0
21.1	70	0.5	-0.13536	0.366109	455.5	3141.8
21.1	70	0.1	-0.13536	0.073222	261.3	1802.4
37.8	100	25	-2.04968	0.222977	386.5	2665.9
37.8	100	10	-2.04968	0.089191	280.7	1935.7
37.8	100	5	-2.04968	0.044595	217.8	1502.3
37.8	100	1	-2.04968	0.008919	118.7	818.7
37.8	100	0.5	-2.04968	0.00446	91.5	630.7
37.8	100	0.1	-2.04968	0.000892	51.2	353.3
54.4	130	25	-3.76925	0.004253	89.8	619.7
54.4	130	10	-3.76925	0.001701	64.2	443.1
54.4	130	5	-3.76925	0.000851	50.4	347.6
54.4	130	1	-3.76925	0.00017	30.2	208.2
54.4	130	0.5	-3.76925	8.51E-05	24.8	171.4
54.4	130	0.1	-3.76925	1.7E-05	16.9	116.2

Table 106: JFA115 MEPDG Outputs

Temp (°C)	Temp (°F)	Frequency (Hz)	Shift Factor	Reduced Frequency	E* (ksi)	E* (MPa)
-10.0	14	25	4.146868	350597.1	2802.4	19328.2
-10.0	14	10	4.146868	140238.9	2720.9	18766.3
-10.0	14	5	4.146868	70119.43	2650.2	18278.1
-10.0	14	1	4.146868	14023.89	2451.9	16911.0
-10.0	14	0.5	4.146868	7011.943	2350.9	16214.4
-10.0	14	0.1	4.146868	1402.389	2079.2	14340.4
4.4	40	25	2.038362	2730.879	2198.0	15159.3
4.4	40	10	2.038362	1092.352	2032.6	14018.5
4.4	40	5	2.038362	546.1758	1897.4	13086.1
4.4	40	1	2.038362	109.2352	1557.5	10742.3
4.4	40	0.5	2.038362	54.61758	1404.5	9686.8
4.4	40	0.1	2.038362	10.92352	1051.7	7253.6
21.1	70	25	-0.13735	18.22165	1162.1	8014.9
21.1	70	10	-0.13735	7.288661	966.7	6667.2
21.1	70	5	-0.13735	3.644331	827.3	5705.7
21.1	70	1	-0.13735	0.728866	545.1	3759.7
21.1	70	0.5	-0.13735	0.364433	445.1	3070.0
21.1	70	0.1	-0.13735	0.072887	265.6	1831.6
37.8	100	25	-2.07985	0.208011	374.3	2581.7
37.8	100	10	-2.07985	0.083204	277.7	1915.0
37.8	100	5	-2.07985	0.041602	219.2	1511.6
37.8	100	1	-2.07985	0.00832	123.9	854.5
37.8	100	0.5	-2.07985	0.00416	96.7	666.7
37.8	100	0.1	-2.07985	0.000832	55.1	380.0
54.4	130	25	-3.82473	0.003743	93.1	642.0
54.4	130	10	-3.82473	0.001497	67.4	464.8
54.4	130	5	-3.82473	0.000749	53.2	366.7
54.4	130	1	-3.82473	0.00015	31.8	219.4
54.4	130	0.5	-3.82473	7.49E-05	26.0	179.4
54.4	130	0.1	-3.82473	1.5E-05	17.2	118.7

Table 107: JFA429 MEPDG Outputs

Temp (°C)	Temp (°F)	Frequency (Hz)	Shift Factor	Reduced Frequency	E* (ksi)	E* (MPa)
-10.0	14	25	4.17512	374162.4	2889.6	19929.2
-10.0	14	10	4.17512	149665	2814.5	19411.7
-10.0	14	5	4.17512	74832.49	2748.6	18957.4
-10.0	14	1	4.17512	14966.5	2561.3	17665.2
-10.0	14	0.5	4.17512	7483.249	2464.3	16996.5
-10.0	14	0.1	4.17512	1496.65	2199.0	15166.8
4.4	40	25	2.052249	2819.613	2310.2	15933.2
4.4	40	10	2.052249	1127.845	2146.7	14805.5
4.4	40	5	2.052249	563.9226	2011.5	13873.3
4.4	40	1	2.052249	112.7845	1666.2	11491.5
4.4	40	0.5	2.052249	56.39226	1508.2	10402.0
4.4	40	0.1	2.052249	11.27845	1138.7	7853.7
21.1	70	25	-0.13829	18.18243	1247.3	8602.3
21.1	70	10	-0.13829	7.272974	1041.1	7180.5
21.1	70	5	-0.13829	3.636487	892.9	6158.6
21.1	70	1	-0.13829	0.727297	590.7	4074.1
21.1	70	0.5	-0.13829	0.363649	483.0	3330.9
21.1	70	0.1	-0.13829	0.07273	289.0	1993.1
37.8	100	25	-2.09402	0.201333	402.7	2777.1
37.8	100	10	-2.09402	0.080533	299.0	2062.3
37.8	100	5	-2.09402	0.040267	236.3	1629.9
37.8	100	1	-2.09402	0.008053	134.4	926.9
37.8	100	0.5	-2.09402	0.004027	105.3	726.4
37.8	100	0.1	-2.09402	0.000805	61.0	420.4
54.4	130	25	-3.85079	0.003525	100.5	693.4
54.4	130	10	-3.85079	0.00141	73.4	506.3
54.4	130	5	-3.85079	0.000705	58.4	402.6
54.4	130	1	-3.85079	0.000141	35.8	246.8
54.4	130	0.5	-3.85079	7.05E-05	29.6	204.3
54.4	130	0.1	-3.85079	1.41E-05	20.2	139.4

Table 108: KP483 MEPDG Outputs

Temp (°C)	Temp (°F)	Frequency (Hz)	Shift Factor	Reduced Frequency	E* (ksi)	E* (MPa)
-10.0	14	25	4.066143	291127.6	2731.0	18835.6
-10.0	14	10	4.066143	116451	2646.7	18254.0
-10.0	14	5	4.066143	58225.51	2574.3	17755.2
-10.0	14	1	4.066143	11645.1	2375.6	16384.3
-10.0	14	0.5	4.066143	5822.551	2276.0	15697.5
-10.0	14	0.1	4.066143	1164.51	2012.4	13879.5
4.4	40	25	1.998683	2492.428	2142.5	14777.1
4.4	40	10	1.998683	996.9714	1984.7	13688.3
4.4	40	5	1.998683	498.4857	1856.6	12805.0
4.4	40	1	1.998683	99.69714	1537.0	10600.4
4.4	40	0.5	1.998683	49.84857	1393.5	9610.8
4.4	40	0.1	1.998683	9.969714	1061.8	7323.0
21.1	70	25	-0.13468	18.33418	1185.9	8179.2
21.1	70	10	-0.13468	7.333673	1000.5	6900.4
21.1	70	5	-0.13468	3.666836	866.7	5977.5
21.1	70	1	-0.13468	0.733367	589.7	4067.1
21.1	70	0.5	-0.13468	0.366684	488.6	3369.9
21.1	70	0.1	-0.13468	0.073337	301.0	2076.1
37.8	100	25	-2.03937	0.228335	426.5	2941.7
37.8	100	10	-2.03937	0.091334	322.7	2225.9
37.8	100	5	-2.03937	0.045667	258.1	1780.0
37.8	100	1	-2.03937	0.009133	148.7	1025.9
37.8	100	0.5	-2.03937	0.004567	116.3	802.0
37.8	100	0.1	-2.03937	0.000913	65.4	451.2
54.4	130	25	-3.75028	0.004443	115.1	794.2
54.4	130	10	-3.75028	0.001777	82.9	572.0
54.4	130	5	-3.75028	0.000889	64.8	446.8
54.4	130	1	-3.75028	0.000178	37.2	256.5
54.4	130	0.5	-3.75028	8.89E-05	29.7	204.6
54.4	130	0.1	-3.75028	1.78E-05	18.3	126.2

Table 109: WVP523 MEPDG Outputs

Temp (°C)	Temp (°F)	Frequency (Hz)	Shift Factor	Reduced Frequency	E* (ksi)	E* (MPa)
-10.0	14	25	4.087379	305716.3	2822.8	19468.5
-10.0	14	10	4.087379	122286.5	2744.6	18929.3
-10.0	14	5	4.087379	61143.26	2676.9	18462.6
-10.0	14	1	4.087379	12228.65	2488.1	17160.4
-10.0	14	0.5	4.087379	6114.326	2392.1	16498.1
-10.0	14	0.1	4.087379	1222.865	2133.6	14715.4
4.4	40	25	2.009121	2553.058	2258.0	15573.1
4.4	40	10	2.009121	1021.223	2101.6	14494.8
4.4	40	5	2.009121	510.6117	1973.3	13609.7
4.4	40	1	2.009121	102.1223	1647.3	11361.7
4.4	40	0.5	2.009121	51.06117	1498.5	10335.1
4.4	40	0.1	2.009121	10.21223	1148.5	7921.2
21.1	70	25	-0.13538	18.30451	1274.8	8792.5
21.1	70	10	-0.13538	7.321805	1077.6	7431.9
21.1	70	5	-0.13538	3.660903	933.8	6440.3
21.1	70	1	-0.13538	0.732181	633.0	4365.5
21.1	70	0.5	-0.13538	0.36609	522.3	3602.2
21.1	70	0.1	-0.13538	0.073218	316.5	2182.7
37.8	100	25	-2.05002	0.222804	451.0	3110.8
37.8	100	10	-2.05002	0.089121	337.7	2329.3
37.8	100	5	-2.05002	0.044561	267.4	1844.0
37.8	100	1	-2.05002	0.008912	149.4	1030.7
37.8	100	0.5	-2.05002	0.004456	115.0	793.0
37.8	100	0.1	-2.05002	0.000891	62.1	428.1
54.4	130	25	-3.76987	0.004247	112.9	778.6
54.4	130	10	-3.76987	0.001699	79.5	548.0
54.4	130	5	-3.76987	0.000849	60.9	420.3
54.4	130	1	-3.76987	0.00017	33.5	231.0
54.4	130	0.5	-3.76987	8.49E-05	26.2	181.0
54.4	130	0.1	-3.76987	1.7E-05	15.6	107.4

Table 110: WV766 MEPDG Outputs

Temp (°C)	Temp (°F)	Frequency (Hz)	Shift Factor	Reduced Frequency	E* (ksi)	E* (MPa)
-10.0	14	25	3.901012	199045.2	2700.8	18627.7
-10.0	14	10	3.901012	79618.07	2614.3	18030.8
-10.0	14	5	3.901012	39809.03	2539.6	17515.4
-10.0	14	1	3.901012	7961.807	2332.2	16085.4
-10.0	14	0.5	3.901012	3980.903	2227.6	15363.7
-10.0	14	0.1	3.901012	796.1807	1949.2	13443.8
4.4	40	25	1.917513	2067.538	2120.1	14622.4
4.4	40	10	1.917513	827.0151	1956.3	13492.9
4.4	40	5	1.917513	413.5075	1822.9	12572.4
4.4	40	1	1.917513	82.70151	1488.8	10268.2
4.4	40	0.5	1.917513	41.35075	1338.9	9234.4
4.4	40	0.1	1.917513	8.270151	994.6	6859.6
21.1	70	25	-0.12921	18.56654	1165.6	8039.4
21.1	70	10	-0.12921	7.426617	972.4	6706.3
21.1	70	5	-0.12921	3.713308	833.3	5747.6
21.1	70	1	-0.12921	0.742662	548.8	3785.2
21.1	70	0.5	-0.12921	0.371331	446.8	3081.8
21.1	70	0.1	-0.12921	0.074266	262.3	1809.3
37.8	100	25	-1.95655	0.276309	407.5	2810.3
37.8	100	10	-1.95655	0.110523	301.2	2077.5
37.8	100	5	-1.95655	0.055262	236.1	1628.5
37.8	100	1	-1.95655	0.011052	129.1	890.6
37.8	100	0.5	-1.95655	0.005526	98.5	679.6
37.8	100	0.1	-1.95655	0.001105	52.4	361.3
54.4	130	25	-3.59798	0.006309	103.8	715.8
54.4	130	10	-3.59798	0.002524	72.4	499.2
54.4	130	5	-3.59798	0.001262	55.2	380.4
54.4	130	1	-3.59798	0.000252	30.0	206.6
54.4	130	0.5	-3.59798	0.000126	23.4	161.2
54.4	130	0.1	-3.59798	2.52E-05	13.8	95.2

Table 111: WVP882 MEPDG Outputs

Temp (°C)	Temp (°F)	Frequency (Hz)	Shift Factor	Reduced Frequency	E* (ksi)	E* (MPa)
-10.0	14	25	4.021699	262808.2	2752.8	18986.0
-10.0	14	10	4.021699	105123.3	2669.8	18413.3
-10.0	14	5	4.021699	52561.63	2597.5	17914.8
-10.0	14	1	4.021699	10512.33	2394.5	16514.7
-10.0	14	0.5	4.021699	5256.163	2290.8	15799.9
-10.0	14	0.1	4.021699	1051.233	2011.8	13875.6
4.4	40	25	1.976836	2370.153	2159.4	14893.2
4.4	40	10	1.976836	948.0611	1992.2	13740.0
4.4	40	5	1.976836	474.0306	1855.2	12795.6
4.4	40	1	1.976836	94.80611	1510.5	10417.6
4.4	40	0.5	1.976836	47.40306	1355.2	9346.8
4.4	40	0.1	1.976836	9.480611	998.3	6885.4
21.1	70	25	-0.13321	18.39643	1143.2	7884.3
21.1	70	10	-0.13321	7.358573	944.4	6513.6
21.1	70	5	-0.13321	3.679287	802.6	5535.4
21.1	70	1	-0.13321	0.735857	516.6	3563.2
21.1	70	0.5	-0.13321	0.367929	416.1	2869.9
21.1	70	0.1	-0.13321	0.073586	238.2	1643.1
37.8	100	25	-2.01708	0.240361	361.6	2494.0
37.8	100	10	-2.01708	0.096144	262.6	1811.3
37.8	100	5	-2.01708	0.048072	203.3	1402.3
37.8	100	1	-2.01708	0.009614	108.7	749.8
37.8	100	0.5	-2.01708	0.004807	82.5	568.9
37.8	100	0.1	-2.01708	0.000961	43.8	301.9
54.4	130	25	-3.70929	0.004883	83.0	572.4
54.4	130	10	-3.70929	0.001953	57.7	397.8
54.4	130	5	-3.70929	0.000977	44.0	303.7
54.4	130	1	-3.70929	0.000195	24.3	167.9
54.4	130	0.5	-3.70929	9.77E-05	19.2	132.7
54.4	130	0.1	-3.70929	1.95E-05	11.8	81.5

Appendix D: Fatigue

Phase Angle Drops

Figure 60: Phase Angle Drop for AA937 S5, S6, and S7

Figure 61: Phase Angle Drop for JAP909 S6, S7, and S8

Figure 62: Phase Angle Drop for JFA060 S5, S6, and S7

Figure 63: Phase Angle Drop for JFA115 S6, S7, and S8

Figure 64: Phase Angle Drop for JFA429 S6, S7, and S8

Figure 65: Phase Angle Drop for KP483 S6, S7, and S8

Figure 66: Phase Angle Drop for WVP523 S6, S7, and S8

Figure 67: Phase Angle Drop for WVP766 S6, S7, and S8

Figure 68: Phase Angle Drop for WVP882 S7, S8, and S9

Alpha-Fatigue Outputs

**North Carolina
State University**

ALPHA-Fatigue Dynamic Modulus Report

Instrotek, Inc.
Raleigh, North Carolina
(919) 875-8371

Project Name:	AA937
Analysis Performed by:	Laura E. Dalton
Analysis Date:	5/20/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\AA937\Inputs
Output Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\AA937\Outputs
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	205.19	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTS	N/A	
C	N/A	

Mastercurve Function	
κ	1.17E+00
β	3.17E+00
δ	-9.16E-01
γ	-4.71E-01

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

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E* (Mpa)	Phase Angle (deg)	Cov. E* (%)	Cov. Phase Angle (deg.)
4	10	1.77E+03	14823	8.77	1.06	4.75
4	1	1.77E+02	11638	11.37	1.5	4.65
4	0.1	1.77E+01	8545.33	15.25	2.74	4.57
20	10	1.37E+01	7724	17.93	2.21	2.41
20	1	1.37E+00	4790.33	23.31	2.19	2.51
20	0.1	1.37E-01	2639.33	28.41	3.49	2.33
40	10	6.34E-02	2108	32.93	4.1	1.96
40	1	6.34E-03	910.83	34.04	7.28	1.94
40	0.1	6.34E-04	379.1	32.14	8.96	2.86
40	0.01	6.34E-05	173.97	28.2	9.66	3.55

Figure 69: Alpha-Fatigue AA937 Peak Dynamic Modulus Output

Project Name:	AA937
Analysis Performed by:	Laura E. Dalton
Analysis Date:	5/20/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\AA937\Inputs
Output Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\AA937\Outputs
Comments:	

Number of Fatigue Tests:	3
Damage Model Function:	Exponential

Damage Model Coefficients	
a	-1.92E-05
b	9.32E-01
y	N/A
z	N/A
alpha	3.711
Parameter r in Failure Crit.	3.83E+05
Parameter s in Failure Crit.	-7.75E-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_{finger}^* (MPa)	Nf	G^R
AA937 S5	15	10	9866.7	11379	4575	3.17E+02
AA937 S6	15	10	9877.4	11140	9655	1.08E+02
AA937 S7	15	10	9883.1	11349	57623	1.18E+01

Figure 70: Alpha-Fatigue AA937 Peak Damage Functions Output

Project Name: AA937
Analysis Performed by: Laura E. Dalton
Analysis Date: 5/20/2016
Testing Performed by: Laura E. Dalton
Default Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\AA937\Inputs

Output Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\AA937\Outputs

Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	1.75E+13
K2	7.188
K3	-5.106

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	6.10E-27
K2	-5.484
K3	6.842

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	6.10E-27
K2	5.484
K3	1.358

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

Traditional Strain Fatigue Relationship (psi units)	
K1	9.16E+08
K2	7.188
K3	-5.106

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	8.40E-26
K2	-5.484
K3	6.842

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	8.40E-26
K2	5.484
K3	1.358

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	51
10	55
15	61
20	70
25	91

Figure 71: Alpha-Fatigue AA937 Peak Model Prediction Output

Project Name: AA937
Analysis Performed by: Laura E. Dalton
Analysis Date: 6/6/2016
Testing Performed by: Laura E. Dalton
Default Directory: E:\GRA\Analysis\Fatigue Data\AA937\Inputs

Output Directory: E:\GRA\Analysis\Fatigue Data\AA937\Output_Default

Comments:

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

Shift Factor Coefficients		
<i>Tr</i>	21.1	deg. C
<i>Ea</i>	205.19	kJ/mol
<i>a1</i>	N/A	
<i>a2</i>	N/A	
<i>A</i>	N/A	
<i>VTs</i>	N/A	
<i>C</i>	N/A	

Mastercurve Function	
<i>κ</i>	1.17E+00
<i>β</i>	3.17E+00
<i>δ</i>	-9.16E-01
<i>γ</i>	-4.71E-01

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

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E* (Mpa)	Phase Angle (deg)	Cov. E* (%)	Cov. Phase Angle (deg.)
4	10	1.77E+03	14823	8.77	1.06	4.75
4	1	1.77E+02	11638	11.37	1.5	4.65
4	0.1	1.77E+01	8545.33	15.25	2.74	4.57
20	10	1.37E+01	7724	17.93	2.21	2.41
20	1	1.37E+00	4790.33	23.31	2.19	2.51
20	0.1	1.37E-01	2639.33	28.41	3.49	2.33
40	10	6.34E-02	2108	32.93	4.1	1.96
40	1	6.34E-03	910.83	34.04	7.28	1.94
40	0.1	6.34E-04	379.1	32.14	8.96	2.86
40	0.01	6.34E-05	173.97	28.2	9.66	3.55

Figure 72: Alpha-Fatigue AA937 Default Dynamic Modulus Output

Project Name:	AA937
Analysis Performed by:	Laura E. Dalton
Analysis Date:	6/6/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	E:\GRA\Analysis\Fatigue Data\AA937\Inputs
Output Directory:	E:\GRA\Analysis\Fatigue Data\AA937\Output_Default
Comments:	

Number of Fatigue Tests:	3
Damage Model Function:	Exponential

Damage Model Coefficients	
a	-2.68E-05
b	9.00E-01
y	N/A
z	N/A
alpha	3.711
Parameter r in Failure Crit.	8.41E+04
Parameter s in Failure Crit.	-5.94E-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* _{finger} (MPa)	Nf	G ^R
AA937 S5	15	10	9866.7	11379	1935	5.03E+02
AA937 S6	15	10	9877.4	11140	4715	1.64E+02
AA937 S7	15	10	9883.1	11349	8055	4.62E+01

Figure 73: Alpha-Fatigue AA937 Default Damage Functions Output

Project Name: AA937
Analysis Performed by: Laura E. Dalton
Analysis Date: 6/6/2016
Testing Performed by: Laura E. Dalton
Default Directory: E:\GRA\Analysis\Fatigue Data\AA937\Inputs
Output Directory: E:\GRA\Analysis\Fatigue Data\AA937\Output_Default
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	2.70E+04
K2	4.237
K3	-2.361

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	2.84E-10
K2	-4.42
K3	3.955

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	2.84E-10
K2	4.42
K3	-0.465

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

Traditional Strain Fatigue Relationship (psi units)	
K1	2.83E+02
K2	4.237
K3	-2.361

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	1.16E-10
K2	-4.42
K3	3.955

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	1.16E-10
K2	4.42
K3	-0.465

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	24
10	24
15	26
20	28
25	34

Figure 74: Alpha-Fatigue AA937 Default Model Prediction Output

Project Name:	JAP909
Analysis Performed by:	Laura E. Dalton
Analysis Date:	5/20/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JAP909\Inputs
Output Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JAP909\Outputs
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	196.16	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTs	N/A	
C	N/A	

Mastercurve Function	
κ	1.58E+00
β	2.76E+00
δ	-5.14E-01
γ	-6.25E-01

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

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E* (Mpa)	Phase Angle (deg)	Cov. E* (%)	Cov. Phase Angle (deg.)
4	10	1.41E+03	18175	11.75	8.72	5.66
4	1	1.41E+02	12997.67	16.19	10.1	4.86
4	0.1	1.41E+01	8387.33	21.81	10.73	4.01
20	10	1.35E+01	8049.67	23.63	4.58	0.13
20	1	1.35E+00	4344	29.71	4.63	0.17
20	0.1	1.35E-01	2003.67	33.46	5.04	0.21
40	10	7.92E-02	1582.33	38.39	5.01	2.37
40	1	7.92E-03	579.13	34.15	2.49	1.47
40	0.1	7.92E-04	227.4	28.23	3.04	1.58
40	0.01	7.92E-05	118.4	22.49	6.93	2.33

Figure 75: Alpha-Fatigue JAP909 Peak Dynamic Modulus Output

Project Name:	JAP909
Analysis Performed by:	Laura E. Dalton
Analysis Date:	5/20/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JAP909\Inputs
Output Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JAP909\Outputs
Comments:	

Number of Fatigue Tests:	3
Damage Model Function:	Exponential

Damage Model Coefficients	
a	-4.80E-04
b	6.67E-01
y	N/A
z	N/A
alpha	3.361
Parameter r in Failure Crit.	4.15E+05
Parameter s in Failure Crit.	-6.74E-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* _{finger} (MPa)	N _f	G ^R
JAP909 S6 at 15C	15	10	10602.8	11859	7135	3.52E+02
JAP909 S7	15	10	10611.5	11921	4895	8.04E+02
JAP909 S8	15	10	10595.1	11803	22363	8.07E+01

Figure 76: Alpha-Fatigue JAP909 Peak Damage Functions Output

Project Name:	JAP909
Analysis Performed by:	Laura E. Dalton
Analysis Date:	5/20/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JAP909\Inputs
Output Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JAP909\Outputs
Comments:	

Traditional Strain Fatigue Relationship (kPa units)	
K1	4.51E+14
K2	4.505
K3	-3.812

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	1.30E-10
K2	-4.22
K3	3.932

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	1.30E-10
K2	4.22
K3	-0.288

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

Traditional Strain Fatigue Relationship (psi units)	
K1	2.87E+11
K2	4.505
K3	-3.812

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	7.43E-11
K2	-4.22
K3	3.932

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	7.42E-11
K2	4.22
K3	-0.288

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	33
10	36
15	42
20	50
25	69

Figure 77: Alpha-Fatigue JAP909 Peak Model Prediction Output

Project Name: JAP909
Analysis Performed by: Laura E. Dalton
Analysis Date: 6/6/2016
Testing Performed by: Laura E. Dalton
Default Directory: E:\GRA\Analysis\Fatigue Data\JAP909\Inputs

Output Directory: E:\GRA\Analysis\Fatigue Data\JAP909\Output_Default

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	196.16	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTs	N/A	
C	N/A	

Mastercurve Function	
κ	1.58E+00
β	2.76E+00
δ	-5.14E-01
γ	-6.25E-01

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

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E' (Mpa)	Phase Angle (deg)	Cov. E' (%)	Cov. Phase Angle (deg.)
4	10	1.41E+03	18175	11.75	8.72	5.66
4	1	1.41E+02	12997.67	16.19	10.1	4.86
4	0.1	1.41E+01	8387.33	21.81	10.73	4.01
20	10	1.35E+01	8049.67	23.63	4.58	0.13
20	1	1.35E+00	4344	29.71	4.63	0.17
20	0.1	1.35E-01	2003.67	33.46	5.04	0.21
40	10	7.92E-02	1582.33	38.39	5.01	2.37
40	1	7.92E-03	579.13	34.15	2.49	1.47
40	0.1	7.92E-04	227.4	28.23	3.04	1.58
40	0.01	7.92E-05	118.4	22.49	6.93	2.33

Figure 78: Alpha-Fatigue JAP909 Default Dynamic Modulus Output

Project Name:	JAP909
Analysis Performed by:	Laura E. Dalton
Analysis Date:	6/6/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	E:\GRA\Analysis\Fatigue Data\JAP909\Inputs
Output Directory:	E:\GRA\Analysis\Fatigue Data\JAP909\Output_Default
Comments:	

Number of Fatigue Tests:	3
Damage Model Function:	Exponential

Damage Model Coefficients	
a	-7.48E-04
b	6.23E-01
y	N/A
z	N/A
alpha	3.361
Parameter r in Failure Crit.	9.14E+04
Parameter s in Failure Crit.	-5.39E-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^* _{finger}$ (MPa)	Nf	G^R
JAP909 S6	15	10	10602.8	11859	3215	4.92E+02
JAP909 S7	15	10	10611.5	11921	2115	1.08E+03
JAP909 S8	15	10	10595.1	11803	6115	1.51E+02

Figure 79: Alpha-Fatigue JAP909 Default Damage Functions Output

Project Name: JAP909
Analysis Performed by: Laura E. Dalton
Analysis Date: 6/6/2016
Testing Performed by: Laura E. Dalton
Default Directory: E:\GRA\Analysis\Fatigue Data\JAP909\Inputs

Output Directory: E:\GRA\Analysis\Fatigue Data\JAP909\Output_Default

Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	8.14E+08
K2	2.899
K3	-2.264

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	5.24E-01
K2	-3.308
K3	2.088

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	5.24E-01
K2	3.308
K3	-1.219

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

Traditional Strain Fatigue Relationship (psi units)	
K1	1.03E+07
K2	2.899
K3	-2.264

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	4.98E-02
K2	-3.308
K3	2.088

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	4.98E-02
K2	3.308
K3	-1.219

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	9
10	10
15	11
20	13
25	17

Figure 80: Alpha-Fatigue JAP909 Default Model Prediction Output

Project Name:	JFA060
Analysis Performed by:	Laura E. Dalton
Analysis Date:	5/20/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JFA060\Inputs
Output Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JFA060\Outputs
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	201.22	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTs	N/A	
C	N/A	

Mastercurve Function	
κ	1.60E+00
β	2.75E+00
δ	-5.30E-01
γ	-5.53E-01

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

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E' (Mpa)	Phase Angle (deg)	Cov. E' (%)	Cov. Phase Angle (deg.)
4	10	1.60E+03	15626	9.8	9.98	3.07
4	1	1.60E+02	11869.67	13.37	9.82	2.35
4	0.1	1.60E+01	8200.33	18.52	9.78	1.54
20	10	1.36E+01	7194	21.69	10.61	2.62
20	1	1.36E+00	4092.33	27.45	11.32	2.11
20	0.1	1.36E-01	2036.67	31.21	12.28	1.54
40	10	6.99E-02	1659	35.56	14.89	1.72
40	1	6.99E-03	666.07	32.74	16.69	2
40	0.1	6.99E-04	283.5	28.02	17.67	3.31
40	0.01	6.99E-05	152.47	23.15	19.5	5.91

Figure 81: Alpha-Fatigue JFA060 Peak Dynamic Modulus Output

Project Name:	JFA060
Analysis Performed by:	Laura E. Dalton
Analysis Date:	5/20/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JFA060\Inputs
Output Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JFA060\Outputs
Comments:	

Number of Fatigue Tests:	3
Damage Model Function:	Exponential

Damage Model Coefficients	
a	-1.11E-04
b	7.89E-01
y	N/A
z	N/A
alpha	3.657
Parameter r in Failure Crit.	4.79E+05
Parameter s in Failure Crit.	-7.06E-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^* _{finger}$ (MPa)	Nf	G^R
JFA060 S5	15	10	9682.1	9502	7075	2.80E+02
JFA060 S6	14.9	10	9723.6	10447	2595	1.84E+03
JFA060 S7	15	10	9705.3	10028	24645	8.16E+01

Figure 82: Alpha-Fatigue JFA060 Peak Damage Functions Output

Project Name: JFA060
Analysis Performed by: Laura E. Dalton
Analysis Date: 5/20/2016
Testing Performed by: Laura E. Dalton
Default Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JFA060\Inputs
Output Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JFA060\Outputs
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	1.75E+16
K2	5.191
K3	-4.399

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	3.57E-16
K2	-5.034
K3	5.095

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	3.57E-16
K2	5.034
K3	0.062

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

Traditional Strain Fatigue Relationship (psi units)	
K1	3.59E+12
K2	5.191
K3	-4.399

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	4.03E-16
K2	-5.034
K3	5.095

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	4.03E-16
K2	5.034
K3	0.062

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	44
10	48
15	55
20	66
25	91

Figure 83: Alpha-Fatigue JFA060 Peak Model Prediction Output

Project Name:	JFA060
Analysis Performed by:	Laura E. Dalton
Analysis Date:	6/6/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	E:\GRA\Analysis\Fatigue Data\JFA060\Inputs
Output Directory:	E:\GRA\Analysis\Fatigue Data\JFA060\Output_Default
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	201.22	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTs	N/A	
C	N/A	

Mastercurve Function	
κ	1.60E+00
β	2.75E+00
δ	-5.30E-01
γ	-5.53E-01

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

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E* (Mpa)	Phase Angle (deg)	Cov. E* (%)	Cov. Phase Angle (deg.)
4	10	1.60E+03	15626	9.8	9.98	3.07
4	1	1.60E+02	11869.67	13.37	9.82	2.35
4	0.1	1.60E+01	8200.33	18.52	9.78	1.54
20	10	1.36E+01	7194	21.69	10.61	2.62
20	1	1.36E+00	4092.33	27.45	11.32	2.11
20	0.1	1.36E-01	2036.67	31.21	12.28	1.54
40	10	6.99E-02	1659	35.56	14.89	1.72
40	1	6.99E-03	666.07	32.74	16.69	2
40	0.1	6.99E-04	283.5	28.02	17.67	3.31
40	0.01	6.99E-05	152.47	23.15	19.5	5.91

Figure 84: Alpha-Fatigue JFA060 Default Dynamic Modulus Output

Project Name:	JFA060
Analysis Performed by:	Laura E. Dalton
Analysis Date:	6/6/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	E:\GRA\Analysis\Fatigue Data\JFA060\Inputs
Output Directory:	E:\GRA\Analysis\Fatigue Data\JFA060\Output_Default
Comments:	

Number of Fatigue Tests:	3
Damage Model Function:	Exponential

Damage Model Coefficients	
a	-1.91E-04
b	7.37E-01
y	N/A
z	N/A
alpha	3.657
Parameter r in Failure Crit.	1.33E+05
Parameter s in Failure Crit.	-6.23E-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 _{finger}$ (MPa)	Nf	G^R
JFA060 S5	15	10	9682.1	9502	3295	3.87E+02
JFA060 S6	14.9	10	9723.6	10447	935	2.85E+03
JFA060 S7	15	10	9705.3	10028	6315	1.32E+02

Figure 85: Alpha-Fatigue JFA060 Default Damage Functions Output

Project Name:	JFA060
Analysis Performed by:	Laura E. Dalton
Analysis Date:	6/8/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	E:\GRA\Analysis\Fatigue Data\JFA060\Inputs
Output Directory:	E:\GRA\Analysis\Fatigue Data\JFA060\Output_Default
Comments:	

Traditional Strain Fatigue Relationship (kPa units)	
K1	1.68E+10
K2	4.077
K3	-3.078

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	7.95E-05
K2	-4.418
K3	3.155

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	7.95E-05
K2	4.418
K3	-1.263

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

Traditional Strain Fatigue Relationship (psi units)	
K1	4.40E+07
K2	4.077
K3	-3.078

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	6.94E-06
K2	-4.418
K3	3.155

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	6.94E-06
K2	4.418
K3	-1.263

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	21
10	23
15	26
20	30
25	39

Figure 86: Alpha-Fatigue JFA060 Default Model Prediction Output

Project Name: JFA115
Analysis Performed by: Laura E. Dalton
Analysis Date: 5/20/2016
Testing Performed by: Laura E. Dalton
Default Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JFA115\Inputs
Output Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JFA115\Outputs
Comments:

Test Protocol: PP-81/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	204.18	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTS	N/A	
C	N/A	

Mastercurve Function	
κ	1.49E+00
β	2.85E+00
δ	-5.93E-01
γ	-5.03E-01

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

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E' (Mpa)	Phase Angle (deg)	Cov. E' (%)	Cov. Phase Angle (deg.)
4	10	1.72E+03	14704.33	9.84	7.65	2.66
4	1	1.72E+02	11116	12.85	7.82	2.32
4	0.1	1.72E+01	7686.67	17.45	6.67	1.41
20	10	1.37E+01	6698.33	20.65	6.09	1.21
20	1	1.37E+00	3915	25.82	5.4	1.34
20	0.1	1.37E-01	2062	29.75	4.63	1.12
40	10	6.50E-02	1657	33.73	5.23	1.81
40	1	6.50E-03	700.5	32.29	5.33	1.96
40	0.1	6.50E-04	305.9	28.67	3.92	1.62
40	0.01	6.50E-05	160.2	24.17	5.74	2.3

Figure 87: Alpha-Fatigue JFA115 Peak Dynamic Modulus Output

Project Name:	JFA115
Analysis Performed by:	Laura E. Dalton
Analysis Date:	5/20/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	C:\Users\user\Desktop\Laura Dalton\GRAVAMPT\Fatigue Data\JFA115\Inputs
Output Directory:	C:\Users\user\Desktop\Laura Dalton\GRAVAMPT\Fatigue Data\JFA115\Outputs
Comments:	

Number of Fatigue Tests:	3
Damage Model Function:	Exponential

Damage Model Coefficients	
a	-2.97E-04
b	6.99E-01
y	N/A
z	N/A
alpha	3.802
Parameter r in Failure Crit.	5.60E+05
Parameter s in Failure Crit.	-6.98E-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'_{finger} (MPa)	Nf	G^R
JFA115 S6	15	10	9031.8	8686	22363	9.70E+01
JFA115 S7	15	10	9028.9	8697	2895	1.73E+03
JFA115 S8	15	10	9054.6	9405	6655	6.80E+02

Figure 88: Alpha-Fatigue JFA115 Peak Damage Functions Output

Project Name: JFA115
Analysis Performed by: Laura E. Dalton
Analysis Date: 5/20/2018
Testing Performed by: Laura E. Dalton
Default Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JFA115\Inputs
Output Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JFA115\Outputs
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	2.70E+16
K2	5.002
K3	-4.286

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	9.69E-13
K2	-5.24
K3	4.714

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	9.69E-13
K2	5.24
K3	-0.526

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

Traditional Strain Fatigue Relationship (psi units)	
K1	6.88E+12
K2	5.002
K3	-4.286

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	3.51E-13
K2	-5.24
K3	4.714

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	3.51E-13
K2	5.24
K3	-0.526

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	48
10	54
15	63
20	76
25	104

Figure 89: Alpha-Fatigue JFA115 Peak Model Prediction Output

Project Name: JFA115
Analysis Performed by: Laura E. Dalton
Analysis Date: 6/6/2016
Testing Performed by: Laura E. Dalton
Default Directory: E:\GRA\Analysis\Fatigue Data\JFA115\Inputs
Output Directory: E:\GRA\Analysis\Fatigue Data\JFA115\Output_Default
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	204.18	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTS	N/A	
C	N/A	

Mastercurve Function	
κ	1.49E+00
β	2.85E+00
δ	-5.93E-01
γ	-5.03E-01

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

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E' (Mpa)	Phase Angle (deg)	Cov. E' (%)	Cov. Phase Angle (deg.)
4	10	1.72E+03	14704.33	9.84	7.65	2.66
4	1	1.72E+02	11116	12.85	7.82	2.32
4	0.1	1.72E+01	7686.67	17.45	6.67	1.41
20	10	1.37E+01	6698.33	20.65	6.09	1.21
20	1	1.37E+00	3915	25.82	5.4	1.34
20	0.1	1.37E-01	2062	29.75	4.63	1.12
40	10	6.50E-02	1657	33.73	5.23	1.81
40	1	6.50E-03	700.5	32.29	5.33	1.96
40	0.1	6.50E-04	305.9	28.67	3.92	1.62
40	0.01	6.50E-05	160.2	24.17	5.74	2.3

Figure 90: Alpha-Fatigue JFA115 Default Dynamic Modulus Output

Project Name: JFA115
Analysis Performed by: Laura E. Dalton
Analysis Date: 6/6/2016
Testing Performed by: Laura E. Dalton
Default Directory: E:\GRA\Analysis\Fatigue Data\JFA115\Inputs
Output Directory: E:\GRA\Analysis\Fatigue Data\JFA115\Output_Default
Comments:

Number of Fatigue Tests: 3
Damage Model Function: Exponential

Damage Model Coefficients	
a	-3.27E-04
b	6.89E-01
y	N/A
z	N/A
alpha	3.802
Parameter r in Failure Crit.	1.22E+05
Parameter s in Failure Crit.	-5.77E-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' _{finger}$ (MPa)	Nf	G^R
JFA115 S6	15	10	9031.8	8686	6115	1.54E+02
JFA115 S7	15	10	9028.9	8697	1115	2.67E+03
JFA115 S8	15	10	9054.6	9405	3015	9.16E+02

Figure 91: Alpha-Fatigue JFA115 Default Damage Functions Output

Project Name: JFA115
Analysis Performed by: Laura E. Dalton
Analysis Date: 6/6/2016
Testing Performed by: Laura E. Dalton
Default Directory: E:\GRA\Analysis\Fatigue Data\JFA115\Inputs
Output Directory: E:\GRA\Analysis\Fatigue Data\JFA115\Output_Default
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	5.21E+09
K2	3.46
K3	-2.659

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	5.18E-03
K2	-4.307
K3	2.843

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	5.18E-03
K2	-4.307
K3	-1.465

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

Traditional Strain Fatigue Relationship (psi units)	
K1	3.07E+07
K2	3.46
K3	-2.659

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	3.06E-04
K2	-4.307
K3	2.843

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	3.06E-04
K2	-4.307
K3	-1.465

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	17
10	19
15	21
20	25
25	33

Figure 92: Alpha-Fatigue JFA115 Default Model Prediction Output

Project Name:	JFA429
Analysis Performed by:	Laura E. Dalton
Analysis Date:	5/20/2018
Testing Performed by:	Laura E. Dalton
Default Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JFA429\Inputs
Output Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JFA429\Outputs
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	205.57	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTs	N/A	
C	N/A	

Mastercurve Function	
K	1.64E+00
β	2.71E+00
δ	-5.61E-01
γ	-5.22E-01

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

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E* (Mpa)	Phase Angle (deg)	Cov. E* (%)	Cov. Phase Angle (deg.)
4	10	1.78E+03	15098.33	9.67	5.44	2.84
4	1	1.78E+02	11805	13	5.17	1.71
4	0.1	1.78E+01	8155.67	17.76	4.77	1.13
20	10	1.37E+01	7395.33	20.54	4.59	1.11
20	1	1.37E+00	4354.67	25.83	4.49	0.91
20	0.1	1.37E-01	2284.67	29.65	4.28	0.29
40	10	6.28E-02	1799.67	33.8	6.91	0.48
40	1	6.28E-03	739.37	31.58	7.08	1.16
40	0.1	6.28E-04	332.93	27.23	8.75	2.46
40	0.01	6.28E-05	189.1	22.52	10.97	3.77

Figure 93: Alpha-Fatigue JFA429 Peak Dynamic Modulus Output

Project Name:	JFA429
Analysis Performed by:	Laura E. Dalton
Analysis Date:	5/20/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JFA429\Inputs
Output Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JFA429\Outputs
Comments:	

Number of Fatigue Tests:	3
Damage Model Function:	Exponential

Damage Model Coefficients	
a	-1.37E-04
b	7.73E-01
y	N/A
z	N/A
alpha	3.85
Parameter r in Failure Crit.	7.89E+05
Parameter s in Failure Crit.	-7.97E-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* _{finger} (MPa)	Nf	G ^R
JFA429 S6	15	10	9695.2	11478	3535	8.61E+02
JFA429 S7	15	10	9678.4	10234	30712	6.37E+01
JFA429 S8	15	10	9688.9	10244	63507	2.22E+01

Figure 94: Alpha-Fatigue JFA060 Peak Damage Functions Output

Project Name: JFA429
Analysis Performed by: Laura E. Dalton
Analysis Date: 5/20/2016
Testing Performed by: Laura E. Dalton
Default Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JFA429\Inputs
Output Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\JFA429\Outputs
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	3.12E+25
K2	7.851
K3	-7.098

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	2.01E-21
K2	-5.731
K3	6.122

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	2.01E-21
K2	5.731
K3	0.391

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

Traditional Strain Fatigue Relationship (psi units)	
K1	3.48E+19
K2	7.851
K3	-7.098

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	4.27E-21
K2	-5.731
K3	6.122

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	4.27E-21
K2	5.731
K3	0.391

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	87
10	75
15	90
20	111
25	154

Figure 95: Alpha-Fatigue JFA429 Peak Model Prediction Output

Project Name: JFA429
Analysis Performed by:
Analysis Date: 6/6/2016
Testing Performed by: Laura E. Dalton
Default Directory: E:\GRA\Analysis\Fatigue Data\JFA429\Inputs
Output Directory: E:\GRA\Analysis\Fatigue Data\JFA429\Output_Default

Test Protocol: PP-81/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	205.57	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTS	N/A	
C	N/A	

Mastercurve Function	
κ	1.64E+00
β	2.71E+00
δ	-5.61E-01
γ	-5.22E-01

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

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E' (Mpa)	Phase Angle (deg)	Cov. E' (%)	Cov. Phase Angle (deg.)
4	10	1.78E+03	15098.33	9.67	5.44	2.84
4	1	1.78E+02	11605	13	5.17	1.71
4	0.1	1.78E+01	8155.67	17.76	4.77	1.13
20	10	1.37E+01	7395.33	20.54	4.59	1.11
20	1	1.37E+00	4354.67	25.83	4.49	0.91
20	0.1	1.37E-01	2284.67	29.65	4.28	0.29
40	10	6.28E-02	1799.67	33.8	6.91	0.48
40	1	6.28E-03	739.37	31.58	7.08	1.16
40	0.1	6.28E-04	332.93	27.23	8.75	2.46
40	0.01	6.28E-05	189.1	22.52	10.97	3.77

Figure 96: Alpha-Fatigue JFA429 Default Dynamic Modulus Output

Project Name:	JFA429
Analysis Performed by:	
Analysis Date:	6/6/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	E:\GRA\Analysis\Fatigue Data\JFA429\Inputs
Output Directory:	E:\GRA\Analysis\Fatigue Data\JFA429\Output_Default
Comments:	

Number of Fatigue Tests:	3
Damage Model Function:	Exponential

Damage Model Coefficients	
a	-1.08E-04
b	7.96E-01
y	N/A
z	N/A
alpha	3.85
Parameter r in Failure Crit.	9.11E+04
Parameter s in Failure Crit.	-5.77E-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* _{finger} (MPa)	Nf	G ^R
JFA429 S6	15	10	9695.2	11478	1455	1.25E+03
JFA429 S7	15	10	9678.4	10234	6775	1.06E+02
JFA429 S8	15	10	9688.9	10244	8315	5.55E+01

Figure 97: Alpha-Fatigue JFA429 Default Damage Functions Output

Project Name:	JFA429
Analysis Performed by:	
Analysis Date:	8/8/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	E:\GRA\Analysis\Fatigue Data\JFA429\Inputs
Output Directory:	E:\GRA\Analysis\Fatigue Data\JFA429\Output_Default
Comments:	

Traditional Strain Fatigue Relationship (kPa units)	
K1	6.35E+08
K2	3.542
K3	-2.621

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	3.63E-06
K2	-4.513
K3	3.35

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	3.63E-06
K2	4.513
K3	-1.164

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

Traditional Strain Fatigue Relationship (psi units)	
K1	4.03E+06
K2	3.542
K3	-2.621

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	3.84E-07
K2	-4.513
K3	3.35

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	3.84E-07
K2	4.513
K3	-1.164

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	17
10	18
15	20
20	23
25	29

Figure 98: Alpha-Fatigue JFA429 Default Model Prediction Output

Project Name:	KP483
Analysis Performed by:	Laura E. Dalton
Analysis Date:	5/23/2018
Testing Performed by:	Laura E. Dalton
Default Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\KP483\Inputs
Output Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\KP483\Outputs
Comments:	

Test Protocol:	PP-81/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	200.21	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTS	N/A	
C	N/A	

Mastercurve Function	
κ	1.29E+00
β	3.05E+00
δ	-7.78E-01
γ	-4.70E-01

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

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E' (Mpa)	Phase Angle (deg)	Cov. E' (%)	Cov. Phase Angle (deg.)
4	10	1.58E+03	14182	9.72	8.4	2.84
4	1	1.58E+02	10907.33	12.49	8.46	2.69
4	0.1	1.58E+01	7807.87	16.47	8.25	2.47
20	10	1.36E+01	6984.33	19.33	4.42	2.19
20	1	1.36E+00	4208.67	24.44	2.89	2.2
20	0.1	1.36E-01	2292.33	28.74	1.94	2.06
40	10	7.17E-02	1929	32.79	7.17	1.94
40	1	7.17E-03	852.1	33.13	8.24	2.04
40	0.1	7.17E-04	365.17	30.8	9.93	2.52
40	0.01	7.17E-05	174.47	26.67	11.32	2.65

Figure 99: Alpha-Fatigue KP483 Peak Dynamic Modulus Output

Project Name:	KP483
Analysis Performed by:	Laura E. Dalton
Analysis Date:	5/23/2018
Testing Performed by:	Laura E. Dalton
Default Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\KP483\Inputs
Output Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\KP483\Outputs
Comments:	

Number of Fatigue Tests:	3
Damage Model Function:	Exponential

Damage Model Coefficients	
a	-1.47E-05
b	9.57E-01
y	N/A
z	N/A
alpha	3.811
Parameter r in Failure Crit.	6.01E+05
Parameter s in Failure Crit.	-7.91E-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' _{finger}$ (MPa)	Nf	G^R
KP483 S6	15	10	9104.7	8161	12871	1.54E+02
KP483 S7	15	10	9100.4	8995	3395	6.42E+02
KP483 S8	15	10	9112.3	9888	23539	5.41E+01

Figure 100: Alpha-Fatigue KP483 Peak Damage Functions Output

Project Name: KP483
Analysis Performed by: Laura E. Dalton
Analysis Date: 5/23/2016
Testing Performed by: Laura E. Dalton
Default Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\KP483\Inputs
Output Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\KP483\Outputs
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	2.97E+21
K2	7.612
K3	-6.45

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	NaN
K2	NaN
K3	NaN

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	NaN
K2	NaN
K3	NaN

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

Traditional Strain Fatigue Relationship (psi units)	
K1	1.16E+16
K2	7.612
K3	-6.45

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	NaN
K2	NaN
K3	NaN

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	NaN
K2	NaN
K3	NaN

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	64
10	70
15	82
20	97
25	131

Figure 101: Alpha-Fatigue KP483 Peak Model Prediction Output

Project Name: KP483
Analysis Performed by: Laura E. Dalton
Analysis Date: 6/21/2016
Testing Performed by: Laura E. Dalton
Default Directory: E:\GRA\Thesis\Analysis\Fatigue Data\KP483\Inputs
Output Directory: E:\GRA\Thesis\Analysis\Fatigue Data\KP483\Output_Default
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	200.21	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTs	N/A	
C	N/A	

Mastercurve Function	
κ	1.29E+00
β	3.05E+00
δ	-7.76E-01
γ	-4.70E-01

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

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E' (Mpa)	Phase Angle (deg)	Cov. E' (%)	Cov. Phase Angle (deg.)
4	10	1.56E+03	14182	9.72	8.4	2.84
4	1	1.56E+02	10907.33	12.49	8.46	2.69
4	0.1	1.56E+01	7807.67	16.47	8.25	2.47
20	10	1.36E+01	6984.33	19.33	4.42	2.19
20	1	1.36E+00	4208.67	24.44	2.89	2.2
20	0.1	1.36E-01	2262.33	28.74	1.94	2.06
40	10	7.17E-02	1929	32.79	7.17	1.94
40	1	7.17E-03	852.1	33.13	8.24	2.04
40	0.1	7.17E-04	365.17	30.8	9.93	2.52
40	0.01	7.17E-05	174.47	26.67	11.32	2.65

Figure 102: Alpha-Fatigue KP483 Default Dynamic Modulus Output

Project Name:	KP483
Analysis Performed by:	Laura E. Dalton
Analysis Date:	6/21/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	E:\GRA\Thesis\Analysis\Fatigue Data\KP483\Inputs
Output Directory:	E:\GRA\Thesis\Analysis\Fatigue Data\KP483\Output_Default
Comments:	

Number of Fatigue Tests:	2
Damage Model Function:	Exponential

Damage Model Coefficients	
a	-1.22E-05
b	9.77E-01
y	N/A
z	N/A
alpha	3.811
Parameter r in Failure Crit.	2.01E+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' _{LVE}$ (MPa)	$ E' _{finger}$ (MPa)	Nf	G^R
KP483 S7	15	10	9100.4	8995	1335	1.01E+03
KP483 S8	15	10	9112.3	9088	6255	1.20E+02

Figure 103: Alpha-Fatigue KP483 Default Damage Functions Output

Project Name: KP483
Analysis Performed by: Laura E. Dalton
Analysis Date: 6/21/2016
Testing Performed by: Laura E. Dalton
Default Directory: E:\GRA\Thesis\Analysis\Fatigue Data\KP483\Inputs
Output Directory: E:\GRA\Thesis\Analysis\Fatigue Data\KP483\Output_Default
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	9.75E+08
K2	6.153
K3	-4.013

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	9.82E-19
K2	-5.453
K3	5.656

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	9.82E-19
K2	5.453
K3	0.203

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

Traditional Strain Fatigue Relationship (psi units)	
K1	4.20E+05
K2	6.153
K3	-4.013

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	1.45E-18
K2	-5.453
K3	5.656

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	1.45E-18
K2	5.453
K3	0.203

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	41
10	43
15	47
20	53
25	67

Figure 104: Alpha-Fatigue KP483 Default Model Prediction Output

Project Name:	WVP523
Analysis Performed by:	Laura E. Dalton
Analysis Date:	5/23/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\WVP523\Inputs
Output Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\WVP523\Outputs
Comments:	

Test Protocol:	PP-81/TP-79
Number of E' Tests:	3
Maximum Limiting Modulus:	Fixed (Hirsch)
Shift Factor Function:	Arrhenius

Shift Factor Coefficients		
<i>Tr</i>	21.1	deg. C
<i>Ea</i>	202.82	kJ/mol
<i>a1</i>	N/A	
<i>a2</i>	N/A	
<i>A</i>	N/A	
<i>VTS</i>	N/A	
<i>C</i>	N/A	

Mastercurve Function	
<i>κ</i>	1.32E+00
<i>β</i>	3.03E+00
<i>δ</i>	-8.06E-01
<i>γ</i>	-5.07E-01

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

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E' (Mpa)	Phase Angle (deg)	Cov. E' (%)	Cov. Phase Angle (deg.)
4	10	1.66E+03	16148.33	9.22	1.93	2.15
4	1	1.66E+02	12443.33	12.06	2.65	2.21
4	0.1	1.66E+01	8903	16.38	3.68	2.1
20	10	1.36E+01	7638.67	19.72	3.15	1.63
20	1	1.36E+00	4553	25.36	4.15	1.57
20	0.1	1.36E-01	2440.67	30.28	5.48	1.54
40	10	6.72E-02	1974	34.63	13.69	2.7
40	1	6.72E-03	844.97	34.79	16.27	1.47
40	0.1	6.72E-04	341.87	32.06	17.66	1.5
40	0.01	6.72E-05	153.07	27.12	15.74	1.1

Figure 105: Alpha-Fatigue WVP523 Peak Dynamic Modulus Output

Project Name:	WVP523
Analysis Performed by:	Laura E. Dalton
Analysis Date:	5/23/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\WVP523\Inputs
Output Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\WVP523\Outputs
Comments:	

Number of Fatigue Tests:	3
Damage Model Function:	Exponential

Damage Model Coefficients	
a	-3.54E-05
b	8.85E-01
y	N/A
z	N/A
alpha	3.629
Parameter r in Failure Crit.	5.37E+05
Parameter s in Failure Crit.	-8.07E-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^* _{finger}$ (MPa)	Nf	G^R
WVP523 S6	15	10	10169.5	10763	2835	5.92E+02
WVP523 S7	15	10	10168.3	10720	12546	1.27E+02
WVP523 S8	15	10	10161.7	10555	68633	1.17E+01

Figure 106: Alpha-Fatigue WVP523 Peak Damage Functions Output

Project Name: WVP523
Analysis Performed by: Laura E. Dalton
Analysis Date: 5/23/2016
Testing Performed by: Laura E. Dalton
Default Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\WVP523\Inputs
Output Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\WVP523\Outputs
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	5.48E+20
K2	8.161
K3	-8.672

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	1.39E-26
K2	-5.42
K3	6.744

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	1.39E-26
K2	5.42
K3	1.323

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

Traditional Strain Fatigue Relationship (psi units)	
K1	1.40E+15
K2	8.161
K3	-8.672

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	1.78E-25
K2	-5.42
K3	6.744

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	1.78E-25
K2	5.42
K3	1.323

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	58
10	63
15	73
20	86
25	117

Figure 107: Alpha-Fatigue WVP523 Peak Model Prediction Output

Project Name: WVP523
Analysis Performed by: Laura E. Dalton
Analysis Date: 6/6/2016
Testing Performed by: Laura E. Dalton
Default Directory: E:\GRA\Analysis\Fatigue Data\WVP523\Inputs
Output Directory: E:\GRA\Analysis\Fatigue Data\WVP523\Output_Default
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	202.82	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTs	N/A	
C	N/A	

Mastercurve Function	
κ	1.32E+00
β	3.03E+00
δ	-8.08E-01
γ	-5.07E-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	1.68E+03	16148.33	9.22	1.93	2.15
4	1	1.68E+02	12443.33	12.06	2.65	2.21
4	0.1	1.68E+01	8903	16.38	3.68	2.1
20	10	1.36E+01	7638.67	19.72	3.15	1.63
20	1	1.36E+00	4553	25.36	4.15	1.57
20	0.1	1.36E-01	2440.67	30.28	5.48	1.54
40	10	6.72E-02	1974	34.63	13.69	2.7
40	1	6.72E-03	844.97	34.79	16.27	1.47
40	0.1	6.72E-04	341.87	32.06	17.66	1.5
40	0.01	6.72E-05	153.07	27.12	15.74	1.1

Figure 108: Alpha-Fatigue WVP523 Default Dynamic Modulus Output

Project Name:	WVP523
Analysis Performed by:	Laura E. Dalton
Analysis Date:	8/8/2018
Testing Performed by:	Laura E. Dalton
Default Directory:	E:\GRA\Analysis\Fatigue Data\WVP523\Inputs
Output Directory:	E:\GRA\Analysis\Fatigue Data\WVP523\Output_Default
Comments:	

Number of Fatigue Tests:	3
Damage Model Function:	Exponential

Damage Model Coefficients	
a	-3.57E-05
b	8.83E-01
y	N/A
z	N/A
alpha	3.629
Parameter r in Failure Crit.	1.08E+05
Parameter s in Failure Crit.	-6.37E-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' _{finger}$ (MPa)	Nf	G^R
WVP523 S6	15	10	10189.5	10763	1095	1.04E+03
WVP523 S7	15	10	10188.3	10720	5095	2.03E+02
WVP523 S8	15	10	10181.7	10555	8355	4.25E+01

Figure 109: Alpha-Fatigue WVP523 Default Damage Functions Output

Project Name: WVP523
Analysis Performed by: Laura E. Dalton
Analysis Date: 6/6/2016
Testing Performed by: Laura E. Dalton
Default Directory: E:\GRA\Analysis\Fatigue Data\WVP523\Inputs
Output Directory: E:\GRA\Analysis\Fatigue Data\WVP523\Output_Default
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	2.44E+08
K2	4.62
K3	-2.851

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	2.42E-11
K2	-4.528
K3	4.146

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	2.42E-11
K2	4.528
K3	-0.383

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

Traditional Strain Fatigue Relationship (psi units)	
K1	9.91E+03
K2	4.62
K3	-2.851

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	1.16E-11
K2	-4.528
K3	4.146

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	1.16E-11
K2	4.528
K3	-0.383

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	25
10	26
15	28
20	30
25	38

Figure 110: Alpha-Fatigue WVP523 Default Model Prediction Output

Project Name: WVP766
Analysis Performed by: Laura E. Dalton
Analysis Date: 5/23/2016
Testing Performed by: Laura E. Dalton
Default Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\WVP766\Inputs
Output Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\WVP766\Outputs
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	192.07	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTS	N/A	
C	N/A	

Mastercurve Function	
κ	1.15E+00
β	3.19E+00
δ	-7.71E-01
γ	-4.94E-01

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

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E' (Mpa)	Phase Angle (deg)	Cov. E' (%)	Cov. Phase Angle (deg.)
4	10	1.27E+03	13985.33	10.22	6.52	3.05
4	1	1.27E+02	10501.67	13.46	7.64	3.11
4	0.1	1.27E+01	7370.67	18.03	7.23	2.95
20	10	1.34E+01	6752	20.45	2.76	0.43
20	1	1.34E+00	3937	26.35	2.2	0.27
20	0.1	1.34E-01	2010	31.31	2.64	1.02
40	10	8.76E-02	1805.33	34.98	5.47	1.07
40	1	8.76E-03	726.47	35.02	5.12	1
40	0.1	8.76E-04	288.2	31.7	3.85	1.91
40	0.01	8.76E-05	129.8	26.21	1.27	1.8

Figure 111: Alpha-Fatigue WVP766 Peak Dynamic Modulus Output

Project Name:	WVP766
Analysis Performed by:	Laura E. Dalton
Analysis Date:	5/23/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\WVP766\Inputs
Output Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\WVP766\Outputs
Comments:	

Number of Fatigue Tests:	3
Damage Model Function:	Exponential

Damage Model Coefficients	
a	-1.01E-04
b	7.92E-01
y	N/A
z	N/A
alpha	3.58
Parameter r in Failure Crit.	5.33E+05
Parameter s in Failure Crit.	-7.47E-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 _{finger}$ (MPa)	Nf	G^R
WVP766 S6	15	10	8872.8	9757	15550	1.05E+02
WVP766 S7	15	10	8867.8	9678	4335	6.48E+02
WVP766 S8	15	10	8878.4	9231	59117	1.97E+01

Figure 112: Alpha-Fatigue WVP766 Peak Damage Functions Output

Project Name: WVP766
Analysis Performed by: Laura E. Dalton
Analysis Date: 5/23/2016
Testing Performed by: Laura E. Dalton
Default Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\WVP766\Inputs
Output Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\WVP766\Outputs
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	6.50E+17
K2	6.154
K3	-5.129

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	3.09E-17
K2	-5.119
K3	5.327

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	3.09E-17
K2	5.119
K3	0.208

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

Traditional Strain Fatigue Relationship (psi units)	
K1	3.30E+13
K2	6.154
K3	-5.129

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	4.62E-17
K2	-5.119
K3	5.327

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	4.62E-17
K2	5.119
K3	0.208

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	56
10	61
15	72
20	85
25	114

Figure 113: Alpha-Fatigue WVP766 Peak Model Prediction Output

Project Name: WVP766
Analysis Performed by: Laura E. Dalton
Analysis Date: 6/6/2016
Testing Performed by: Laura E. Dalton
Default Directory: E:\GRA\Analysis\Fatigue Data\WVP766\Inputs

Output Directory: E:\GRA\Analysis\Fatigue Data\WVP766\Output_Default

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	192.07	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTS	N/A	
C	N/A	

Mastercurve Function	
κ	1.15E+00
β	3.19E+00
δ	-7.71E-01
γ	-4.94E-01

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

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E' (Mpa)	Phase Angle (deg)	Cov. E' (%)	Cov. Phase Angle (deg.)
4	10	1.27E+03	13985.33	10.22	6.52	3.05
4	1	1.27E+02	10501.67	13.48	7.64	3.11
4	0.1	1.27E+01	7370.67	18.03	7.23	2.95
20	10	1.34E+01	6752	20.45	2.76	0.43
20	1	1.34E+00	3937	28.35	2.2	0.27
20	0.1	1.34E-01	2010	31.31	2.64	1.02
40	10	8.76E-02	1805.33	34.98	5.47	1.07
40	1	8.76E-03	726.47	35.02	5.12	1
40	0.1	8.76E-04	288.2	31.7	3.85	1.91
40	0.01	8.76E-05	129.8	28.21	1.27	1.8

Figure 114: Alpha-Fatigue WVP766 Default Dynamic Modulus Output

Project Name: WVP766
Analysis Performed by: Laura E. Dalton
Analysis Date: 8/6/2016
Testing Performed by: Laura E. Dalton
Default Directory: E:\GRA\Analysis\Fatigue Data\WVP766\Inputs
Output Directory: E:\GRA\Analysis\Fatigue Data\WVP766\Output_Default
Comments:

Number of Fatigue Tests: 3
Damage Model Function: Exponential

Damage Model Coefficients	
a	-9.34E-05
b	7.98E-01
y	N/A
z	N/A
alpha	3.58
Parameter r in Failure Crit.	7.90E+04
Parameter s in Failure Crit.	-5.40E-01

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

$$C = 1 - yS^z$$

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

Test Name	Temperature (deg. C)	Frequency (Hz)	$ E' _{LVE}$ (MPa)	$ E' _{finger}$ (MPa)	Nf	G^R
WVP766 S5	15	10	8872.8	9757	5515	1.73E+02
WVP766 S7	15	10	8867.8	9678	1835	9.82E+02
WVP766 S7 at 15C	15	10	8878.4	9231	7955	8.13E+01

Figure 115: Alpha-Fatigue WVP766 Default Damage Functions Output (S7 at 15°C is S8)

Project Name: WVP766
Analysis Performed by: Laura E. Dalton
Analysis Date: 6/6/2016
Testing Performed by: Laura E. Dalton
Default Directory: E:\GRA\Analysis\Fatigue Data\WVP766\Inputs
Output Directory: E:\GRA\Analysis\Fatigue Data\WVP766\Output_Default
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	1.45E+07
K2	3.241
K3	-2.202

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	2.97E-04
K2	-3.845
K3	2.828

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	2.97E-04
K2	3.845
K3	-1.018

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

Traditional Strain Fatigue Relationship (psi units)	
K1	2.07E+05
K2	3.241
K3	-2.202

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	4.17E-05
K2	-3.845
K3	2.828

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	4.17E-05
K2	3.845
K3	-1.018

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	18
10	18
15	18
20	20
25	25

Figure 116: Alpha-Fatigue WVP766 Default Model Prediction Output

Project Name:	WVP882
Analysis Performed by:	Laura E. Dalton
Analysis Date:	5/23/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\WVP882\Inputs
Output Directory:	C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\WVP882\Outputs
Comments:	

Test Protocol:	PP-81/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	198.02	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTS	N/A	
C	N/A	

Mastercurve Function	
κ	1.22E+00
β	3.12E+00
δ	-8.80E-01
γ	-5.11E-01

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

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E' (Mpa)	Phase Angle (deg)	Cov. E' (%)	Cov. Phase Angle (deg.)
4	10	1.47E+03	14490.67	10.36	4.27	4.17
4	1	1.47E+02	10880	13.74	5.49	3.93
4	0.1	1.47E+01	7487.33	18.5	6.48	3.66
20	10	1.35E+01	6463.33	21.89	3.64	1.75
20	1	1.35E+00	3640	27.64	3.78	2.03
20	0.1	1.35E-01	1837.67	31.84	4.12	1.96
40	10	7.56E-02	1554	36.2	3.91	1
40	1	7.56E-03	614.9	35.23	5.45	1.43
40	0.1	7.56E-04	239.33	31.57	5.15	1.8
40	0.01	7.56E-05	111.53	26.09	2.15	3.91

Figure 117: Alpha-Fatigue WVP882 Peak Dynamic Modulus Output

Project Name: WVP882
Analysis Performed by: Laura E. Dalton
Analysis Date: 5/23/2016
Testing Performed by: Laura E. Dalton
Default Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\WVP882\Inputs
Output Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\WVP882\Outputs
Comments:

Number of Fatigue Tests: 3
Damage Model Function: Exponential

Damage Model Coefficients	
a	-2.74E-04
b	7.14E-01
y	N/A
z	N/A
alpha	3.531
Parameter r in Failure Crit.	3.23E+05
Parameter s in Failure Crit.	-6.47E-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^*_{finger} (MPa)	Nf	G^R
WVP882 S7	15	10	8821.6	9419	30394	4.07E+01
WVP882 S8	15	10	8838.7	9676	2455	2.07E+03
WVP882 S9	15	10	8830.2	8978	5175	5.12E+02

Figure 118: Alpha-Fatigue WVP882 Peak Damage Functions Output

Project Name: WVP882
Analysis Performed by: Laura E. Dalton
Analysis Date: 5/23/2018
Testing Performed by: Laura E. Dalton
Default Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\WVP882\Inputs
Output Directory: C:\Users\user\Desktop\Laura Dalton\GRA\AMPT\Fatigue Data\WVP882\Outputs
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	1.04E+13
K2	4.178
K3	-3.423

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	8.21E-10
K2	-4.538
K3	3.978

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	8.21E-10
K2	-4.538
K3	-0.56

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

Traditional Strain Fatigue Relationship (psi units)	
K1	1.40E+10
K2	4.178
K3	-3.423

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	2.78E-10
K2	-4.538
K3	3.978

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	2.78E-10
K2	-4.538
K3	-0.56

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	33
10	36
15	41
20	49
25	66

Figure 119: Alpha-Fatigue WVP882 Peak Model Prediction Output

Project Name:	WVP882
Analysis Performed by:	Laura E. Dalton
Analysis Date:	6/6/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	E:\GRA\Analysis\Fatigue Data\WVP882\Inputs
Output Directory:	E:\GRA\Analysis\Fatigue Data\WVP882\Output_Default
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	198.02	kJ/mol
a1	N/A	
a2	N/A	
A	N/A	
VTS	N/A	
C	N/A	

Mastercurve Function	
κ	1.22E+00
β	3.12E+00
δ	-8.80E-01
γ	-5.11E-01

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

Temperature (deg. C)	Frequency (Hz)	Reduced Frequency (Hz)	E* (Mpa)	Phase Angle (deg)	Cov. E* (%)	Cov. Phase Angle (deg.)
4	10	1.47E+03	14490.67	10.36	4.27	4.17
4	1	1.47E+02	10880	13.74	5.49	3.93
4	0.1	1.47E+01	7487.33	18.5	6.48	3.66
20	10	1.35E+01	6463.33	21.89	3.64	1.75
20	1	1.35E+00	3640	27.64	3.78	2.03
20	0.1	1.35E-01	1837.67	31.84	4.12	1.96
40	10	7.56E-02	1554	36.2	3.91	1
40	1	7.56E-03	614.9	35.23	5.45	1.43
40	0.1	7.56E-04	239.33	31.57	5.15	1.8
40	0.01	7.56E-05	111.53	26.09	2.15	3.91

Figure 120: Alpha-Fatigue WVP882 Default Dynamic Modulus Output

Project Name:	WVP882
Analysis Performed by:	Laura E. Dalton
Analysis Date:	6/6/2016
Testing Performed by:	Laura E. Dalton
Default Directory:	E:\GRA\Analysis\Fatigue Data\WVP882\Inputs
Output Directory:	E:\GRA\Analysis\Fatigue Data\WVP882\Output_Default
Comments:	

Number of Fatigue Tests:	3
Damage Model Function:	Exponential

Damage Model Coefficients	
a	-3.85E-04
b	6.80E-01
y	N/A
z	N/A
alpha	3.531
Parameter r in Failure Crit.	7.48E+04
Parameter s in Failure Crit.	-5.41E-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' _{finger}$ (MPa)	Nf	G^R
WVP882 S7	15	10	8821.6	9419	6635	8.34E+01
WVP882 S8	15	10	8838.7	9676	935	3.03E+03
WVP882 S9	15	10	8830.2	8978	2255	7.35E+02

Figure 121: Alpha-Fatigue WVP882 Default Damage Functions Output

Project Name: WVP882
Analysis Performed by: Laura E. Dalton
Analysis Date: 8/8/2016
Testing Performed by: Laura E. Dalton
Default Directory: E:\GRA\Analysis\Fatigue Data\WVP882\Inputs
Output Directory: E:\GRA\Analysis\Fatigue Data\WVP882\Output_Default
Comments:

Traditional Strain Fatigue Relationship (kPa units)	
K1	2.36E+08
K2	3.089
K3	-2.296

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

Traditional Stress Fatigue Relationship 1 (kPa units)	
K1	1.14E-01
K2	-3.62
K3	2.328

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

Traditional Stress Fatigue Relationship 2 (kPa units)	
K1	1.14E-01
K2	3.62
K3	-1.292

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

Traditional Strain Fatigue Relationship (psi units)	
K1	2.81E+06
K2	3.089
K3	-2.296

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

Traditional Stress Fatigue Relationship 1 (psi units)	
K1	9.38E-03
K2	-3.62
K3	2.328

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

Traditional Stress Fatigue Relationship 2 (psi units)	
K1	9.38E-03
K2	3.62
K3	-1.292

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

Endurance Limit (microstrain)	
Temperature (deg. C)	Endurance Limit
5	11
10	12
15	14
20	16
25	21

Figure 122: Alpha-Fatigue WVP882 Default Model Prediction Output

Appendix E: Flow Number

Francken Model Fitting Coefficients

Mix	REP	A	B	C	D
AA937	S8	1865	0.399	1714	0.0017
	S9	1944	0.384	2204	0.0013
	S10	1762	0.398	1797	0.0015
	S11	1823	0.393	1734	0.0014
JAP909	S5	1377	0.467	1436	0.0039
	S9	2075	0.412	1545	0.0040
	S10	1972	0.410	2125	0.0031
	S11	1977	0.422	1266	0.0041
JFA060	S8	2117	0.398	1686	0.00351
	S9	2018	0.403	1456	0.00323
	S10	1870	0.427	617	0.00458
	S11	1753	0.392	1030	0.00235
JFA115	S9	1905	0.417	818	0.00485
	S10	2230	0.393	1177	0.00416
	S11	2111	0.366	1057	0.00247
JFA429	S9	1709	0.390	903	0.00284
	S10	1508	0.396	693	0.00217
KP483	S5	1344	0.428	584	0.00314
	S9	1831	0.374	936	0.00213
	S10	1590	0.410	612	0.00306
	S11	1737	0.392	721	0.00265
WVP523	S9	1252	0.412	1674	0.00153
	S10	1381	0.410	1351	0.00183
	S11	1265	0.418	1361	0.00183
	S12	1475	0.401	2289	0.00158
WVP766	S9	1751	0.442	900	0.00566
	S10	2017	0.418	1102	0.00478
	S11	1511	0.428	955	0.00351
	S12	1878	0.412	771	0.00447
WVP882	S5	1379	0.493	744	0.00538
	S6	1485	0.458	1000	0.00413
	S10	1942	0.430	1195	0.00454
	S11	2024	0.417	1479	0.00377

Appendix F: Additional Images of Laboratory Equipment

Figure 123: Coring and Sawing Laboratory Equipment

Figure 124: CoreLok Adjustments for Gyrotory Samples

Figure 125: Conditional Chamber for Temperatures 17°C and Lower